

SACE TWO AUSTRALIAN CURRICULUM

CHEMISTRY

WORKBOOK
FOURTH EDITION

MARIE DAZIANI
KATE FRYER
STEPHEN TULIP



ADELAIDE
TUITION
CENTRE

THE AUTHORS

Marie Daziani B.Ed (Sec), B.Sc

Marie has extensive teaching experience in SACE and International Baccalaureate Chemistry across Catholic and Independent schools in South Australia. Marie has a passion for teaching and has thoroughly enjoyed her volunteer work with Cambodia Husk Schools in recent years.

Kate Fryer B.Sc. (Biomedical Science), B.Ed., Grad.Cert.Ed

Kate has taught senior Chemistry since 2009, bringing extensive expertise in SACE moderation and exam assessment. With earlier tertiary qualifications in Education and Biomedical Science, she is currently completing her Doctorate in Education at the University of South Australia. Alongside her nearly 15 years of middle and senior-level leadership experience across Catholic and Independent schools, she is committed to supporting the holistic development of all students, maintaining both an academic and pastoral focus.

Stephen Tulip M.Teach, B.Sc.(Hons) (Chemistry), B.A.

Stephen graduated from the University of Adelaide with a B.Sc. in Chemistry and a B.A. in Psychology and French. After teaching and demonstrating undergraduate Chemistry at the University of Adelaide for six years, he obtained his M.Teach from the University of South Australia. Stephen has been teaching middle and senior Science at Gleeson College in Golden Grove since 2019.

PUBLISHING INFORMATION

This Workbook is part of the Essentials series, designed to support the teaching of SACE Stage 1 and 2 subjects in South Australia. It is specially designed to meet the requirements of the SACE Stage 2 Australian Curriculum Chemistry.

The Essentials Education series is published by

Adelaide Tuition Centre,

PO Box 997, North Adelaide SA 5006.

TELEPHONE (08) 8180 0695

Essentialseducation.com.au

LIBRARY CATALOGUE:

Daziani; Marie - Fryer; Kate - Tulip; Stephen

1. Chemistry, SACE2 Australian Curriculum - 2. **Essentials Workbook**

ISBN - 978-1-925505-64-1

Fourth Edition 2025.

Copyright © Essentials Education 2025.

COPYRIGHT INFORMATION

The copyright of the text of this book remains the property of the authors and the copyright of the diagrams and cartoons belongs to the publisher. All rights are reserved except under the conditions described in the Copyright Act 1968 of Australia and subsequent amendments. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, without the prior permission of the publisher. While every care has been taken to trace and acknowledge copyright, the publishers tender apologies for any accidental infringement where copyright has proved traceable.

Preface

Welcome to SACE Stage 2 Chemistry.

This book has been thoughtfully developed to support students and educators on their journey through the Stage 2 Chemistry curriculum, following the structure outlined in the SACE Subject Outline. Each of the four topics presents a detailed exploration of the prescribed content, complete with clear explanations, informative diagrams, exam-style questions, and topic summary tests.

The Science as a Human Endeavour (SHE) highlights provide students with insights into the historical development of key concepts, collaborative projects at local and international levels, and how chemistry interacts with society and technology. This approach helps students engage with the subject and appreciate its impact on global challenges and ongoing innovations shaping our modern world. Teachers and students should note that the space allocated in this resource to answer SHE questions do not necessarily reflect the student response length required to answer the question with full marks.

This resource is designed to consolidate understanding through real-world applications and prepare students for the school-based and external assessment they will encounter. Recommended solutions for all questions and tests are provided at the back of the book for ease of study.

The questions in this workbook are structured to build students' confidence in meeting the SACE Performance Standards. They vary in type, length, and complexity, allowing students to develop their ability to recall core concepts, apply them to practical scenarios, and transfer their knowledge across diverse contexts. Knowledge from Stage 1 Chemistry is assumed, allowing this resource to go beyond foundational ideas and introduce students to more complex and nuanced aspects of chemistry.

Each chapter concludes with a summary test that mirrors the style and rigor of the SACE external assessment. These tests are designed to help students self-assess their progress and gain a better understanding of the types of questions they may encounter.

As authors, we hope this book will inspire curiosity, deepen understanding, and help students recognise the integral role that chemistry plays in our everyday lives. We believe that chemistry has the power to shape society and solve pressing issues, and we hope this course will spark a lifelong interest in the field.

We wish you every success in your studies.

Marie Daziani
Kate Fryer
Stephen Tulip

Topic 1: Monitoring the environment	1
1.1 Global warming and climate change.	1
1.2 Photochemical smog.	22
1.3 Volumetric analysis.	38
1.4 Chromatography.	76
1.5 Atomic spectroscopy.	90
Summary test 1: Monitoring the environment.	111
Topic 2: Managing chemical processes	120
2.1 Rates of reaction.	120
2.2 Equilibrium and yield.	135
2.3 Optimising Production.	147
Summary test 2: Managing chemical processes.	154
Topic 3: Organic and biological chemistry	160
3.1 Introduction.	160
3.2 Alcohols.	170
3.3 Aldehydes and Ketones.	176
3.4 Carbohydrates.	185
3.5 Carboxylic acids.	191
3.6 Amines.	200
3.7 Esters.	205
3.8 Amides.	216
3.9 Triglycerides.	224
3.10 Proteins.	241
Summary test 3: Organic and biological chemistry.	256
Topic 4: Managing resources	271
4.1 Energy.	271
4.2 Water.	316
4.3 Soil.	332
4.4 Materials.	359
Summary test 4: Managing resources.	398
Solutions	347
Topic 1 solutions: Monitoring the environment.	409
Summary test 1 solutions: Monitoring the environment.	438
Topic 2 solutions: Managing chemical processes.	444
Summary test 2 solutions processes.	453
Topic 3 solutions: Organic and biological chemistry.	457
Summary test 3 solutions: Organic and biological chemistry.	474
Topic 4 solutions: Managing resources.	482
Summary test 4 solutions: Managing resources.	507
Appendices	514
Appendix 1: Molar masses of the elements.	514
Appendix 2: The periodic table of elements.	515
Appendix 3: SI prefixes, symbols and values.	516

Topic 1: Monitoring the environment

1.1 Global warming and climate change

Science understanding

Some gases in the atmosphere, called 'greenhouse gases', keep the Earth's atmosphere warmer than it would be without these gases. This is known as the 'greenhouse effect'.

Describe the action of the common greenhouse gases, carbon dioxide and methane, to maintain a steady temperature in the Earth's atmosphere.

© SACE 2025

The greenhouse effect

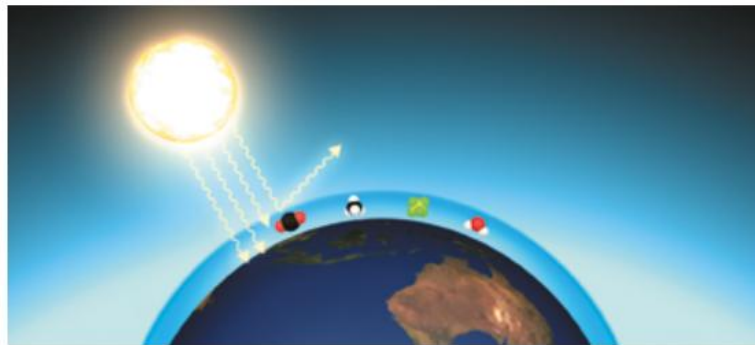


Figure 1.1.1: Solar radiation entering Earth's atmosphere.

Solar radiation entering Earth's atmosphere consists of infrared radiation, visible light and ultraviolet radiation (UV). Solar radiation is composed largely of visible wavelengths, longer infrared wavelengths, and a smaller component of shorter ultraviolet wavelengths.

Approximately 30% of the solar radiation reaching Earth is reflected to space by ice, snow, and clouds. The remaining 70% is absorbed by the atmosphere and the surface of the Earth, warming it (Figure 1.1.1). All objects emit thermal radiation, including the Earth, which emits mostly in the infrared region of the electromagnetic spectrum. Overall, the thermal radiation emitted by the Earth corresponds to lower energy and longer wavelengths than the solar radiation it absorbs.

There are many gases in the atmosphere that allow the transmission of shorter-wavelength visible light but which readily absorb longer-wavelength infrared energy. These gases absorb the Earth's thermal radiation and distribute it around the atmosphere and surface, decreasing the amount of energy escaping to space and increasing the average temperature of the Earth's surface and **troposphere** (the lower layer of the atmosphere) (Figure 1.1.2). This effect is called the **greenhouse effect**, and the gases are **greenhouse gases**, by analogy with garden greenhouses, which use glass to trap heat in a similar way (Figure 1.1.3).

The greenhouse effect raises the Earth's average temperature from below 0 °C to approximately 15 °C, sustaining life on Earth.

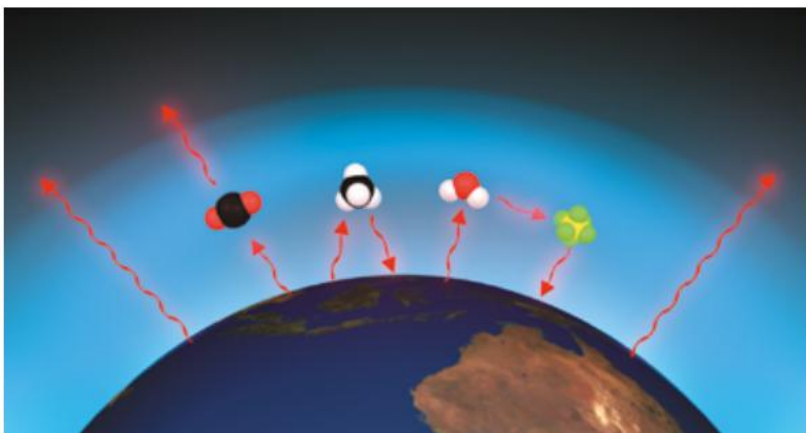


Figure 1.1.2: The natural greenhouse effect.

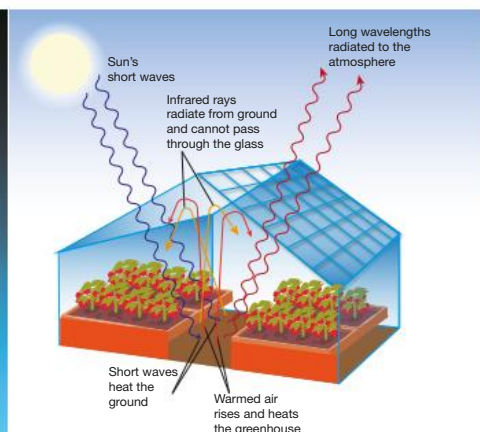


Figure 1.1.3: The greenhouse effect in a garden greenhouse.

Greenhouse gases

Greenhouse gases absorb thermal radiation in the infrared region of the electromagnetic spectrum. Greenhouse gases originate from both natural and synthetic sources (Figure 1.1.4). The most important greenhouse gases are water vapour, carbon dioxide, methane, and nitrous oxide. Greenhouse gases can be compared to carbon dioxide in their relative ability to absorb thermal radiation. This value is referred to as the **global warming potential (GWP)**.

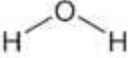
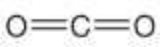
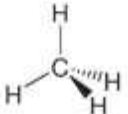
Compound	water (vapour)	carbon dioxide	methane	nitrous oxide
Molecular structure	 	 	 	 
Molecular formula	H ₂ O	CO ₂	CH ₄	N ₂ O
Molecular geometry	v-shaped	linear	tetrahedral	linear
Global Warming Potential (GWP)	–	1	28	265

Figure 1.1.4: Natural and synthetic greenhouse gases.

Cycles in nature, such as the **carbon cycle**, the **water cycle** and **nitrogen cycle**, are responsible for the formation of naturally occurring greenhouse gases that enter the atmosphere. **Anthropogenic** (originating from human activity) influences have added to the concentrations of naturally occurring greenhouse gases, while also introducing synthetic greenhouse gases.

Greenhouse Gas	Natural Sources	Anthropogenic Sources
Water vapour	Water is present in the atmosphere as water vapour, which has a warming effect, and clouds, which have a cooling effect. Water moves between the soil, natural bodies of water (such as oceans and lakes), and the atmosphere via the water cycle.	Humans are not directly increasing the amount of water vapour in the atmosphere, but the amount is expected to rise as global warming raises the temperature of the Earth and causes additional evaporation from the oceans.
Carbon dioxide (<5% anthropogenic)	Carbon dioxide is released during the aerobic respiration and decomposition of organisms, natural combustion of vegetation, and volcanic eruptions.	Humans release large amounts of carbon dioxide by burning fossil fuels to generate heat and electricity (85%), clearing forests (10%), and producing and using cement (5%).
Methane (65% anthropogenic)	Methane is released during the anaerobic decomposition of organisms by microbes in soil, wetlands, and the ocean. It is also released when ice containing methane hydrates melts.	Humans release methane in many ways, including by extracting, transporting and using fossil fuels (35%), through raising livestock with methanogenic gut bacteria (30%), and promoting anaerobic decay in landfills (15%).
Nitrous oxide (40% anthropogenic)	Nitrous oxide is released by some microbes in the soil and ocean and is produced by lightning strikes and other chemical reactions in the atmosphere.	Humans increase the amount of nitrous oxide produced by bacteria by using fertilisers in agriculture (70%). Burning fossil fuels also produces nitrous oxide (10%).

Science understanding

Anthropogenic increases in greenhouse gases disrupt the thermal balance of the atmosphere.

Explain the warming associated with global climate change and its consequences for the environment.

© SACE 2025

Earth's thermal balance

On average, the temperature at the Earth's surface is approximately 32 °C higher than it would be in the absence of greenhouse gases. The greenhouse effect is most strongly influenced by carbon dioxide and water vapour.

Mean surface temperature (°C) (without the greenhouse effect)	-17
Mean surface temperature (°C) (with the greenhouse effect)	15
Greenhouse warming	32

For thousands of years, the temperature of the Earth's atmosphere has been in **thermal balance**, with the amount of thermal radiation entering the atmosphere in equilibrium with the amount of thermal radiation emitted back into space (Figure 1.1.5).

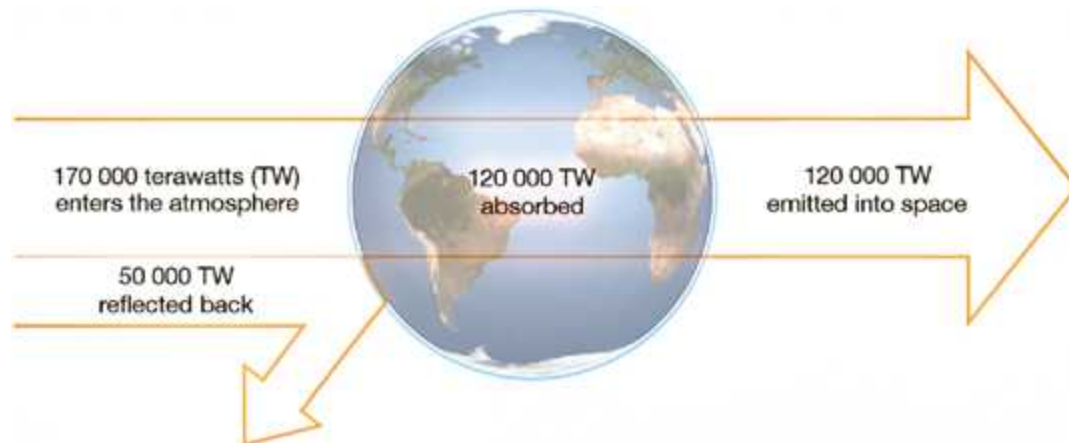


Figure 1.1.5: Thermal balance.

Global warming

As concentrations of greenhouse gases have risen due to human activity, less thermal radiation is escaping the Earth, generating a **thermal imbalance**. The Earth's temperature will rise until a new equilibrium is established, when the increased temperature of the Earth causes it to emit the same amount of thermal energy as it is absorbing (Figure 1.1.6). This resulting increase in temperature is referred to as **global warming**.

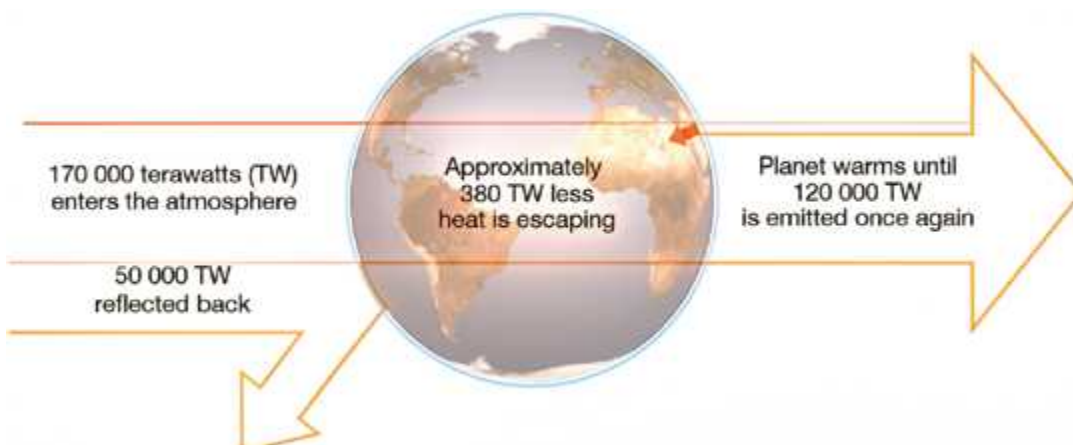


Figure 1.1.6: Thermal imbalance.



Science as a human endeavour

Global Climate Monitoring Networks

The establishment and evolution of global climate monitoring networks exemplifies the power of international scientific collaboration in addressing complex environmental challenges. This worldwide effort began with pioneering work at Hawaii's Mauna Loa Observatory, where Charles Keeling initiated systematic CO₂ measurements, and has expanded to include facilities such as Tasmania's Cape Grim station. These monitoring stations have created an unprecedented record of atmospheric changes, fundamentally transforming our understanding of global climate systems.

The sophistication of climate monitoring has grown through the integration of multiple data sources and technologies. Scientists have successfully merged historical data from ice cores with modern atmospheric measurements, creating a comprehensive record of Earth's atmospheric composition spanning thousands of years. The deployment of the Argo float network has revolutionised ocean monitoring, providing crucial data about ocean temperature, salinity, and acidification patterns. This extensive monitoring network operates through carefully standardised measurement protocols, ensuring data consistency and reliability across global locations.

The collaborative nature of climate monitoring has produced transformative scientific insights. Researchers have documented conclusive evidence of rising greenhouse gas concentrations and their relationship to global temperature changes. Ocean monitoring has revealed concerning patterns of acidification and their impacts on marine ecosystems. These findings have demonstrated regional variations in climate change effects and validated climate model predictions with increasing accuracy. The resulting scientific understanding has informed international policy decisions and highlighted the urgent need for collective action in addressing climate change.

Question

1. (a) Identify an example that demonstrates how collaboration between scientists using different technologies or data sources has enhanced our understanding of climate change. Explain why these diverse sources are valuable.

(3 marks) **KA3**

-
- (b) Identify an example of how the development of new technologies has improved climate monitoring. Discuss the significance of this improvement for global climate research.

(3 marks) **KA3**

-
-
- (c) Identify an example that shows how scientific knowledge from climate monitoring can be used to make predictions about environmental trends. Explain one benefit and one limitation of relying on this data for predictive purposes.

(3 marks) **KA3**

2. The impact of warming due to greenhouse gases can be seen by comparing Earth to other planets in our solar system. The details are summarised in the table below.

	Reflectivity (albedo) (%)	Mean surface temperature (without greenhouse effect) (°C)	Mean surface temperature (with greenhouse effect) (°C)	Greenhouse warming (°C)	Carbon dioxide present in the atmosphere (%w/v)
Earth	36	−17	15	32	0.040
Mars	25	−55	−50	5	95 (very thin atmosphere)
Venus	72	−42	467	509	96

- (a) Earth's atmosphere maintains temperatures that are suitable to sustain life.
- (i) **State** the mean surface temperature experienced on Earth without the greenhouse effect.
(1 mark) **IAE3**
- (ii) Explain how greenhouse gases cause the Earth to have a higher average temperature than it would in the absence of these gases.
(3 marks) **KA1**
- (iii) Explain how the anthropogenic increase in the atmospheric concentration of carbon dioxide and methane have caused a thermal imbalance.
(3 marks) **KA1**
- (b) Albedo refers to the reflectivity of the surface and atmosphere of the planet.
Suggest why albedo is taken into account when determining greenhouse warming.
(2 marks) **KA2**
- (c) Venus has a mean surface temperature of 467 °C and Mars −50 °C.
- (i) **Explain**, using data in the table, why the mean surface temperature of Venus is considerably higher than that of Earth.
(2 marks) **IAE3**

- (ii) The percentages of carbon dioxide in the atmospheres of Mars and Venus are almost equal.

Suggest one reason for the difference in the mean surface temperature of Mars and Venus.

(1 mark) **KA2**

3. An investigation was undertaken to determine the action of carbon dioxide as a greenhouse gas.

STEP 1: Two 2 L plastic bottles were assembled, one containing air and the other a small pellet of dry ice (solid carbon dioxide), with the lids removed. A carbon dioxide sensor was inserted into each bottle to measure the concentration of carbon dioxide. The concentration of carbon dioxide present in the air in the first bottle was found to be 404 ppm. On sublimation, the dry ice produced a concentration of 826 ppm of carbon dioxide in the second bottle.

STEP 2: A temperature sensor was inserted into each bottle and the opening sealed.

STEP 3: Both bottles were placed at equal distances from a 60-watt incandescent lamp and the temperature recorded at five-minute intervals for a period of 30 minutes.

- (a) From the procedure outlined,

- (i) **Identify** and **explain** the importance of the control of one factor in the investigation

(2 marks) **IAE1**

- (ii) **Identify** the independent variable in the investigation.

(1 mark) **IAE1**

- (iii) Hence, **state** a suitable hypothesis for the investigation.

(2 marks) **IAE1**

- (b) The results obtained are summarised in the table below.

	Concentration of CO ₂	
	404 ppm	826 ppm
Time (min)	Temperature (°C)	Temperature (°C)
0	22.0	22.0
5	22.5	24.0
10	24.0	25.5
15	25.0	28.0
20	26.0	29.5
25	26.5	31.0
30	27.0	33.0

Using the data obtained,

- (i) **Graph** both sets of data on the same set of axes.



(6 marks) **IAE2**

- (ii) **State** one conclusion that can be drawn from the data in relation to carbon dioxide as a greenhouse gas.

(1 mark) **IAE3**

4. With reference to the greenhouse effect and thermal imbalance, **state** and **explain** one similarity and one difference between the Earth and a garden greenhouse.

(4 marks) **KA2**

Anthropogenic (human) influences

Human activity has steadily increased the atmospheric concentrations of carbon dioxide and other greenhouse gases over the past 250 years. A growing population living in an increasingly industrialised and developed world has led to greater demand for natural resources and the subsequent increased release of greenhouse gases. The most significant change has been the increase in atmospheric carbon dioxide.

Since the industrial revolution (c. 1750), natural carbon deposits called **fossil fuels** (coal, crude oil, and natural gas) that had been undisturbed for millions of years have been mined and consumed for energy production and as **feedstock** (raw material) for the chemical industry. This leads to the release of large amounts of carbon dioxide and other greenhouse gases.

Greenhouse gases are slowly removed from the atmosphere via chemical reactions. For example, carbon dioxide is used during photosynthesis or absorbed into the ocean. However, these processes occur over thousands of years, and humans currently release far more greenhouse gases into the atmosphere each year than can be removed.

Global measurements

Atmospheric carbon dioxide concentrations have been accurately and reliably recorded by the scientific community for over 50 years.



Science as a human endeavour

Keeling's Curve

Charles Keeling of Scripps Institution of Oceanography was one of the first scientists to make regular measurements of atmospheric carbon dioxide concentrations. In 1958, Keeling began taking measurements of carbon dioxide concentration from Hawaii's Mauna Lao volcano observatory and at the South Pole. Before Keeling's measurements the scientific community had generally thought that concentrations of carbon dioxide in the atmosphere were highly variable with no significant trends apparent in recorded values.

Keeling's measurements initially revealed variation over the day and between seasons. The decay of plant matter over winter increases carbon dioxide levels; new growth of plants in spring reduces carbon dioxide levels due to increased levels of photosynthesis.

The long-term trend from measurements taken since 1958 at Mauna Lao observatory revealed a steady increase in atmospheric carbon dioxide concentrations, Keeling correlated this increase with the increased combustion of fossil fuels around the globe.

Today, carbon dioxide levels are monitored from sites all over the globe using increasingly sophisticated methods. Charles Keeling passed away in 2006. His son, Ralph Keeling, has carried on with his father's research.



Question

5. (a) Explain how the global monitoring of carbon dioxide levels demonstrates the SHE concept of Communication and Collaboration.

(3 marks) **KA3**

- (b) Explain how the impact of Keeling's findings on public policy regarding climate change demonstrates the SHE concept of Application and Limitation.

(4 marks) **KA3**

The recorded concentrations of carbon dioxide from atmospheric monitoring have been combined with carbon dioxide readings obtained from ice-core samples (Figure 1.1.7). Together, these readings represent thousands of years of data.

The data show that carbon dioxide levels have increased considerably over the past 1000 years. Although there is cyclical variation over periods of tens of thousands of years, carbon dioxide concentrations in the atmosphere are currently at the highest recorded levels in human history, with values exceeding 400 ppm. This trend correlates very closely with measurements taken for average global temperature.

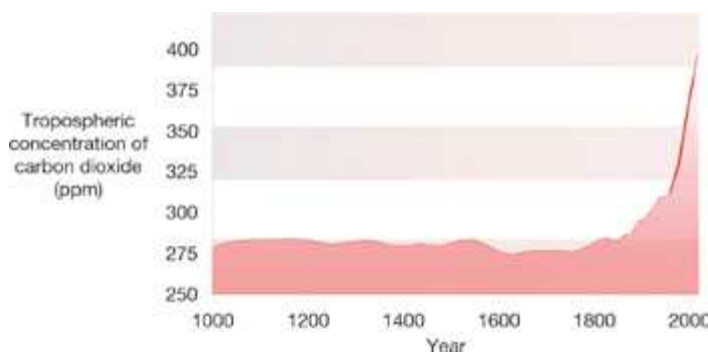


Figure 1.1.7: Variation in the tropospheric concentration of CO_2 over the past 1000 years.

Climate change

Climate can be monitored over periods of decades through the record of measurable patterns in the weather, such as temperature and rainfall. The impacts of global climate change are already significant and the rate of change continues to accelerate.

Global temperature rise

Globally, the average temperature has risen by nearly 1.5° C since 1850 (Figure 1.1.8). More than two-thirds of the warming has occurred since 1975 and the rate of warming continues to increase. The rising temperature is the driving force behind most major aspects of climate change, including shifts in rainfall patterns, melting of land and sea ice, rising sea levels, and increased frequency of extreme weather events.

Global feedback mechanisms have also driven further increases in temperature. For example, at higher temperatures more water vapour is present in the atmosphere due to greater evaporation, which in turn absorbs more energy while acting as a greenhouse gas, increasing temperatures in the troposphere.

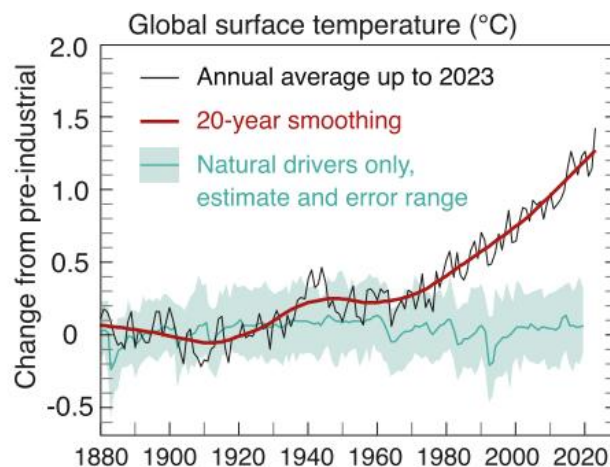


Figure 1.1.8: Global surface air temperature.

Melting ice

Rising temperatures cause land and sea ice to melt. The arctic is warming much faster than other parts of the Earth and the amount of arctic sea ice has declined by more than 50% since the first satellite records were made. Land ice and sea ice are important ecosystems that support hundreds of species of animals, but it is predicted that summertime sea ice will cease to exist in the next few decades.

Melting ice enters the Earth's oceans, causing a change in the temperature and salinity (hence density) in regions of the ocean. These changes are predicted to affect the circulation of global ocean currents.

The loss of reflectivity has a significant impact. With a decline in ice and snow, the reflectivity of the Earth is reduced, resulting in a decrease in reflected solar radiation and increased global temperatures, once again altering the global climate.

The decline in the extent of sea ice, land ice, and glaciers is shown in Figures 1.1.9, Figure 1.1.10, and Figure 1.1.11.

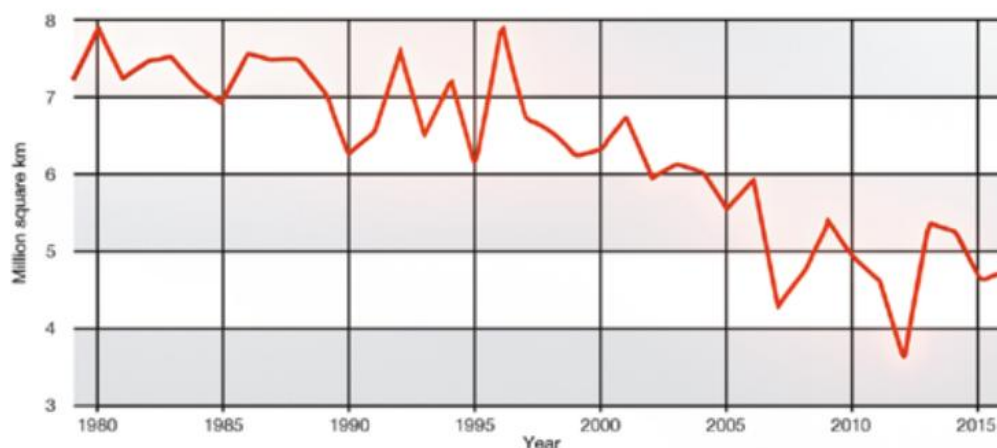


Figure 1.1.9: Arctic sea ice (1979–2017).

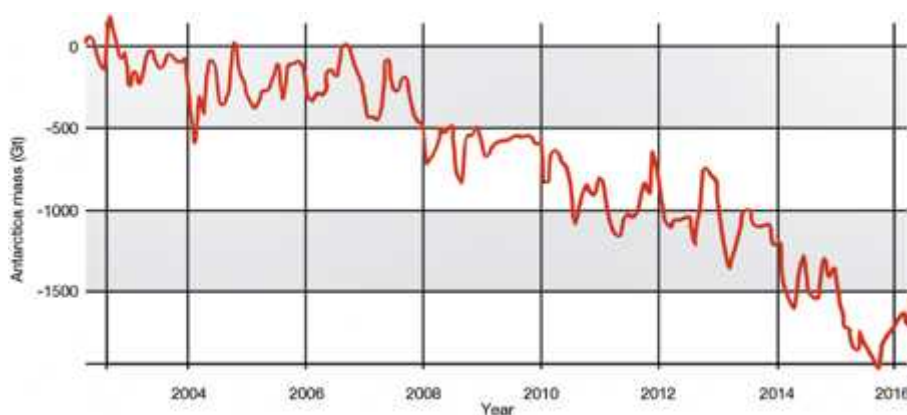


Figure 1.1.10: Ice mass measurements, Antarctica (2002–2017).

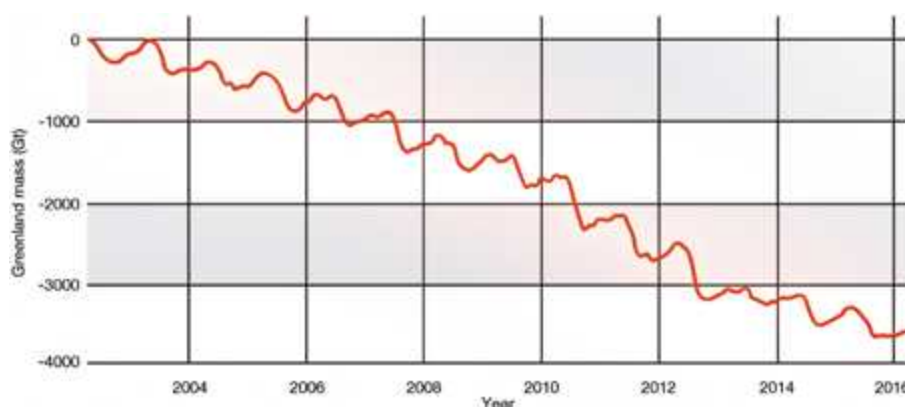


Figure 1.1.11: Ice mass measurements, Greenland (2002–2017).

Thawing permafrost (frozen soil and rock) in Greenland, Alaska and Siberia has also led to the release of methane (from methane hydrates in the ice) and other trapped greenhouse gases formed during the anaerobic decay of organic matter, contributing further to global warming.

Rising sea levels

Globally, sea levels have risen by approximately 20 cm in the last 100 years (Figure 1.1.12). As ocean temperatures increase, the water in the oceans undergoes thermal expansion and increases in volume, causing a subsequent rise in sea levels. Rising sea levels already threaten low-lying coastal communities in localised regions, particularly the Pacific Islands.

The sea level responds very slowly to changes in temperature, so the sea level rise will continue to accelerate until at least 2050 as a result of warming that has already happened. Depending on the amount of greenhouse gas emissions over the coming decades, total sea level rise by 2100 could be as low as 30 cm or as high as 1.6 m.

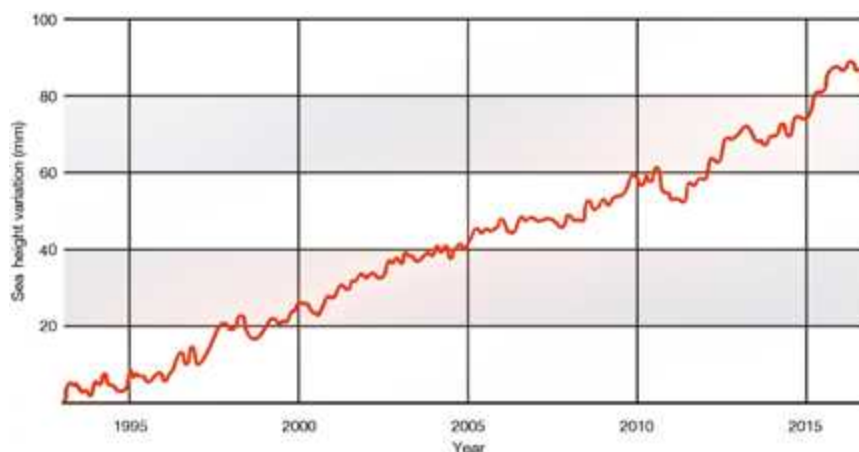


Figure 1.1.12: Satellite measurements of variation in sea height (1993–2017).

Changing rainfall patterns

Global warming is causing an increased rate of evaporation from the oceans and an increase in global average rainfall. However, the change in rainfall patterns is very unevenly distributed; some areas are receiving much more rainfall, while others receive much less. Shifts in rainfall patterns change the distribution of natural vegetation, causing extinctions and other permanent changes in ecosystems. Reduced rainfall also makes it harder to grow crops; the greatest direct threat of climate change to humanity is that changes in rainfall could cause the collapse of modern agriculture and lead to global famine.

Extreme weather events

Increased average temperature and changes in rainfall patterns significantly increase the frequency and severity of extreme weather events such as floods, fires, heatwaves, and damaging storms. These events can damage human infrastructure, cause widespread suffering and death, and put further strain on ecosystems.

Warming of oceans

Ocean temperatures and ocean heat content have steadily increased globally. The majority of the additional heat generated by the enhanced greenhouse effect is being absorbed by the world's oceans. The high specific heat capacity of water allows large quantities of energy to be absorbed. Much of the impact of the enhanced greenhouse effect on the surface of the globe has been masked by this absorption of energy.

An Australian perspective

The most evident effects of climate change in Australia are the increased frequency and severity of extreme weather events such as bushfires, floods, droughts, and cyclones.

Furthermore, the warming oceans around Australia threaten ocean ecosystems like the Great Barrier Reef through coral bleaching. Rates of sea level rise to the north, west, and southeast of Australia have exceeded the global average.



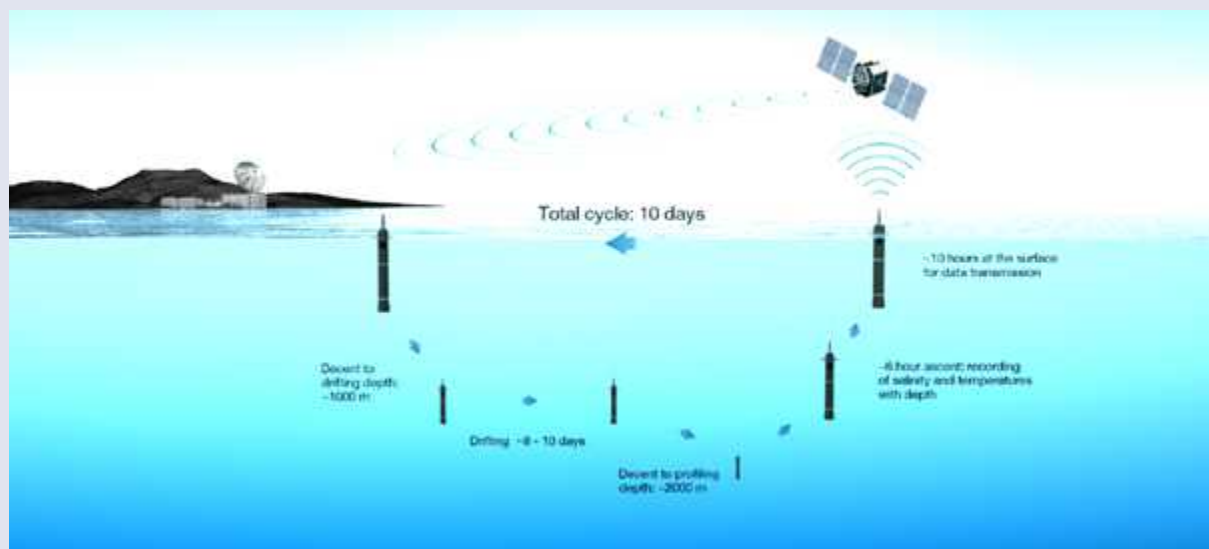
Science as a human endeavour

Argo – integrated global observation strategy

The Argo submersible program is an example of international collaboration with the support of more than 30 nations worldwide.

Argo consists of an array of more than 3800 submersible floats distributed throughout the world's oceans. The array is being used to record real-time data of ocean temperature, salinity and currents.

Submersible floats descend slowly to a depth of 2000 m and drift with the ocean currents while communicating with satellites to register global positioning and transfer data. Measurements of ocean temperature during the submersibles, descents have revealed that warming has extended to at least these recorded depths worldwide.



Question

6. (a) Describe how the development of the Argo submersible floats has contributed to our understanding of oceanographic conditions. Provide a specific example from the passage above.

(2 marks) **KA3**

- (b) Suggest how data collected by the Argo program could influence other scientific fields and/or public policy.

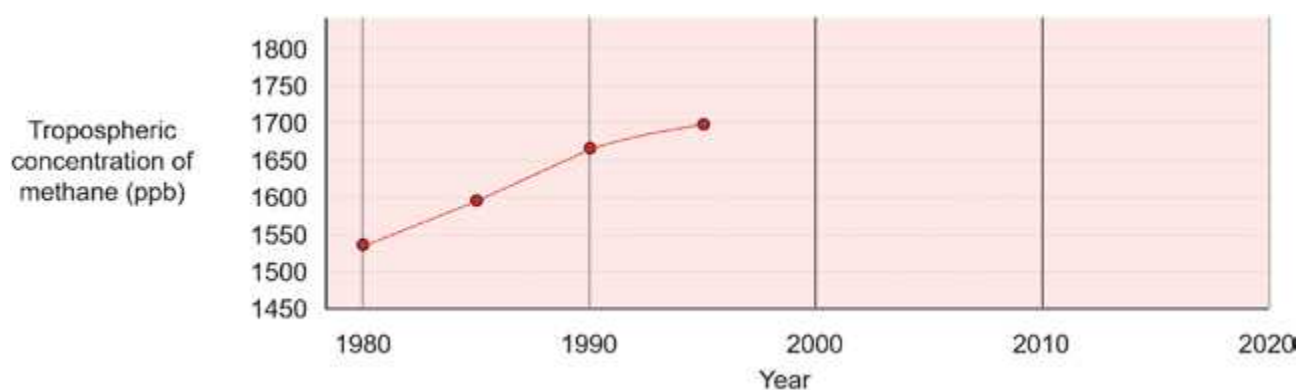
(2 marks) **KA3**

7. Atmospheric methane concentrations have increased steadily over the last century.

- (a) Methane concentrations have been recorded by the CSIRO, at Cape Grim near Tasmania, since 1978. Changes in the atmospheric concentration of methane can be seen in the table and graph below.

Year	Methane concentration (ppb)
1980	1540
1985	1602
1990	1666
1995	1701
2000	1732
2005	1731
2010	1751
2015	1789

Plot the remaining data for methane.



(2 marks) **KA4**

- (b) Large sinkholes have appeared in regions of Siberia, where trapped methane hydrate deposits in surface ice have suddenly and violently escaped into the atmosphere.
- (i) Methane sinkholes have been appearing more frequently across regions of Siberia in recent years.

Suggest one reason why the rate of formation of methane sinkholes has increased in recent years.

(1 mark) **KA2**

- (ii) **Explain** how methane emissions contribute to increased temperature in the Earth's troposphere.

(3 marks) **KA2**

- (iii) Methane is approximately 30 times more effective than carbon dioxide as a greenhouse gas. **Suggest**, however, one reason why the contribution of methane to global warming is less significant than carbon dioxide.

(1 mark) **KA2**

- (c) Methane is also formed from the decay of organic matter in landfill.

- (i) **State** one other source of methane derived from human activities.

(1 mark) **KA1**

- (ii) Methane generated in landfill may be collected in pipes below the landfill and burnt as a fuel source to produce electricity.

Discuss one advantage and one disadvantage of this process, in terms of greenhouse emissions.

(2 marks) **KA3**



Science as a human endeavour

A new study has revealed that adding an Australian native red seaweed called *asparagopsis armata* to cattle feed can significantly reduce methane emissions from dairy farms. Published in an international journal, the study found that incorporating seaweed-infused canola oil into feedlots dramatically reduced methane emissions without affecting milk quality or quantity. This offers dairy farmers a chance to lower their carbon footprints and opens up a new marketing opportunity for “low emissions” products.

The *asparagopsis* seaweed contains bromoform, which inhibits methane production in cows, sheep, and goats. Studies over the past decade have shown that this feed additive can cut methane emissions by 80 to 98 percent. In Victoria, agriculture contributes significantly to greenhouse emissions, with livestock methane making up about 70 percent. Reducing these emissions by 80 percent could equate to removing approximately 2 million cars from the roads. Immersion Group, the only company in Victoria licensed to farm and sell *asparagopsis*, achieved its first commercial harvest in 2022. The seaweed can be either freeze-dried and sprinkled over cattle feed or soaked in canola oil.



Question

8. (a) Explain how the potential for new “low emissions” marketing strategies for dairy products demonstrates the SHE concept of Influence.

(3 marks) **KA3**

- (b) Identify and explain an example from the passage of the SHE concept of Application and Limitation.

(3 marks) KA3

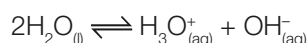
Science understanding

Calculate the pH of solutions given the concentration of H^+ or OH^- , and vice versa.

© SACE 2025

Amphiprotic water

Water is an amphiprotic substance that can both donate and accept a proton.



The resulting equilibrium, established at 25°C , results in an equal concentration of both hydronium ions (H_3O^+) and hydroxide ions (OH^-). Both ions are present at a concentration of $1.0 \times 10^{-7} \text{ mol L}^{-1}$ under these conditions. In aqueous solutions, $[\text{H}_3\text{O}^+]$ is equivalent to $[\text{H}^+]$.

The concentrations of hydronium ions and hydroxide ions present in solution are extremely small. It is more convenient to express these concentrations as values on the **pH scale**.

pH is calculated from the concentration of hydronium ions present, and represents the **acidity** of an aqueous solution. **pOH** is calculated from the concentration of hydroxide ions present, and represents the **alkalinity** of an aqueous solution.

Calculations of pH and concentration of hydronium ions

To calculate the pH of a solution, the concentration of hydronium ions, $[\text{H}_3\text{O}^+]$, expressed in mol L^{-1} , is required.

$$\text{pH} = -\log_{10} [\text{H}_3\text{O}^+]$$

For a strong monoprotic acid, the concentration of hydronium ions is equivalent to the concentration of the acid.

To calculate the concentration of hydronium ions, $[\text{H}_3\text{O}^+]$, in solution, the pH value is substituted into a rearrangement of the pH equation.

$$[\text{H}_3\text{O}^+] = 10^{-\text{pH}}$$

Example

Nitric acid is generated in the atmosphere from nitrogen dioxide present in exhaust emissions. This can lead to the formation of acid rain. In one sample of acid rain, the concentration of nitric acid was determined to be $6.31 \times 10^{-5} \text{ L}^{-1}$. Calculate the pH of the sample.

	Explanation	Calculation
STEP 1	Nitric acid is a strong monoprotic acid, therefore the concentration of hydronium ions is equal to the concentration of the acid.	$[\text{H}_3\text{O}^+] = [\text{HNO}_3]$ $\therefore [\text{H}_3\text{O}^+] = 6.31 \times 10^{-5} \text{ mol L}^{-1}$
STEP 2	The value is substituted into the expression for pH.	$\text{pH} = -\log_{10} [\text{H}_3\text{O}^+]$ $\text{pH} = -\log_{10} (6.31 \times 10^{-5})$ $\text{pH} = 4.21$

Example

Acid rain in some industrialised cities has been recorded at pH values as low as 2.4.

Calculate the concentration of hydronium ions at this pH.

	Explanation	Calculation
STEP 1	The pH value is substituted into the expression.	$[\text{H}_3\text{O}^+] = 10^{-\text{pH}}$ $[\text{H}_3\text{O}^+] = 10^{-2.4}$
STEP 2	Concentration units are applied to the value.	$[\text{H}_3\text{O}^+] = 3.98 \times 10^{-3} \text{ mol L}^{-1}$

Question**1**

9. Changes in the population and diversity of species of frogs near creeks and rivers can be used to assess the health of a waterway. Some species of frogs are able to tolerate pH values ranging from 6.5 to 4.0.
- (a) (i) **Calculate** the concentration of hydronium ions, in mol L^{-1} , at a pH of 6.5 and 4.0 and hence determine the highest concentration of hydronium ions the frogs can tolerate.

(5 marks) **KA4**

- (ii) **State** whether a shift in pH from 6.5 to 4.0 represents an increase or decrease in the acidity of the waterway.

(1 mark) **KA1**

- (iii) **Explain** why a small shift in pH from 6.5 to 4.0 represents a significant shift in hydronium ion concentration.

(2 marks) **KA2**

- (b) **Suggest** one human activity that could contribute to lowering the pH to a value of 4.0 in the waterway.

(1 mark) **KA1**

- (c) Frog eggs are made from calcium carbonate, CaCO_3 .

Suggest why lowered pH in creeks and rivers may cause damage to the eggs.

(1 mark) **KA2**



Science as a human endeavour

Acid rain

Acid rain is precipitation with a low pH. Typically, acid rain has a pH range from 4 to 5, whereas neutral water in the natural environment usually has a pH between 6.5 and 8.5. The primary causes of acid rain are emissions of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) associated with the burning of fossil fuels. These pollutants react with water molecules in the atmosphere to produce sulfuric acid and nitric acid, which then fall to the ground as acid rain.

The environmental impact of acid rain is extensive. In forests, acid rain weakens tree bark, making trees more susceptible to environmental stressors such as drought, extreme temperatures, and pests, and it depletes nutrients essential for plant growth like calcium and magnesium in soils. Aquatic ecosystems are negatively affected by the altered composition of the water, and the populations of microbes and insects are also affected.

Acid rain has significant impacts on human infrastructure too, causing paint to peel, accelerating the corrosion of steel structures such as bridges, and leading to the weathering of stone buildings and statues.



Extensive research on acid rain began in the 1960s, documenting its harmful effects on both the environment and human-made structures. Initially, scientists focused on local effects, but a systematic study on the long-distance transportation of pollutants from the United Kingdom to Norway was completed by Brynjulf Ottar in the 1970s. He was influenced by Waldemar Christofer Brøgger, who first recognised the international nature of the problems, and Swedish soil scientist Svante Odén, who highlighted Europe's acid rain problem in popular newspapers and a landmark paper in 1968.

This scientific study prompted governments in Europe and North America to sign the Convention on Long-Range Transboundary Air Pollution and enact air pollution regulations to reduce sulfur dioxide and nitrogen oxide emissions. These regulations have had positive outcomes, demonstrating the effective application of scientific knowledge in public policy.

Question

10. (a) Explain how the international cooperation in the research of acid rain demonstrates the SHE concept of Communication and Collaboration.

(3 marks) **KA3**

- (b) Explain how the enactment of air pollution regulations in response to acid rain demonstrates the SHE concept of Application and Limitation.

(3 marks) **KA3**

Calculations of pOH and pH from the concentration of hydroxide ions

To calculate the pOH of a solution, the concentration of hydroxide ions, $[\text{OH}^-]$, expressed in mol L^{-1} , is required.

$$\text{pOH} = -\log_{10} [\text{OH}^-]$$

For a strong base, the concentration of the hydroxide ions is determined using the formula of the compound. The concentration of the base is multiplied by the number of hydroxide ions, $[\text{OH}^-]$, present in the formula.

To calculate the concentration of hydroxide ions in solution, the pOH value is substituted into a rearrangement of the pH equation.

$$[\text{OH}^-] = 10^{-\text{pOH}}$$

pH is then determined using the equation for the ionic product of water, linking pH to pOH.

$$\text{pH} + \text{pOH} = 14$$

Example

Flue Gas Desulfurisation (FGD) is a process used to neutralise sulfur dioxide emissions formed during the generation of electricity in coal-fired power stations. Sulfur dioxide is passed over a wet slurry of sodium hydroxide (NaOH) at a concentration of $0.0100 \text{ mol L}^{-1}$ and calcium hydroxide ($\text{Ca}(\text{OH})_2$) at a concentration of $0.0203 \text{ mol L}^{-1}$.

Calculate the pH of the sodium hydroxide and calcium hydroxide in the solution.

	Explanation	Calculation
STEP 1	Sodium hydroxide is a strong base therefore the concentration of hydroxide ions is equal to the concentration of the formula unit.	$[\text{OH}^-] = [\text{NaOH}]$ $[\text{OH}^-] = 0.0100 \text{ mol L}^{-1}$
STEP 2	The value is substituted into the expression for pOH.	$\text{pOH} = -\log_{10} [\text{OH}^-]$ $\text{pOH} = -\log_{10} (0.0100)$ $\text{pOH} = 2.00$
STEP 3	The equation linking pH to pOH is rearranged and the value for pOH subtracted from 14.	$\text{pH} = 14 - \text{pOH}$ $\text{pH} = 14 - 2.00$ $\text{pH} = 12.0$

	Explanation	Calculation
STEP 1	Calcium hydroxide is a strong base therefore the concentration of hydroxide ions is double the concentration of the formula unit.	$[\text{OH}^-] = 2 \times [\text{Ca}(\text{OH})_2]$ $\therefore [\text{OH}^-] = 2 \times 0.0203$ $[\text{OH}^-] = 0.0406 \text{ mol L}^{-1}$
STEP 2	The value is substituted into the expression for pOH.	$\text{pOH} = -\log_{10} [\text{OH}^-]$ $\text{pOH} = -\log_{10} (0.0406)$ $\text{pOH} = 1.39$
STEP 3	The equation linking pH to pOH is rearranged and the value for pOH subtracted from 14.	$\text{pH} = 14 - \text{pOH}$ $\text{pH} = 14 - 1.49$ $\text{pH} = 12.6$

Science understanding

Ocean acidification is caused by the ocean absorbing higher levels of carbon dioxide from the atmosphere.

Describe and write equations to show how carbon dioxide lowers the pH of the oceans.

Calculate the pH of solutions given the concentration of H^+ or OH^- , and vice versa.

The exoskeletons and shells of many marine organisms are made of calcium carbonate and are vulnerable to dissolution at low pH.

Explain, using equilibrium principles, the impact of altering ocean pH on the formation of carbonates.

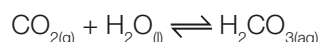
Write equations for carbonates reacting in acidic conditions.

© SACE 2025

Ocean acidification

A large proportion of the carbon dioxide released from anthropogenic activities is absorbed by the oceans and natural bodies of water (Figure 1.1.13)

Carbon dioxide is soluble in the sea and reacts to form carbonic acid (H_2CO_3).



Carbonic acid is a weak acid and partially ionises, forming hydronium ions (H_3O^+) and hydrogencarbonate ions (HCO_3^-).

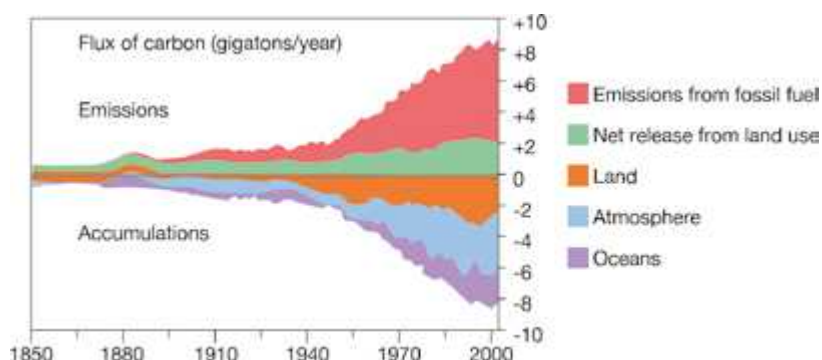
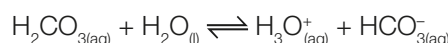
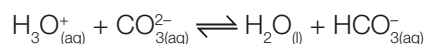


Figure 1.1.13: Carbon dioxide emissions and accumulation



Hydronium ions react with carbonate ions to produce hydrogencarbonate ions and water.



Overall, an increase in the concentration of CO_2 dissolved in the ocean leads to the conversion of CO_3^{2-} to HCO_3^- and a decrease in pH.

The oceans on Earth are slightly alkaline, on average recording a pH of approximately 8.2. Between 1950 and 2020, the average pH value of the ocean surface is estimated to have decreased from approximately 8.15 to 8.05. Although this is a small change in numerical pH, because the scale is logarithmic, this represents an increase of around 26% in the concentration of hydrogen ions.

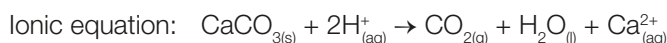
Reaction of acids and carbonates

Acids react with metal carbonates and hydrogen carbonates to form carbon dioxide, water and a salt as products. These reactions can be expressed as both **fully balanced chemical equations** and **ionic equations**.

Example

Calcium carbonate ($CaCO_3$) is commonly found as limestone in the sedimentary geology of marine environments. Limestone cliffs can be eroded from exposure to sulfuric acid formed in air pollution from nearby industries.

Write a fully balanced chemical equation and an ionic equation for the reaction of sulfuric acid with calcium carbonate.



pH and carbonates

Marine calcifying organisms build their shells and skeletons from calcium carbonate, which is abundant in the ocean. These organisms form the base of the ocean food web and include shellfish, corals, coralline algae, pteropods, calcareous plankton, and others. A delicate **equilibrium** (the reaction occurs in both forward and backward directions) exists between carbonate and hydrogen carbonate ions in the ocean, which is affected by changes in pH (Figure 1.1.14).

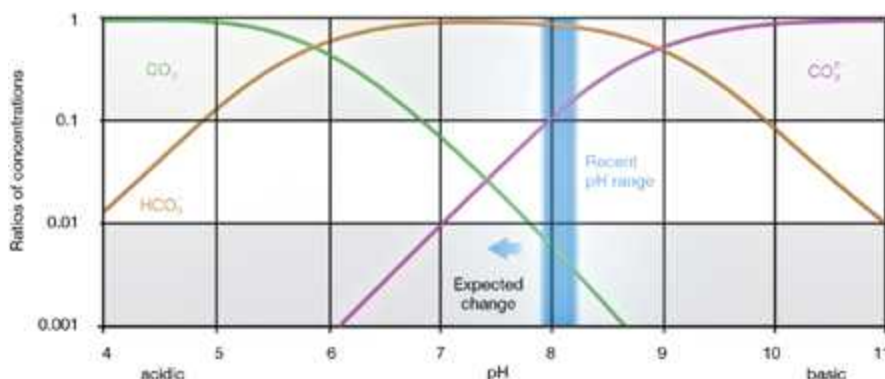


Figure 1.1.14: Chemical species present at varying ocean pH.

As pH decreases, the concentration of available carbonate ions decreases, limiting the ability of marine calcifying organisms to form shells and skeletons. Also as pH decreases, dissolution rates of calcium carbonate increase, weakening calcium carbonate structures of marine species and limiting the formation of new structures. For example, ocean acidification has been found to significantly reduce the ability of reef-building corals to form exoskeletons and reproduce.

The ecological implications of ocean acidification are complex, but it is clear that many ecosystems will be adversely affected. Any significant disruption to the ocean food web would also be devastating to the many human communities who depend on fishing and coast-based tourism for their livelihoods.

Question

11. Natural bodies of water, such as lakes and oceans, register differing acidity and alkalinity based upon the concentration of dissolved ions present.

- (a) Rainwater entering natural bodies of water has a pH of approximately 5.6 due to dissolved carbon dioxide from the atmosphere.

(i) **State** whether this results in a pH of rainwater that is slightly acidic or alkaline.

(1 mark) **KA1**

- (ii) **Write an equation** for the formation of carbonic acid from carbon dioxide gas dissolving in water in the atmosphere.

(2 marks) **KA4**

- (b) Lake Natron in Tanzania has a pH of 10.5 due to sodium carbonate and other minerals flowing into the lake from surrounding hills.

(i) Sodium carbonate can be dissolved by acidic water running through rocks and soil.

Write an ionic equation for the reaction between sodium carbonate and acidic water.

(2 marks) **KA4**

- (ii) **Calculate** the concentration of hydroxide ions, in mol L^{-1} , present in the water at a pH of 10.5.

(3 marks) **KA2**

12. Marine environments are influenced by a variety of chemical processes, including the absorption of carbon dioxide (CO_2) from the atmosphere. This process leads to ocean acidification, which has significant effects on marine organisms, especially those with calcium carbonate structures.

- (a) The ionisation of carbonic acid in seawater leads to the formation of hydrogen ions (H^+) and hydrogencarbonate ions (HCO_3^-).

- (i) Write the chemical equation for the dissociation of carbonic acid in seawater.

(2 marks) **KA4**

- (ii) Explain how the increase in hydrogen ion concentration impacts the pH of seawater.

(2 marks) **KA1**

- (iii) The concentration of hydrogen ions in a sample of seawater was found to be $1.7 \times 10^{-8} \text{ mol L}^{-1}$. Calculate the pH of the sample.

(2 marks) **KA1**

- (b) Marine organisms such as shellfish and corals rely on calcium carbonate (CaCO_3) for their exoskeletons. The dissolution of calcium carbonate in acidic conditions threatens these organisms.

- (i) Explain the effect of decreased pH on the availability of carbonate ions (CO_3^{2-}) in seawater.

(3 marks) **KA2**

- (ii) Write the chemical equation for the reaction between calcium carbonate (CaCO_3) and hydrogen ions (H^+).

(2 marks) **KA4**

- (iii) Explain how this reaction affects the structural integrity of shells and exoskeletons of marine organisms.

(2 marks) **KA2**

(c) Ocean acidification has a cascading effect on marine food webs and biodiversity.

- (i) Describe the potential impact of reduced calcium carbonate availability on the population of a specific marine organism, such as calcareous plankton.

(2 marks) **KA2**

- (ii) Explain how changes in the populations of organisms could affect the broader marine food web.

(2 marks) **KA2**

- (iii) Describe the implications of ocean acidification on marine ecosystems and human communities that depend on them.

(3 marks) **KA3**

- (iv) Suggest a strategy that could be implemented to reduce the impact of ocean acidification on marine life.

(2 marks) **KA3**

1

1.2 Photochemical smog

Science understanding

Nitrogen oxides are formed in high-temperature engines and furnaces.

Write equations for the formation of nitrogen oxides NO and NO₂.

© SACE 2025

Composition of the Earth's atmosphere

The **atmosphere** consists of a complex mixture of gases that form a thin layer surrounding the planet that is critical to sustaining life on Earth. Concentrations of gaseous components are variable in the atmosphere due to natural phenomena and human activity. The average chemical composition of the atmosphere is described in Figure 1.2.1.

Element	Percent by volume (%)	Concentration (ppm)
Major constituents		
nitrogen (N ₂)	78.084	780840
oxygen (O ₂)	20.946	209460
Minor constituents		
argon (Ar)	0.934	9340
carbon dioxide (CO ₂)	0.0400	400
neon (Ne)	0.00182	18.2
helium (He)	0.000524	5.24
methane (CH ₄)	0.000170	1.70
krypton (Kr)	0.000114	1.14
hydrogen (H ₂)	0.0000550	0.550
nitrous oxide (N ₂ O)	0.0000500	0.500
xenon (Xe)	0.00000900	0.0900
ozone (O ₃)	0.00000700	0.0700
nitrogen dioxide (NO ₂)	0.00000200	0.0200
Water		
water vapour (H ₂ O)	Variable between 0.00100 and 5.00	

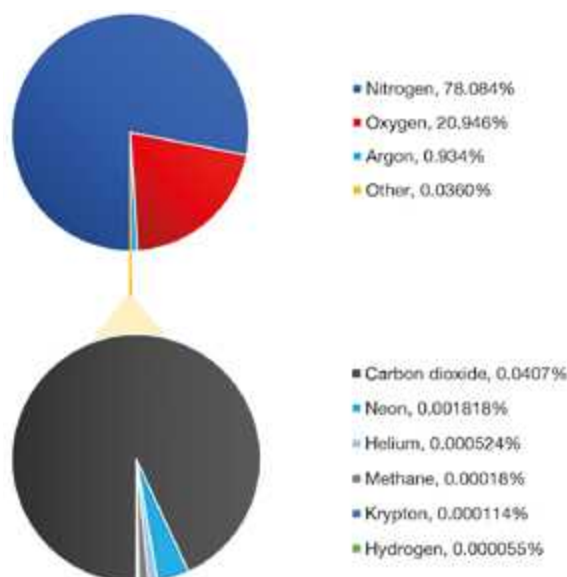


Figure 1.2.1: Average composition of the Earth's atmosphere.

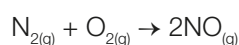
Formation of oxides of nitrogen

Nitrogen (N_2) exists in the atmosphere as a diatomic molecule, with nitrogen atoms held together by a strong covalent triple bond. A large input of energy is required to break the triple bond in forming new compounds. Hence, nitrogen is a relatively stable and inert molecule in the atmosphere.

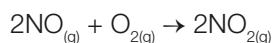
The energy required for the conversion of nitrogen to new compounds can be provided through either natural phenomena or human activities.

Natural	Anthropogenic
Lightning	Internal combustion engines
Volcanic activity	Jet engines
Bushfires	Industrial kilns and furnaces

The high temperatures of these events provide sufficient energy to break the existing bonds in nitrogen and oxygen (reactants) and form nitric oxide (NO) (product).



Nitric oxide is further oxidised in the atmosphere to form nitrogen dioxide (NO_2) (product).



Science understanding

Nitrogen oxides and ozone are pollutants in the troposphere that are associated with photochemical smog.

Describe and write equations showing the role of nitrogen oxides in the formation of ozone in the troposphere.

© SACE 2025

The troposphere

The troposphere is the lowest layer of the atmosphere (closest to the surface of the Earth; Figure 1.2.2) and its composition is most affected by human activities.

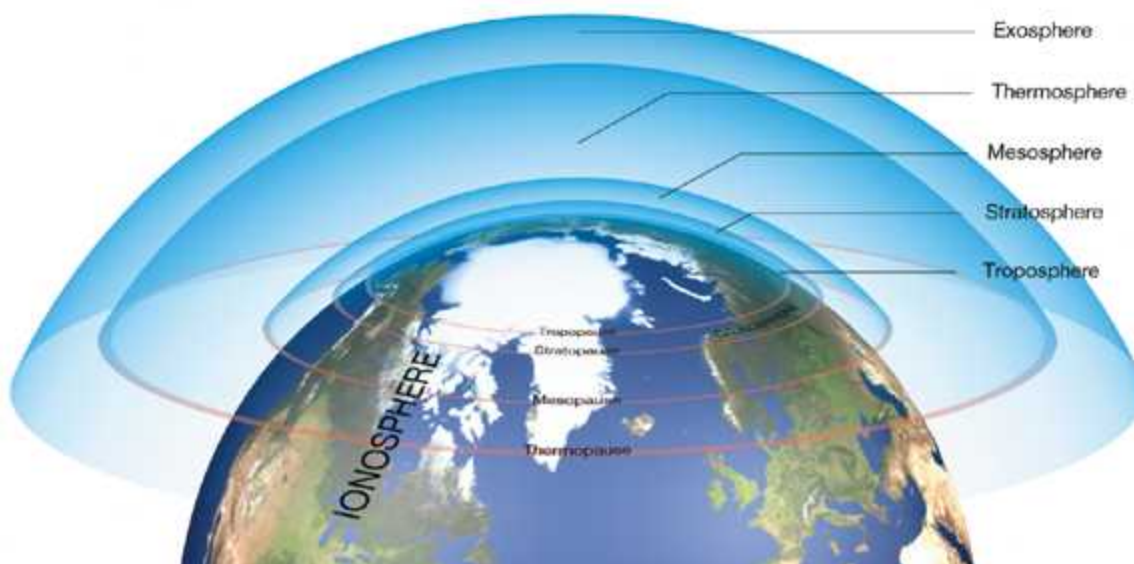


Figure 1.2.2: Layers of the atmosphere.

The troposphere contains a substantial component (75% by mass) of all the gases present in the atmosphere. It also contains nearly all the available water vapour present in the atmosphere. Human activities are responsible for releasing many pollutants directly into the troposphere.

Photochemical smog

Photochemical smog is a complex mixture of chemicals that have been released directly by human activities (**primary pollutants**), or formed by reactions between primary pollutants and molecules that exist in the atmosphere (**secondary pollutants**). Many of the reactions that produce secondary pollutants require light or heat to proceed.

Photochemical smog is typically experienced in densely populated urban areas, where fossil fuels are used for transportation, industry, and electricity production. The following conditions are necessary for the formation of photochemical smog.

Condition	Explanation
High concentration of pollutants	Photochemical smog tends to form in densely populated areas in industrialised cities, with concentrations of pollutants changing periodically over the day.
Sunlight	Many reactions in the formation of photochemical smog are initiated by the absorption of ultraviolet radiation (UV) and heat.
Still air mass	Pollution can be dispersed or displaced depending upon prevailing weather patterns.
Temperature inversion	Warmer air containing pollutants becomes trapped between layers of cooler denser air (Figure 1.2.3).
Valley topography	Valleys can trap air pollutants, as surrounding hills or mountains prevent air flow. This causes smog to accumulate and linger.

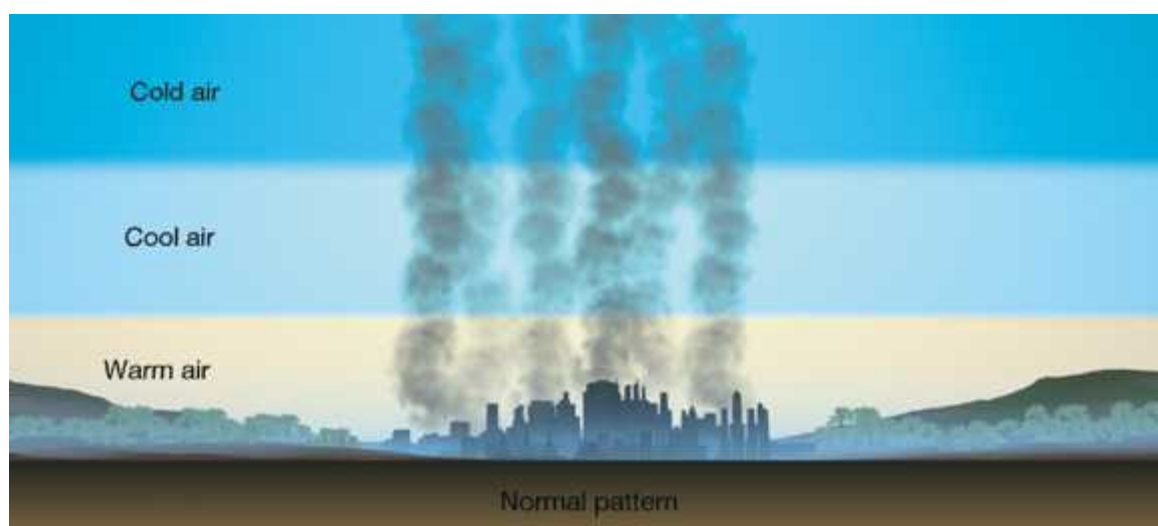


Figure 1.2.3: Temperature inversion during smog formation.

Two main components of photochemical smog are ozone (O_3) and nitrogen dioxide (NO_2). The presence of nitrogen dioxide gas causes the brown haze associated with photochemical smog.

Emissions from motor vehicles are the most significant contributors to the formation of photochemical smog in urbanised areas.

When stoichiometric ratios are not met during fuel combustion, many undesirable products are formed. These include carbon (C), carbon monoxide (CO), and volatile organic compounds (VOCs) such as unburnt hydrocarbons.

A large component of the oxides of nitrogen (collectively referred to as NO_x) responsible for photochemical smog comes directly from motor vehicle exhaust emissions. The high temperatures generated by the combustion of hydrocarbon fuels (petrol, diesel, and natural gas) in internal combustion engines provide the energy for the reactions that produce the oxides of nitrogen.

In densely populated urban areas with heavy traffic flow, transport patterns lead to peak times for emissions of primary pollutants and subsequent formation of secondary pollutants (Figure 1.2.4)

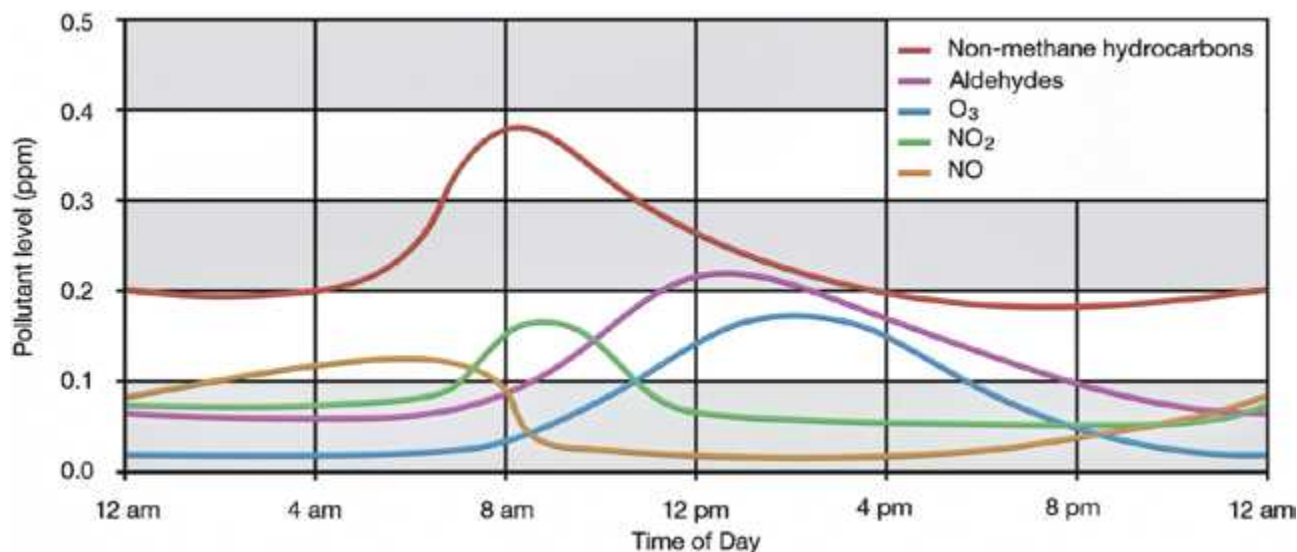
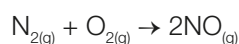
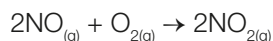


Figure 1.2.4: Pollutant levels over the day in urban cities.

Remember, at high temperatures, atmospheric nitrogen and oxygen react to form nitric oxide (NO), which is further oxidised to nitrogen dioxide (NO_2).



Energy is released when fuel is combusted inside an internal combustion engine. The heat released from the combustion of fuel provides the energy needed to initiate the reaction of nitrogen and oxygen. Concentrations of nitric oxide peak early in the morning as they are released directly from the exhaust systems of motor vehicles. Nitric oxide is oxidised during or after exhaust is emitted from a motor vehicle to form nitrogen dioxide. Nitrogen dioxide concentrations, therefore, peak after nitric oxide levels.



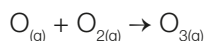
Nitrogen dioxide concentrations therefore peak after nitric oxide levels.

Formation of ozone

At noon (12pm), when ultraviolet radiation concentrations are elevated, nitrogen dioxide photodissociates in the presence of ultraviolet radiation (UV) to form nitric oxide and a highly reactive oxygen radical (O).



The oxygen radical rapidly combines with an oxygen molecule to form ground level (tropospheric) ozone. Therefore, ozone concentrations peak after midday.



Increased concentrations of ozone and the oxides of nitrogen have implications for the natural and built environment.

Question

13. The flight paths, altitudes and burn rates of fuels for aircraft on global flights have been studied in an attempt to reduce their contribution to the formation of nitrogen oxides in the upper troposphere.

(a) Elemental nitrogen is an abundant element in the troposphere. It exists as a diatomic molecule, N_2 .

(i) **State** the type of bonding present in the nitrogen molecule.

(1 mark) **KA1**

(ii) **Draw** a diagram to show the bonding and shape of N_2 .

(2 marks) **KA4**

(b) When fuel undergoes combustion in aircraft engines, oxides of nitrogen are produced.

Explain, with the aid of two equations, how nitrogen oxides are produced from aircraft engines.

(4 marks) **KA1**

(c) Nitrogen dioxide gas (NO_2) is emitted in the exhaust stream of aircraft in flight. Nitrogen dioxide undergoes photodissociation after its emission into the atmosphere.

(i) **State** the type of chemical reaction in which energy is absorbed.

(1 mark) **KA1**

(ii) **Describe**, with the aid of two equations, how the photodissociation of nitrogen dioxide can lead to the formation of ozone.

(4 marks) **KA1**

(d) Mathematical modelling of fuel burn-rates, altitudes, flight distance, and the extent of intercontinental crossings were analysed in terms of the production of nitrogen oxides, NO_x .

(i) **Suggest** why flight paths are considered in terms of the production of NO_x .

(1 mark) **KA3**

(ii) Modelling of alternative flight paths and altitudes provided evidence of lower emissions for the oxides of nitrogen in some cases, but also higher emissions of carbon dioxide.

Discuss one environmental problem associated with increased carbon dioxide concentrations in the troposphere.

(3 marks) **KA2**

Science understanding

Describe the harmful effects of nitrogen oxides and ozone in the troposphere.

© SACE 2025

Effects of photochemical smog

Elevated concentrations of ozone and the oxides of nitrogen present during the formation of photochemical smog can have detrimental effects on humans, animals, plants and synthetic materials, including some polymers.

Humans and animals

Photochemical smog is harmful to humans and animals due to exposure to ozone, oxides of nitrogen and other reactive species. Exposure to elevated concentrations of these pollutants can have severe health effects.

Smog causes eye irritation, as pollutants react in the fluid secreted to lubricate the eyes. Oxides of nitrogen make the fluid more acidic due to the formation of acids such as nitric acid.

Pollutants present in photochemical smog cause respiratory distress. In particular, ozone in photochemical smog irritates and damages respiratory tissue during inhalation. Ozone damages tissues lining the lungs, thus reducing the rate of diffusion of oxygen to the lungs over time. The young, elderly, and those susceptible to asthma, bronchitis and allergies are more severely affected by exposure to increased concentrations of ozone (Figure 1.2.5).



Figure 1.2.5: Photochemical smog in Shanghai.

Plants and vegetation

During photosynthesis, atmospheric gases (including carbon dioxide and ozone) enter gas-exchange pores (stoma) on the surface of leaves.

Exposure to high levels of ozone cause stomata on the leaves of plants to close, limiting the exchange of gases required for photosynthesis. Ozone entering plant cells also undergoes a range of reactions as a strong oxidant, further disrupting photosynthesis and other cell reactions. As a result, plant growth is limited and plants are left more susceptible to disease and extreme weather conditions, such as drought (Figure 1.2.6).

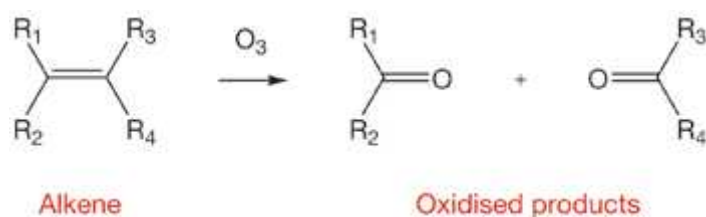


Figure 1.2.6: Leaves exposed to ozone.

Polymers

Ozone can damage **elastomers** (elastic polymers), making these materials more brittle and susceptible to cracking under stress.

Ozone causes degradation of the polymer chains. The carbon-carbon double bonds (C=C) in unsaturated polymers readily undergo reaction with ozone, and saturated polymers undergo slow oxidation.



Ozone breaks cross-links that are comprised of carbon-carbon double bonds, decreasing their frequency in the polymer and causing a reduction in elasticity (Figure 1.2.7). Ozone cleaves the polymer chains where carbon-carbon double bonds exist, producing smaller molecules and thus reducing the strength of interactions due to dispersion forces. As a strong oxidant, ozone also causes changes in the chemical composition of the polymers, resulting in weaker interactions between polymer chains.



Figure 1.2.7: Car tyres (synthetic polymer) cracking due to ozone exposure.

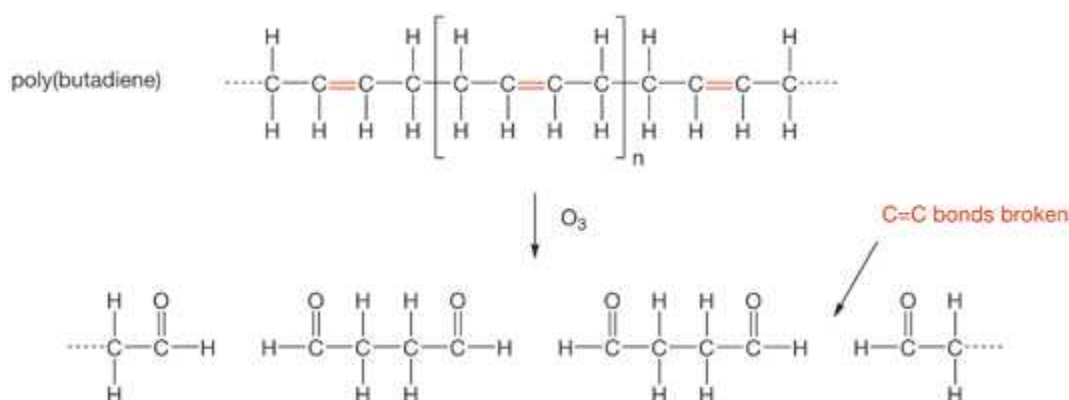


Figure 1.2.8: Degradation of the synthetic polymer chain in poly(butadiene).



Science as a human endeavour

Monitoring Photochemical Smog

The composition and chemical reactions involved in photochemical smog were not well understood until the 1950s. In 1948, flavour chemist Arie Haagen-Smit adapted his equipment to analyse polluted air, identifying ozone as a component of Los Angeles smog. He discovered that nitrogen oxides from vehicle exhaust and hydrocarbons from cars and refineries, when exposed to sunlight, formed ozone and smog.

Haagen-Smit worked with Arnold Beckman, who developed instruments to detect smog, including gas concentration recorders and air quality monitoring vans.

Knowledge about the long-term effects of air pollution and its link to asthma is still developing. Experiments simulating conditions like the 1952 Great Smog of London showed that early-life pollution exposure could lead to asthma. Modern studies, including one in *Nature* magazine, found that smog episodes in Jinan, China, from 2011 to 2015, correlated with a 6% increase in mortality rates, emphasizing the health impact of air pollution. A similar study in Xi'an also connected air pollution to higher respiratory disease mortality.

The U.S. EPA created an Air Quality Index to inform the public about pollution levels. They categorise 8-hour average ozone concentrations of 85 to 104 ppb as “Unhealthy for Sensitive Groups,” 105 to 124 ppb as “Unhealthy,” and 125 to 404 ppb as “Very Unhealthy.” These guidelines were detailed in their 1998 booklet “Smog—Who Does It Hurt? What You Need to Know About Ozone and Your Health,” aimed at raising awareness about ozone exposure and health risks.



1

Questions

14. (a) From the passage above, identify and explain one example of the ‘Science as a Human Endeavour’ concept of Collaboration.

(3 marks) **KA3**

- (b) Explain the importance of communicating scientific findings about smog and air quality to the general public and policymakers.

(2 marks) **KA3**

- (c) Discuss how the development of the U.S. EPA’s Air Quality Index helps the public make informed decisions about their health in relation to air pollution levels.

(3 marks) **KA3**

- (d) Identify one limitation in our current understanding of the long-term effects of air pollution exposure and suggest why further research is necessary.

(2 marks) **KA3**

15. Many athletes in highly populated cities are choosing to train indoors due to increased concentrations of photochemical smog and air pollution.
- (a) An Air Quality index, such as the one below, has been developed for schools in the Los Angeles area that are exposed to high levels of ozone from photochemical smog. Recommendations for varying levels of physical activity have been made based on the concentration of ozone in ppm.

	0–50 ppm	51–100 ppm	101–150 ppm	151–200 ppm	201–300 ppm
Activity	Low	Moderate	Unhealthy for sensitive groups	Unhealthy	Extremely unhealthy
Recess (15 minutes)	No restrictions	No restrictions	Make indoor space available for individuals with asthma or respiratory problems	Make indoor space available for any individual experiencing respiratory problems	Restrict all outdoor activities to light exercise
Physical education (1 hour)	No restrictions	Limit intense activity for sensitive groups	Make indoor space available for individuals with asthma or respiratory problems	Make indoor space available for any individual experiencing respiratory problems	Restrict all outdoor activities to light exercise not exceeding 1 hour
Sports training (2–4 hours)	No restrictions	Limit intense activity for sensitive groups	Individuals with asthma, respiratory or cardiovascular disease should medically manage the condition and include rest breaks	Activities over 2 hours should be decreased in intensity and duration and include frequent rest breaks	Sustained rigorous exercise for more than 1 hour must be rescheduled or moved indoors

- (i) **Suggest** one reason why increased physical activity leads to greater exposure to ozone.

(1 mark) **KA1**

- (ii) With reference to the table, **discuss** the conclusions that can be drawn about exposure to ozone from photochemical smog.

(2 marks) **KA3**

- (b) Exposure to ozone leads to respiratory irritation and impaired performance during physical exercise. Oxides of sulfur cause respiratory irritation when they combine with moisture in the lungs to form acids.

- (i) **Write an equation** for the formation of sulfuric acid in the lungs from sulfur trioxide, SO_3 .

(2 marks) **KA4**

- (ii) **State** the effect of the ionisation of sulfuric acid on the pH of the moisture in the lungs.

(1 mark) **KA1**

Credit will be given for answers that are coherent and contain only relevant information, including at least one equation.

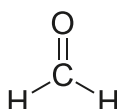
- (c) A runner in Los Angeles was considering what time of day would limit their exposure to pollutants associated with photochemical smog. Three times of the day were considered: early morning (7–8am), just after midday (12–1pm), later in the evening (8–9pm).

Discuss the advantages and disadvantages of running during each period, in terms of exposure to ozone and the oxides of nitrogen present in photochemical smog.

1

(8 marks) IAE3, KA4

16. Concerns have been raised over the adverse long-term health effects of exposure to a range of volatile chemicals released in office buildings.
- (a) Volatile organic compounds (VOCs) are released from paints, plastics and synthetic carpets. They are released in higher concentrations when these materials are new.
- (i) Methanal, commonly known as formaldehyde, is emitted from a range of building materials in office environments.



- (1) **State** the shape of the methanal molecule.

(1 mark) KA1

- (2) **Explain** why the C=O bond in methanal is polar.

(2 marks) KA1

- (3) **Explain** why methanal exhibits a low boiling point, and therefore why it is a volatile organic compound.

(3 marks) KA2

- (ii) VOCs and nitrogen dioxide, NO_2 , are responsible for the formation of ozone in the lower atmosphere.

Write equations to show the formation of ozone from nitrogen dioxide.

(4 marks) **KA4**

- (b) High-voltage electrical discharges (from the use of photocopiers and laser printers) result in ozone formation. Small quantities of ozone are released by these office machines; health concerns have been expressed about these machines being placed in poorly ventilated areas.

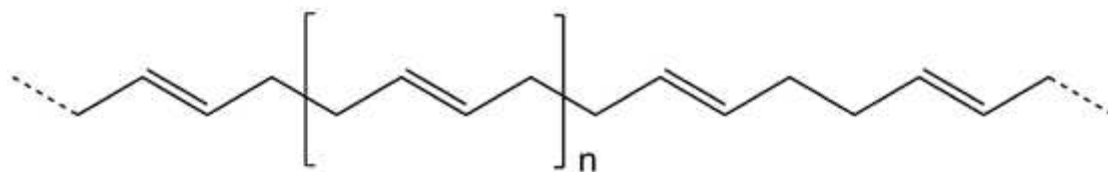
- (i) **State** why ventilation is required.

(1 mark) **KA1**

- (ii) **State** one harmful effect on humans from exposure to high concentrations of ozone.

(1 mark) **KA1**

- (c) Photocopier components such as rollers are made from synthetic rubber. The structure of the synthetic rubber polybutadiene is shown below.



- (i) **State** whether or not this polymer has been formed from an addition reaction.

(1 mark) **KA1**

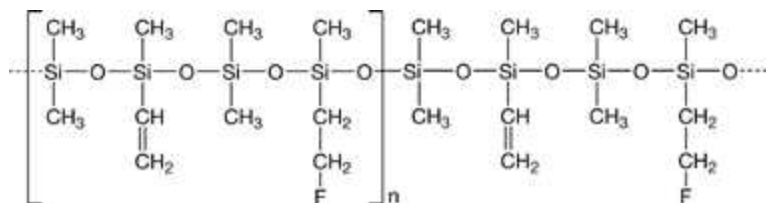
- (ii) **Draw** the monomer of polybutadiene.

(2 marks) **KA4**

- (iii) **Describe** one disadvantage of exposing synthetic rubber to ozone.

(2 marks) **KA2**

- (iv) Silicone rollers can also be used in photocopiers. The structure of a silicone-based polymer is shown below.



Suggest one reason why this polymer would be preferable to synthetic rubber for use in a photocopier.

(1 mark) **KA2**

Science understanding

Describe and write equations showing how catalytic converters reduce the quantities of nitrogen oxides generated by motor vehicles.

© SACE 2025

Catalytic converters

Catalytic converters were introduced into the exhaust system of motor vehicles to reduce the impact of pollutants released as exhaust emissions. When operating temperatures have been achieved and air to fuel stoichiometric ratios are maintained within a suitable range, catalytic converters are able to convert a number of the precursor compounds of photochemical smog to less harmful products.



Science as a human endeavour

Catalytic converters

The catalytic converter was first invented by the French mechanical engineer, Eugene Houdry, who was living in America in the 1950s. He was concerned with the findings of early studies in Los Angeles that linked air pollution to exhaust emissions from motor vehicles and industry. Houdry founded the company Oxy-Catalyst to develop catalytic converters for industry and, later, motor vehicles.

Two-way catalytic converters were used in the 1970s with increased awareness of pollutants and interest in their methods of reduction. These were phased out in 1981 when three-way converters were introduced. Three-way converters continue to be used in motor vehicles today.

The platinum-group metals, used as the catalysts in modern three-way catalytic converters, are rare and expensive. Nanotechnology is being applied to disperse nano-sized particles of these precious metals onto the porous bed of the converter. As the surface area to volume ratio is greatly increased, the rate of surface-catalysed reactions increases. This limits the quantity of precious metal required by the converter. This allows an effective converter to be produced at a lower cost.

Question

17. (a) **Identify** and **explain** how the development and implementation of catalytic converters illustrates the importance of collaboration between scientists and industry in addressing global environmental issues.

(3 marks) **KA3**

- (b) **Describe** one beneficial effect and one possible limitation of using catalytic converters to reduce vehicle emissions.

(2 marks) **KA3**

- (c) **Explain** how economic considerations might affect the use of catalytic converters in less wealthy countries.

(3 marks) **KA3**

- (d) **Explain** how the development of catalytic converters in the 1970s and 1980s demonstrates the need for communication between scientists and the wider community.

(3 marks) **KA3**

Three-way catalytic converters

Current three-way catalytic converters typically consist of a porous ceramic (cordierite) block with parallel channels along the length to allow for the flow of exhaust emissions. The porous ceramic block is coated with a thin layer of highly porous alumina (aluminium oxide), with very small amounts of the precious platinum-group metals (platinum, palladium and rhodium) bonded to the surface in the alumina coating at varying percentages (Figure 1.2.10).

Exceptional surface area is achieved through the use of channels and the porosity of the alumina, providing greater opportunity for hot exhaust gases passing through to contact the metal catalysts and thus increase the rate of reaction.

The purpose of the three-way catalyst is to simultaneously remove carbon monoxide, oxides of nitrogen, and unburnt hydrocarbon components of the fuel through catalysed redox reactions.

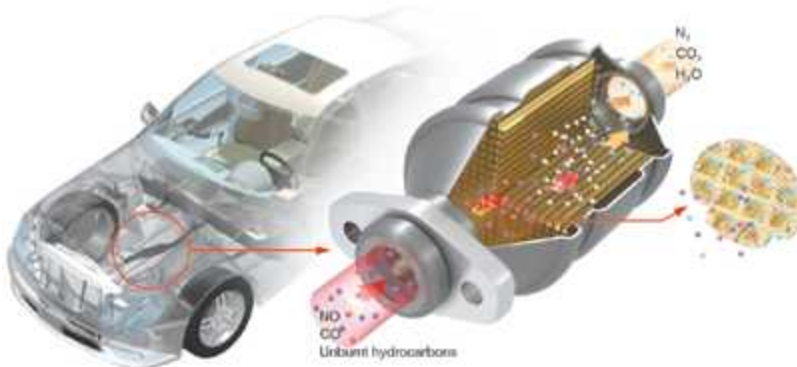


Figure 1.2.10: Three-way catalytic converter.

Carbon monoxide

The adsorption of carbon monoxide and oxygen onto the surface of the three metals, in particular palladium, catalyses the oxidation of carbon monoxide to carbon dioxide (Figure 1.2.11).

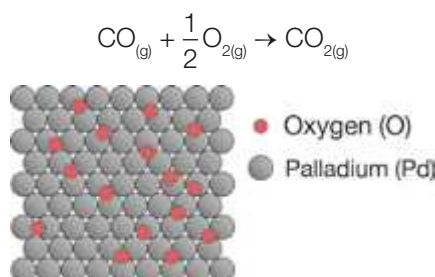
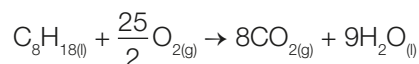


Figure 1.2.11: Oxygen atoms on the surface of a palladium catalyst.

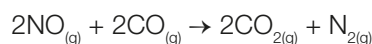
Unburnt hydrocarbons

The adsorption of hydrocarbons (saturated, unsaturated and aromatic) onto the surface of the metals, in particular platinum, catalyses their oxidation.



Nitric oxide

Nitric oxide can be removed by reduction with carbon monoxide. Of the three platinum-group metals, rhodium is the most effective component for catalysing this reaction.





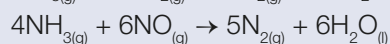
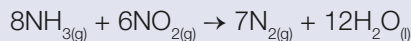
Science as a human endeavour

Catalysts used in diesel engines

Oxides of nitrogen can be removed from diesel emissions through selective catalytic reduction (SCR). SCR involves the addition of urea to the into the exhaust system where it forms ammonia.



The ammonia adsorbs onto a catalyst such as vanadium oxide, to catalyse the formation of nitrogen and water.



Selective Catalytic Reduction (SCR) technology was patented in the US by the Engelhard Corporation in 1957. Development continued in both the US and Japan, and the first large-scale SCR was installed in 1978 by the Japanese IHI Corporation. More recent innovation has been driven by increasingly strict regulatory standards, like the EURO 6 diesel emissions standards for heavy trucks, cars, and light commercial vehicles. SCR systems are also used on industrial-scale boilers and large diesel ships.

SCR technology evolved from simple catalytic reactions to the use of advanced catalysts such as vanadium, titanium, and zeolites, which increased the technology's effectiveness and adaptability. The introduction of nanotechnology played a significant role in enhancing catalyst performance by boosting surface area, which optimised the reaction process. This technological advancement had a direct impact on the automotive and industrial sectors, necessitating design changes in diesel engines and industrial systems to integrate SCR units effectively. While SCR is efficient at reducing NO_x emissions, it also presents challenges. Catalyst poisoning occurs when impurities, such as sulfur compounds, deactivate the catalyst, reducing its efficiency. Ammonia slip refers to the excess ammonia that escapes unreacted into the environment if not fully converted in the process, potentially leading to secondary pollution issues. Additionally, SCR systems require high operating temperatures, which can limit their effectiveness in cooler environments.

Economic factors also affect SCR adoption, with the high cost of vanadium-based catalysts and system installation being significant barriers. For example, smaller industrial facilities may struggle to afford these systems compared to larger plants that can better absorb these costs into their operational budgets.

Question

18. (a) From the passage above, **identify** and **explain** one example of the 'Science as a Human Endeavour' concept of Communication and Collaboration.

(4 marks) **KA3**

- (b) From the passage above, **identify** and **explain** one example of the 'Science as a Human Endeavour' concept of Development.

(4 marks) **KA3**

- (c) From the passage above, **identify** and **explain** one example of the 'Science as a Human Endeavour' concept of Influence.

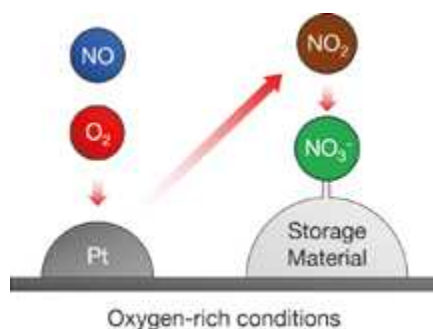
(4 marks) **KA3**

- (d) From the passage above, identify and explain one example of an **Application** and another example of a **Limitation**.

(6 marks) **KA3**

19. Lean Nitrogen Oxide Traps (LNT) have been developed for lean-burning (oxygen-rich combustion) internal combustion engines, such as diesel engines. The aim of LNTs is to reduce emissions of oxides of nitrogen.

- (a) Under lean, oxygen-rich conditions, nitric oxide (NO) undergoes oxidation to nitrogen dioxide (NO₂) in the presence of a platinum catalyst.



- (i) **Describe** one advantage of reducing motor vehicle emissions of oxides of nitrogen.

(2 marks) **KA1**

- (ii) **Write an equation** for the conversion of nitric oxide to nitrogen dioxide.

(2 marks) **KA4**

(b) Nitrogen dioxide is temporarily adsorbed onto the surface of a zeolite (porous silicate) material as nitrate ions, NO₃⁻.

- (i) **State and explain** whether this conversion represents an oxidation or reduction reaction.

(3 marks) **KA2**

Eventually the zeolite material becomes completely coated with adsorbed nitrate ions.

The surface is flushed with diesel fuel to generate rich, oxygen-deprived conditions. During these conditions, nitric oxide (NO) and carbon monoxide (CO) are generated in higher concentrations and sent through a catalytic converter.

(ii) **State** the type of combustion in which carbon monoxide is a product.

(1 mark) **KA1**

(iii) **State** one advantage of the catalytic converter having a highly porous structure.

(1 mark) **KA1**

(iv) **Write a balanced equation** for the conversion of nitric oxide and carbon monoxide to nitrogen and carbon dioxide.

(2 marks) **KA4**

1

1.3 Volumetric analysis

Science understanding

Concentrations can be described by using a number of standard conventions.

Calculate concentration and interconvert units, including: mol L^{-1} , g L^{-1} , %w/v, ppm, and ppb.

© SACE 2025

Volumetric analysis

Volumetric analysis is a **quantitative** analytical technique used to determine amounts or concentrations of unknown reagents. Calculations are applied to fixed stoichiometric ratios in chemical reactions. A **titration** is a laboratory procedure undertaken to determine these concentrations through measured quantities.

Titration is widely used in monitoring concentrations in the environment, and in the quality control of consumer products. Examples of where quantitative analysis may be used include water quality checks, wine production, and in administering some medicines.

In these applications, the concentrations measured may vary considerably. Because of this, a range of units are applied as standard convention, to allow concentrations to be expressed appropriately.

Review of quantities

Measuring and calculating quantities related to moles and concentration requires a working knowledge of a range of units.

Quantity	Symbol	Definition	Unit
Mass	m	A measure of the amount of matter.	g
Volume	V	The space that a substance occupies.	L (dm^3)
Density	ρ	The mass per unit volume.	kg L^{-1}
Avogadro's constant	N_A	The number of fundamental particles contained in exactly 12 g of carbon-12 is 6.022×10^{23} , this number represents Avogadro's constant.	mol^{-1}
Mole	n	Measure of the amount of fundamental particles (atoms, ions, molecules, formula units) in a given mass of material.	mol
Molar mass	M	The mass of one mole of a substance.	g mol^{-1}

Derivation of equations from units

Equations encountered in volumetric analysis can be derived from units using **dimensional analysis** (an analysis of the relationship between quantities).

Mass and moles

Equations for both mass and moles can be derived from the unit of molar mass.

Molar mass

$$M = \frac{\text{g}}{\text{mol}} = \frac{m}{n} \quad \text{rearrangements} \quad n = \frac{m}{M} \quad \text{and} \quad m = n \times M$$

Question

20. Platinum, palladium and rhodium are present in three-way catalytic converters in motor vehicles in varying quantities.

- (a) A catalytic converter from a truck was analysed to determine the mass of each element present.

Complete the table, calculating the mass and moles for each element:

Element	Symbol	Atomic mass	m (g)	n (mol)
platinum	Pt	195.1	2.93	
palladium	Pd	106.4		0.0325
rhodium	Rh	102.9	8.61	

(3 marks) **KA2**

- (b) Developments in materials science have allowed chemists to bind platinum nanoparticles to nanofibers on the surface of catalytic converters.

Suggest one advantage of the use of nanoparticles of platinum.

(1 mark) **KA3**

Mass concentration and molar concentration

Equations for mass and concentration can be derived from their respective units.

Mass concentration represents the mass, in grams, of solute per litre of solution.

Mass concentration (ρ) g L⁻¹

$$\rho = \frac{g}{L} = \frac{m}{V} \quad \text{rearrangements} \quad V = \frac{m}{\rho} \quad \text{and} \quad m = \rho \times V$$

Molar concentration (also referred to as molarity) represents the moles of solute, in mol, per litre of solution.

The units of molar concentration are moles per litre (mol L⁻¹).

$$c = \frac{\text{mol}}{L} = \frac{n}{V} \quad \text{rearrangements} \quad V = \frac{n}{c} \quad \text{and} \quad n = c \times V$$

Percentage weight per unit volume represents the mass of solute, in grams, per 100 mL of solution.

Percentage weight per unit volume (c) %w/v.

$$\frac{g}{100 \text{ mL}} = \frac{m}{V} \times 100\%$$

Concentration conversions

Multiple conventions are used to convey concentration, which are often linked to a specific application. Monitoring trace amounts of substances in bodies of water and the atmosphere may require the application of units in the range of **parts per million (ppm)** or **parts per billion (ppb)**. The concentration of commercial products is more commonly expressed as percentage weight per volume (%w/v).

Commonly encountered concentration units include: mole per litre (mol L^{-1}), gram per litre (g L^{-1}), parts per million (ppm), part per billion (ppb) and percentage weight per unit volume (%w/v). Interconversion can be undertaken between concentration units (Figure 1.3.4).

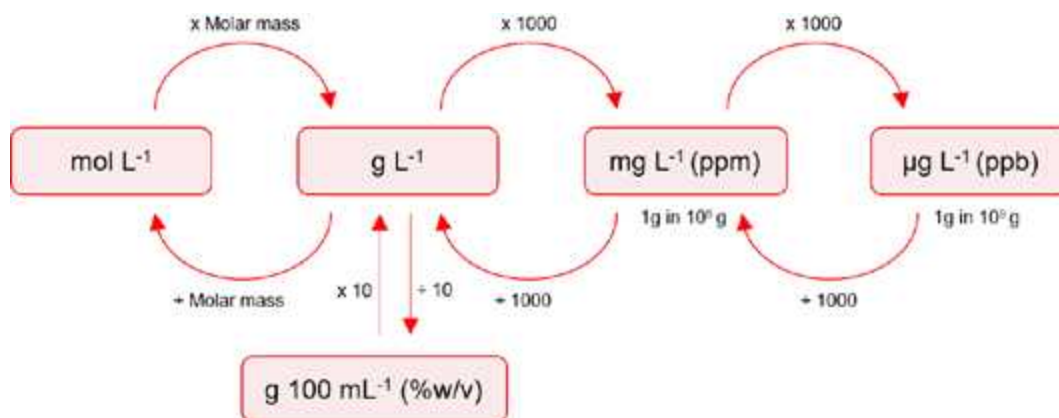


Figure 1.3.1: Processes for concentration conversions.

Simple conversions

Simple conversions require the application of an appropriate factor or the calculation of moles or mass.

Worked example

Monochloramine (NH_2Cl) can be used as a disinfectant in water supplies as an alternative to chlorine due to its greater stability. Monochloramine can be added to the water supply at what is considered a safe concentration of 4.0 ppm.

- (a) **Calculate** this concentration in %w/v.

	Explanation	Calculation
STEP 1	Equate ppm with mg L^{-1} .	$4.0 \text{ ppm} = 4.0 \text{ mg L}^{-1}$
STEP 2	Convert from mg L^{-1} to g L^{-1} by dividing by a factor of 10^3 .	$\frac{\text{mg}}{\text{L}} \div 10^3 = \frac{\text{g}}{\text{L}}$ $= \frac{4.0}{10^3} = 0.0040 \text{ g L}^{-1}$
STEP 3	Convert from g L^{-1} to $\text{g } 100 \text{ mL}^{-1}$ by dividing by 10. Equate g per 100 mL^{-1} with %w/v.	$= \frac{0.0040}{10} = 0.00040$ $= 4.0 \times 10^{-4} \text{ g } 100 \text{ mL}^{-1}$

Question

1

21. Bottled water is analysed for trace elements, a number of which are required to be displayed on packaging. Analysis of one brand of bottled water produced the following results.

		Atomic mass	Concentration units			
		g mol^{-1}	mol L^{-1}	g L^{-1}	ppm	ppb
lead	Pb	207.2		0.00020		
cadmium	Cd	112.4	9.65×10^{-7}			
arsenic	As	74.92			0.050	
mercury	Hg	200.6				180
zinc	Zn	65.38			4.0	
selenium	Se	78.96		0.0015		
sodium	Na	22.99	6.05×10^{-4}	0.0139	13.9	13900
calcium	Ca	40.08	2.07×10^{-4}	0.0083	8.3	8300
magnesium	Mg	24.31	5.64×10^{-4}	0.0137	13.7	13700

- (a) **Complete the table** above by calculating the unknown concentrations.

(4 marks) **KA2**

- (b) Sodium, calcium and magnesium concentrations are commonly displayed on bottled water.

- (i) Arsenic is lethal to humans at a concentration of 763 ppm. **Calculate** the volume of bottled water, containing arsenic at a concentration of 0.05 ppm, required to reach lethal levels in a 55.0 kg adult. Assume that the human body has the same density as water, 1 kg/L.

(3 marks) **KA4**

- (ii) **Suggest** one reason why it is important to analyse other elements, even if their values are not displayed.

(1 mark) **KA3**

22. The ocean has a sodium chloride (NaCl) concentration of approximately 0.60 mol L^{-1} . The volume of the ocean is approximately $1.35 \times 10^{21} \text{ L}$.

- (a) Calculate the concentration of sodium chloride in the ocean in g/L and ppm.

(2 marks) **KA2**

- (b) Calculate the total mass of sodium chloride in the ocean in grams.

(2 marks) KA2

Complex conversions

Complex conversions require the construction and rearrangement of statements through dimensional analysis.

Worked example

Sodium monofluorophosphate ($\text{Na}_2\text{PO}_3\text{F}$), sodium fluoride (NaF) and tin(II) fluoride (SnF_2) are common sources of fluoride in toothpaste. There are health concerns related to absorption of high levels of fluoride in human beings.

- (a) **Calculate** the percentage composition of F in $\text{Na}_2\text{PO}_3\text{F}$.

	Explanation	Calculation
STEP 1	Percentage composition represents the molar mass of the element expressed as a percentage of the molar mass of the compound. Determine the atomic mass of fluorine and the molar mass of sodium monofluoride. Substitute the values into the equation and calculate the %.	$\% \text{ composition} = \frac{M(\text{element})}{M(\text{compound})} \times 100$ $= \frac{19.00}{((2 \times 22.99) + 30.97 + (3 \times 16.00) + 19.00)} \times 100$ $= \frac{19.00}{143.95} \times 100 = 13.20\%$

- (b) In one brand of toothpaste the fluoride concentration is 13 g kg^{-1} .

- (i) **Calculate** the percentage, by mass, of fluoride in the toothpaste.

	Explanation	Calculation
STEP 1	Percentage mass (also referred to as %w/w) represents the mass of an element as a percentage of the mass of the compound or mixture.	$\%w/w = \frac{m(\text{element})}{m(\text{compound})} \times 100$
STEP 2	Recognise that percentage represents a number out of 100. Analyse the unit of g per kg and convert to g for both.	$13 \text{ g in } 1 \text{ kg}$ $= 13 \text{ g in } 1000 \text{ g}$
STEP 3	Convert to a mass out of 100 g.	$= 1.3 \text{ g in } 100 \text{ g} = 1.3\%$

- (ii) A 32 kg child uses 0.80 g of a 110 g tube of the toothpaste to brush their teeth and swallows all of the toothpaste while brushing.

Calculate the concentration, in ppm, of fluoride that the child consumes.

	Explanation	Calculation
STEP 1	Concentration of fluoride is 13 g in 1 kg or 1.3% by mass.	$13 \text{ g in } 1 \text{ kg} = 1.3\%$
STEP 2	Multiply the 0.8 g consumed by 1.3%.	$= 0.8 \times 0.013$ $= 0.0104 \text{ g}$
STEP 3	Consider that the mass of fluoride calculated is now contained in a 32 kg child.	$= 0.0104 \text{ g in } 32 \text{ kg}$
STEP 4	Calculate the mass, in g, of fluoride in 1 kg.	$= \frac{0.0104}{32} \text{ g in } 1 \text{ kg}$
STEP 5	Calculate the mass, in mg, of fluoride in 1 kg. Equate that $1 \text{ mg kg}^{-1} = 1 \text{ mg L}^{-1} = \text{ppm}$.	$= \frac{0.0104}{32} \times 10^3 \text{ mg in } 1 \text{ kg}$ $= 0.33 \text{ ppm}$

Question

1

23. Swordfish contains some of the highest recorded levels of mercury due to biomagnification (increased concentration through the food chain) in this deep-sea species. Mercury is absorbed in the fish as methyl mercury.
- (a) **Calculate** the mass of mercury, in mg, contained in a 150 g portion of swordfish with a mercury concentration of 0.995 ppm.

(3 marks) KA2

- (b) **Calculate** the concentration of mercury, in ppm, present in a 75 kg adult who has consumed 150 g of swordfish containing mercury at a concentration of 0.995 ppm.

(3 marks) KA2

- (c) Mercury is a cumulative poison, building in concentration through repeated consumption or exposure. It has been recommended that people should not consume seafood with mercury levels above 1 ppm.

General population	Children (up to 6)	Pregnant women
2–3 serves of any fish or seafood not listed below	2–3 serves of any fish or seafood not listed below	2–3 serves of any fish or seafood not listed below
OR	OR	OR
1 serve per week of shark, marlin, or swordfish	1 serve per fortnight of shark, marlin, or swordfish	1 serve per fortnight of shark, marlin, or swordfish

Explain the recommendations made, for the daily intake of fish and seafood for the general population compared to children, and pregnant women.

(2 marks) KA3

Science understanding

Apply SI prefix conventions to quantities.

© SACE 2025

? Science inquiry skills

Skills in context

Scientific notation and SI prefixes

Measurements and calculations in chemistry often require the representation of values as either very large or very small numbers. These numbers can be made more manageable by applying SI prefixes. Each SI prefix has a prefix symbol as well as a unit symbol.

Unit prefix	Unit prefix symbol	Multiplying Factor		Examples	
				Unit name	Unit symbol
tera	T	1 000 000 000 000	10^{12}	terawatt	TW
giga	G	1 000 000 000	10^9	gigalitre	GL
mega	M	1 000 000	10^6	megajoule	MJ
kilo	k	1 000	10^3	kilogram	kg
-	-	1	10^0	-	-
milli	m	0.001	10^{-3}	millimole	mmol
micro	μ	0.000 001	10^{-6}	microlitre	μL
nano	n	0.000 000 001	10^{-9}	nanometre	nm
pico	p	0.000 000 000 001	10^{-12}	picogram	pg

Both large and small numbers are often expressed in chemistry using scientific notation. Scientific notation allows for the number of significant figures to be clearly expressed.

Example

Quantity	Value in Standard Units	Scientific notation	Value using SI Prefix	Significant figures
Volume of fresh water on Earth	10 530 000 000 L	$1.053 \times 10^{10} \text{ L}$	10.53 GL (= $10.53 \times 10^9 \text{ L}$)	4
Concentration of H^+ in acid rain at a pH of 5.6	0.00002512 mol L^{-1}	$2.512 \times 10^{-5} \text{ mol L}^{-1}$	25.12 $\mu\text{mol L}^{-1}$ (= $25.12 \times 10^{-6} \text{ mol L}^{-1}$)	4
Concentration of atmospheric CO_2	404 ppm	$4.04 \times 10^2 \text{ ppm}$	404 ppm (= 404 mg/L)	3

Question

24. Complete the table below by expressing the concentrations in the desired format.

(3 marks) KA4

Quantity	Value in Standard Units	Scientific notation	Value using SI Prefix	Significant figures
Gold in the human body	0.0002 g			
Concentration of H^+ in bleach at a pH of 12.6			0.25 $\mu\text{mol L}^{-1}$	
Number of particles in a mole		$6.02214076 \times 10^{23}$	Value is unitless	

Science understanding

Knowledge of the mole ratios of reactants can be used in quantitative calculations.

Perform stoichiometric calculations when given the reaction equation and the necessary data.

© SACE 2025

Stoichiometry

Stoichiometry uses the ratios obtained from balanced chemical equations to determine unknown quantities from known quantities.

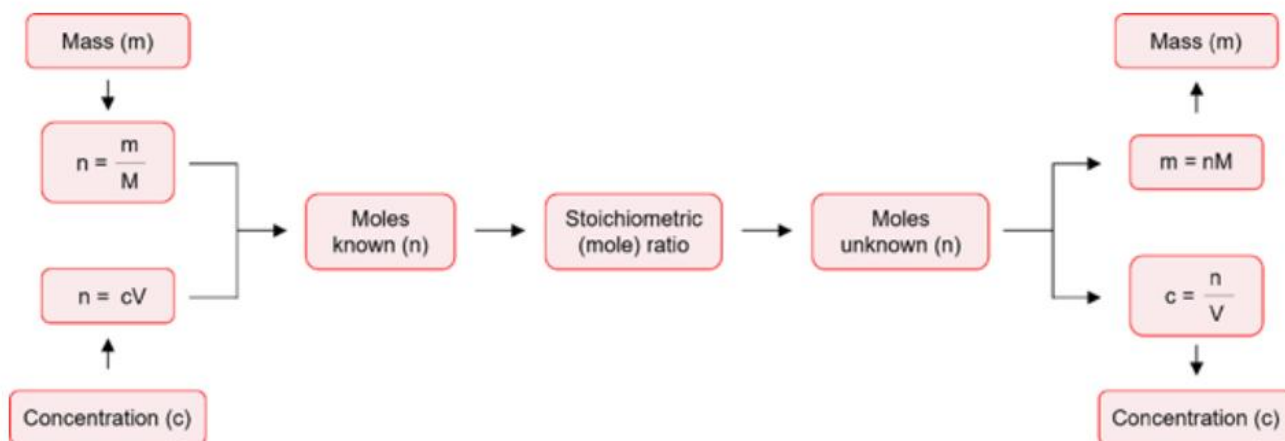


Figure 1.3.2: Processes for stoichiometric calculations.

Mass–mass stoichiometry

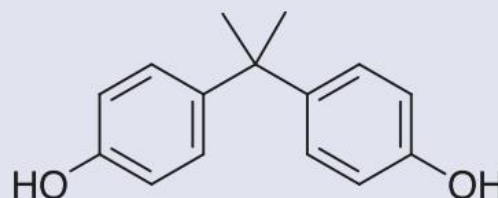
The moles are determined from the mass of a known species. A stoichiometric (mole) ratio is applied to the unknown species and then the mass is determined.



Science as a human endeavour

Bisphenol A (BPA) as a synthetic molecule has been used in the production of polycarbonate and as a coating on some food and beverage container packaging.

Most people are frequently exposed to trace levels of BPA. Although exposure is common, BPA does not accumulate within the body, with toxicokinetic studies showing the biological half-life in adult humans to be around two hours. This allows exposure to be easily determined by urine testing, facilitating convenient biomonitoring of populations.



The health effects of BPA have been widely debated in both public and scientific communities, with over 18,000 scientific papers published on the topic up to 2024. The primary concern is BPA's potential ability to disrupt the human endocrine system by mimicking estrogen. Due to lifelong exposure, there is worry about potential cumulative effects, but studying long-term, low-dose interactions is challenging. Research findings vary significantly regarding the impact of BPA and the exposure levels at which it becomes harmful. Industry-funded studies often indicate that BPA is safer than government or academic studies suggest.

Public health agencies in the EU, US, Canada, Australia, Japan, and the WHO have all reviewed the health risks of BPA and found that normal exposure levels are below those currently associated with risk. Nevertheless, due to scientific uncertainty, many jurisdictions have taken steps to reduce exposure on a precautionary basis. In particular, infants are considered to be at greater risk, leading to bans on the use of BPA in baby bottles and related products by the US, Canada, the EU, and other regions. Bottle producers have largely switched from polycarbonate to polypropylene, and there is some evidence that BPA exposure in infants has decreased as a result.

Question

25. (a) Discuss the role of public perception and scientific uncertainty in driving the precautionary measures taken by governments regarding BPA use in baby products.

(3 marks) **KA3**

- (b) Explain why collaboration between government agencies and scientific researchers in the use of biomonitoring technology is crucial when assessing and managing the health risks of substances like BPA.

(3 marks) **KA3**

- (c) Explain why industry-funded studies might differ in their findings on BPA's safety compared to those funded by academic or government institutions.

(3 marks) **KA3**

- (d) Suggest why studying long-term, low-dose interactions of BPA in humans poses a challenge for researchers.

(3 marks) **KA3**

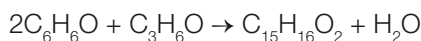
- (e) Imagine that a major new study found conclusive evidence of severe health risks at low exposure levels. Suggest how plastic manufacturers and public health agencies might change their communication strategies in light of this information.

(4 marks) **KA3**

Worked example

Bisphenol A (BPA) is a synthetic molecule used in the formation of the group of polymers called polycarbonates. Polycarbonates are often used to store food and water.

- (a) Bisphenol A can be formed from the condensation reaction between phenol ($\text{C}_6\text{H}_6\text{O}$) and propanone ($\text{C}_3\text{H}_6\text{O}$) shown in the equation below.



Approximately 3.6×10^6 tonnes of BPA is used by manufacturers each year.

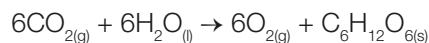
Calculate the mass, in kg, of phenol that would be required to produce this quantity of BPA.

	Explanation	Calculation
STEP 1	Convert the mass of the known (BPA) into grams. Calculate the molar mass of BPA.	$m = 3.6 \times 10^6 \times 10^6 \text{ g}$ $M(\text{C}_{15}\text{H}_{16}\text{O}_2) = ((15 \times 12.01) + (16 \times 1.008) + (2 \times 16.00))$ $= 228.278 \text{ g mol}^{-1}$
STEP 2	Calculate the number of moles of BPA.	$n = \frac{m}{M}$ $= \frac{3.6 \times 10^{12}}{228.278}$ $= 1.577 \times 10^{10} \text{ mol}$
STEP 3	Apply the stoichiometric ratio to determine the unknown moles of phenol.	$= \frac{n(\text{phenol})}{n(\text{BPA})} = \frac{2}{1}$ $n(\text{phenol}) = 2 \times n(\text{BPA})$ $= 2 \times 1.577 \times 10^{10} \text{ mol}$ $= 3.154 \times 10^{10} \text{ mol}$
STEP 4	Calculate the molar mass of phenol. Calculate the mass of phenol from the moles and molar mass.	$M(\text{C}_6\text{H}_6\text{O}) = ((6 \times 12.01) + (6 \times 1.008) + (16.00))$ $= 94.108 \text{ g mol}^{-1}$ $m = n \times M$ $= 3.15 \times 10^{10} \times 94.108$ $= 2.968 \times 10^{12} \text{ g} = 2.968 \times 10^9 \text{ kg}$

Question

26. A mature eucalypt tree can absorb 21.8 kg of carbon dioxide per year.

(a) Carbon dioxide is converted into glucose through photosynthesis, shown in the equation below:



(i) **Calculate** the mass of glucose, in kg, formed by a mature eucalypt tree in one year.

(6 marks) **KA4**

(ii) **Calculate** the mass of oxygen, in g, generated by a mature eucalypt tree in one year.

(3 marks) **KA4**

(b) The average vehicle produces approximately 4.7 tonnes (1 tonne = 1000 kg) of carbon dioxide per year.

(i) **Calculate** the number of mature eucalypt trees required to offset the annual emissions of carbon dioxide from one motor vehicle.

(2 marks) **KA4**

(ii) **State** one conclusion that can be drawn from these findings.

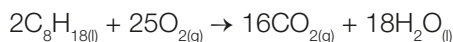
(1 mark) **KA3**

Limiting-excess calculations

In some cases, the number of moles of reactants present is not consistent with the stoichiometric ratio. In these instances, one reagent will limit, through the stoichiometric ratio, the consumption of other reagents and hence the amount of products that may be formed.

Worked example

Octane, a component of petrol, undergoes combustion according to the following equation.



The mass of one litre of octane is 692 g. If this mass of octane underwent combustion with 3.0×10^3 g of oxygen, determine the limiting reagent and hence calculate the mass of carbon dioxide produced per litre of octane undergoing combustion.

	Explanation	Calculation
STEP 1	Calculate the moles available from both reactant species using the mass and molar mass for both octane and oxygen.	$n = \frac{m}{M}$ $n(\text{C}_8\text{H}_{18}) = \frac{692}{114.224} = 6.058 \text{ mol}$ $n(\text{O}_2) = \frac{3000}{32.00} = 93.75 \text{ mol}$
STEP 2	Consider the stoichiometric ratio applied to reactants. Determine which reactant is completely consumed (the limiting reagent) and which has moles remaining (the excess reagent).	$n(\text{C}_8\text{H}_{18}) = \frac{6.058 \text{ mol}}{2} = 3.029$ $n(\text{O}_2) = \frac{93.75 \text{ mol}}{25} = 3.75$ $3.029 < 3.75$ $\therefore \text{C}_8\text{H}_{18} \text{ limiting @ } 3.029 \text{ mol}$ $\text{O}_2 \text{ is in excess}$
STEP 3	Using the number of moles from the limiting reagent, determine the number of moles of carbon dioxide produced.	$n(\text{O}_2) = 16 \times 3.029 \text{ mol} \quad \leftarrow \text{limiting moles}$ ↑ stoichiometric coefficient of CO_2 $= 48.464 \text{ mol}$
STEP 4	Using the molar mass of carbon dioxide, and the calculated number of moles, calculate the mass of carbon dioxide.	$M(\text{CO}_2) = (12.01 + (2 \times 16.00))$ $= 44.01 \text{ g mol}^{-1}$ $m = n \times M$ $= 48.446 \times 44.01 = 2133 \text{ g}$

Question

27. An experiment was conducted to study metal corrosion.

- (a) 2.00 g of zinc metal was added to 100 mL of 0.100 mol L⁻¹ copper(II) nitrate (Cu(NO₃)₂) solution. Elemental copper was formed as one product.

- (i) Write an equation for the reaction of zinc metal with copper(II) nitrate, and state the molar ratio between the reactants.

(3 marks) **KA1**

- (ii) Determine the number of moles of each reactant that were combined. Hence, state which reactant is in excess.

(4 marks) **KA2**

- (iii) State the molar ratio between the limiting reagent and elemental copper product. Hence, state the number of moles of copper that were produced.

(2 marks) **KA4**

- (iv) Calculate the mass of copper produced.

(2 marks) **KA4**

- (b) A 1.20 g sample of magnesium was dissolved in 50.0 mL of 0.500 mol.L⁻¹ hydrochloric acid solution.

- (i) Write an equation for the reaction of magnesium with hydrochloric acid.

(2 marks) **KA1**

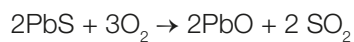
- (ii) Determine the limiting reagent.

(4 marks) **KA2**

- (iii) Calculate the mass that will remain when the reaction is complete for the reactant that is in excess.

(4 marks) **KA2**

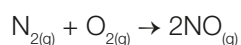
28. Lead is extracted from lead(II) sulfide (PbS) by heating in the presence of oxygen to produce lead(II) oxide.



Determine the maximum mass of lead(II) oxide that can be formed when 50 kg of lead(II) sulfide is reacted with 15 kg of O₂.

(6 marks) **KA2**

29. The high temperatures generated in an internal combustion engine allow the formation of nitric oxide according to the equation below:



0.300 g of oxygen (O₂) and 1.60 g of nitrogen (N₂) were available as diatomic molecules in 1 L of air that had been heated to a very high temperature.

- (a) **Determine** the limiting reagent.

(5 marks) **KA4**

- (b) Hence, **calculate** the mass of nitric oxide produced.

(4 marks) **KA4**



Science as a human endeavour

Bio-Agtive methods

Traditional fertiliser is a source of carbon emissions, contributing to climate change. In Canada, agricultural emissions account for 10% of all carbon emissions. In 2020, the Canadian government announced a target to reduce fertiliser emissions by 30%.

Bio-Agtive is a Canadian company run by Gary Lewis, a farmer from southern Alberta. The company sells a technology (also called 'Bio-Agtive') that collects exhaust from diesel engines in tractors and other agricultural machinery and combines it with water to produce a carbon-based fertiliser. This fertiliser can be distributed with seeds or through irrigation systems. The increased concentration of carbon dioxide and oxides of nitrogen in the soil is thought to increase microbial activity.

One of the main challenges faced by alternative fertiliser startups is convincing farmers to try these new products. Many farmers are sceptical and hesitant to risk their livelihoods on an unproven product—only a few hundred farmers have used the Bio-Agtive system, which mounts on the front of tractors and sells for between \$65,000 and \$95,000. However, interest in Bio-Agtive significantly increased after Russia's invasion of Ukraine in 2022 caused fertiliser prices to spike.

Early research indicated that Bio-Agtive is, at the very least, not harmful to the soil. However, whether it can fully replace traditional fertiliser has not yet been determined. It is also unclear whether the carbon emissions injected into the soil remain there and for how long. Further research is underway at Olds College in Alberta, including measuring crop yields and analysing soil samples.

Reference: Bakx, K. and McElligott, D. (2022). *One farmer's uphill battle to provide cheaper, more environmentally friendly alternative to fertilizer.* [online] CBC. Available at: <https://www.cbc.ca/news/canada/calgary/bakx-fertilizer-bio-agtive-olds-1.6582561>.

Question

30. From the passage above, identify and explain one example of the 'Science as a Human Endeavour' concept of:

(a) **Development.**

(3 marks) **KA3**

(b) **Influence.**

(3 marks) **KA3**

(c) An **Application** and another example of a **Limitation.**

(6 marks) **KA3**

Dilution

Dilution allows solutions of higher concentrations to be accurately made up at lower concentrations. This is important in volumetric analysis where working concentrations and volumes need to remain relatively low.

Serial dilutions may also be used to generate sets of solutions from a single standard, for the construction of calibration graphs in instrumental analysis. Many consumer products also require dilution before use. Examples include garden fertilisers and flavouring used to make up carbonated drinks.

Typically, dilution is achieved through the addition of solvent to a volume of an existing solution (Figure 1.3.3). In this procedure, the measured volume contains a set number of moles of solute which remains unchanged. The fixed moles of solute are distributed through the diluted solution on the addition of solvent to a desired volume. An expression for dilution can be derived by equating the number of moles.

$$c_{\text{original}} = \frac{n_{\text{original}}}{V_{\text{original}}} \text{ and } c_{\text{diluted}} = \frac{n_{\text{diluted}}}{V_{\text{diluted}}}$$

$$n_{\text{original}} = n_{\text{diluted}} \text{ therefore } c_{\text{original}} \times V_{\text{original}} = c_{\text{diluted}} \times V_{\text{diluted}}$$

$$c_1 \times V_1 = c_2 \times V_2$$



Figure 1.3.3: Stages in dilution.

Worked example

Copper sulfate is added, in low concentrations, to waterways and reservoirs to control the growth of blue-green algae.

Mount Bold reservoir in the Adelaide Hills required the upper level of the water to be treated with a volume of 1.848 GL of water. 1000 L of concentrated copper sulfate solution was added to achieve a final concentration of 1.800 ppm. Calculate the concentration of the original solution.

	Explanation	Calculation
STEP 1	Identify the values which represent c_1 , V_1 , c_2 and V_2 from the information provided, hence identify the unknown.	$c_1 \times V_1 = c_2 \times V_2$
STEP 2	Rearrange the equation to determine the unknown variable.	$c_1 = \frac{c_2 \times V_2}{V_1}$
STEP 3	Substitute the known values into the equation and calculate the unknown.	$c_1 = \frac{1.8 \times 1.848 \times 10^9}{1000}$ $c_1 = 3.326 \times 10^7 \text{ ppm}$

Question

31. The herbicide DCMU, commercially known as Diuron[®], is used to control weeds in a range of cereal crops across Australia. Farmers purchase the herbicide in drums at a concentration of 900 g L^{-1} . The concentrated herbicide is then diluted to a recommended concentration suitable for spraying onto crops.

- (a) **Calculate** the concentration of the commercial stock herbicide, in mol L^{-1} , given that the molar mass of Diuron[®] is 233.1 g mol^{-1} .

(2 marks) **KA4**

- (b) In one application of the herbicide, two 20 L drums of Diuron[®] were added to a spray unit of 6000 L capacity and diluted with water.

Calculate the final concentration of the diluted solution, in mol L^{-1} .

(3 marks) **KA4**

- (c) Copper sulfate is added, in low concentrations, to waterways and reservoirs to control the growth of blue-green algae.

Mount Bold reservoir in the Adelaide Hills has a volume of 1.848GL of water. 20 000 L of concentrated copper sulfate solution was added to achieve a final concentration of 1.800ppm. Calculate the concentration of the original solution.

(2 marks) **KA4**

Science understanding

A titration can be used to determine the concentration of a solution of a reactant in a chemical reaction.

Describe and explain the procedure involved in carrying out a titration, particularly rinsing glassware and determining the end-point.

© SACE 2025

Standard solutions

A **standard solution** is a prepared solution that contains a precisely known concentration. Standard solutions are used to determine the concentration of unknown solutions during **titrations**, and to calibrate analytical instruments.

A standard solution is prepared in a volumetric flask. An accurately measured volume of an appropriate solvent is added to an accurately weighed mass (hence number of moles) of solute. The solute chosen for the preparation is referred to as a **primary standard**. The compound chosen as the primary standard is selected due to its *stability*, *purity*, and *detectability* during a reaction.

Question

32. Anhydrous sodium carbonate (Na_2CO_3) and sodium hydroxide (NaOH) were supplied analytical reagents (provided at an analytical grade of purity) for the preparation of separate standard solutions.

Each compound was required to prepare individual 0.100 mol L^{-1} standard solutions for analysis during an acid–base titration, with an appropriate indicator.

A detectable colour change was evident during the reaction.

- (a) The sodium carbonate was supplied as an anhydrous analytical-grade reagent.

(i) **State** whether the solution prepared would be acidic or alkaline.

(1 mark) KA1

(ii) **Suggest** one reason why anhydrous sodium carbonate is chosen.

(1 mark) KA1

(iii) **Suggest** one reason why it is important to use an analytical-grade reagent.

(1 mark) KA1

(iv) State the name given to the point at which the colour changes.

(1 mark) KA1

Each compound was weighed out accurately, using their relatively large molar mass, onto separate watch glasses on an electronic balance.

- (b) The samples were left for a period of time, and it was noted that the appearance of the sodium hydroxide had altered. On reweighing it was discovered that the mass of the sodium carbonate had not changed, but the mass of the sodium hydroxide had increased. The masses are summarised in the following table.

	Anhydrous sodium carbonate	Sodium hydroxide
Initial mass	1.103 g	4.002 g
Final mass	1.103 g	7.601 g

- (i) **Calculate** the number of moles of sodium hydroxide present initially.

(2 marks) KA4

Sodium hydroxide absorbs water (it is hygroscopic), but it also absorbs carbon dioxide. Assume that the increase in mass of the sodium hydroxide is due to water.

- (ii) **Calculate** the moles of water absorbed.

(3 marks) **KA4**

- (iii) Hence, **determine** the formula of the hydrated compound.

(2 marks) **KA4**

- (iv) A sample of sodium hydroxide had been left exposed to air for an extended period of time before being weighed and used in the final preparation of a standard solution.

Explain the effect of this exposure on the final concentration of the sodium hydroxide solution.

(2 marks) **IAE4**

- (v) Hence, **suggest** one reason why sodium carbonate, rather than sodium hydroxide, is often chosen as an effective primary standard.

(1 mark) **KA1**

Common glassware used during volumetric analysis

A range of glassware is used during the production of standard solutions, dilutions, and in performing titrations. This includes both standard and volumetric glassware.

Glassware	Resolution	Typical tolerance and uncertainty (Class A glassware)	Cleaning procedure
250 mL volumetric flask	Holds an accurate measure 250 mL	+/- 0.12 mL	Rinsed with distilled water
25 mL volumetric pipette	Delivers an accurate measure 25 mL	+/- 0.03 mL	Rinsed with distilled water and then the solution to be transferred
50 mL burette	0.1 mL (predictions may be made to 0.05 mL)	+/- 0.03 mL	Rinsed with distilled water and then the solution to be transferred
250 mL conical flask	25 mL	+/- 10 mL	Rinsed with distilled water
100 mL measuring cylinder	1 mL	+/- 0.6 mL	Rinsed with distilled water

? Science inquiry skills

Skills in context

Resolution

Resolution of an instrument is related to the smallest measurable increment. Different apparatus provide different levels of resolution. Glassware is selected for an intended purpose, dependent on the level of resolution required.

Example

An approximate volume of 50 mL of solution can be transferred to a reaction vessel using a beaker, conical flask, or measuring cylinder. Recording the volume of a titration to the closest millilitre requires the use of a burette reading to a resolution of the closest 0.1 mL.

Preparation of a standard solution

A standard solution is prepared to have a desired concentration and volume. This involves working back from the concentration (c), to calculate the required number of moles (n) for the set volume (V) of the chosen volumetric flask. The mass (m) is then calculated after determining the molar mass (M) of the compound.

A number of successful methods are used in laboratories in the preparation of a standard solution.

Method 1

- Place a clean dry beaker onto the pan of the electronic balance and tare (zero) the balance.
- Using a clean dry spatula, carefully add the mass of solute to the beaker until a value is achieved that is close to that calculated. Record this value to the full resolution of the balance.
- Add a small volume of water to the beaker, and completely dissolve the solute by stirring with a clean glass stirring rod.
- Transfer the solution in the beaker to a volumetric flask, using a clean dry funnel.
- Ensure to rinse all residues present in the beaker and funnel into the volumetric flask, including the surface of the stirring rod.
- Rinse down the internal neck of the flask, ensuring to add less than half of the total volume of the volumetric flask.



Figure 1.3.4: Weighing out the solute.

Method 2

- Tare (zero) the electronic balance.
- Place a clean dry watch glass onto the pan of the balance and record its mass to the full resolution of the balance.
- Using a clean dry spatula, carefully add the mass of solute to the watch glass until a mass is achieved close to that calculated. Record this value to the full resolution of the balance.
- Carefully transfer the solute to the volumetric flask through a clean dry funnel.
- Return the watch glass to the balance and reweigh to account for remaining solute on the surface.
- Rinse all residues on the surface of the funnel and internal neck of the flask into the volumetric flask, ensuring to add less rinsings than half of the total volume of the volumetric flask.

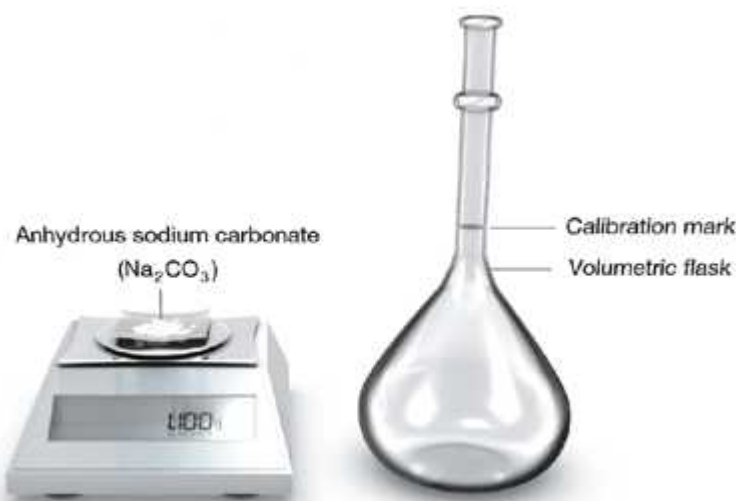


Figure 1.3.5: Alternative weighing of the solute.

Question

Credit will be given for answers which correctly use appropriate chemical terms and effectively communicate knowledge and understanding of chemistry.

33. **Consider** the two alternative procedures outlined earlier.

Evaluate the effectiveness of the two procedures presented for weighing and transferring the solute in the preparation of the standard solution.

1

(6 marks) IAE4

Completing the procedure

- Approximately half the volume of solvent is added to the volumetric flask after the solute has been transferred. The flask is swirled gently to encourage the solute to dissolve in the solvent (Figure 1.3.6).
- The flask is made up to close to the calibration line with distilled water (Figure 1.3.7). The final volume may be added more effectively using a Pasteur pipette. The final volume is added with the volumetric flask positioned at eye level, until the bottom of the meniscus of the solution sits on the calibration line.
- At this point the volumetric flask is stoppered and inverted to ensure the **homogeneity** of the solution (uniform concentration throughout).
- The volumetric flask is inverted prior to use.



Figure 1.3.6:
Swirling to dissolve solute.

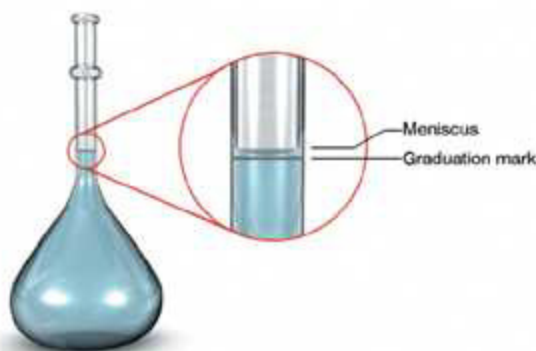


Figure 1.3.7: Filling to the calibration mark.

Volumetric pipette: preparation and use

Volumetric pipettes are available in a range of volumes and are used to deliver an accurate volume (aliquot) of aqueous solution or liquid material.

Prior to use, several important steps are undertaken to ensure their accuracy in delivering desired quantities of reactants.

Preparation

- Initially the pipette should be checked to ensure it is free from defects.
- The pipette is initially cleaned thoroughly with distilled water to remove remaining contaminants from previous use.
- The pipette is cleaned by drawing up a small volume of water with a bulb or syringe type filler, removing the filler, and running the water over the internal surfaces, while holding the pipette horizontally. A small volume of water is run through the pipette when it is returned to a vertical position.
- This process may be repeated several times to ensure the removal of contaminants.
- If the pipette is being used to simply deliver a volume of distilled water, then the preparation is complete.

Delivery

- To prepare the volumetric pipette for the delivery of a solution, further steps are necessary.
- A small volume of the solution being delivered is drawn into the pipette with a pipette filler, the filler removed and the solution run horizontally over internal surfaces and through the tip of the pipette on returning it to the vertical position.
- The filler is then returned to the pipette in readiness to draw up the desired volume of solution.
- The pipette is lowered into the solution to avoid the generation of air bubbles while drawing up solution.
- The solution is drawn past the calibration mark, the pipette removed from the solution and the meniscus of the solution slowly lowered to the calibration mark by carefully releasing solution. This step is undertaken with the pipette held vertically at eye level until the bottom of the meniscus sits directly on the calibration line.
- The **aliquot** (volume) is then carefully transferred to a conical flask.
- The aliquot is released with the tip of the pipette touching the inside of the flask (or alternative glassware) to avoid any splashing and consequent loss of volume (Figure 1.3.8).
- The pipette is removed from the surface. Any solution remaining in the tip of the pipette is removed by touching the tip onto the inner glass surface of the flask until the final volume of material has been transferred. Volume remaining after this procedure is accounted for in the calibration of the pipette.
- A wash bottle is used to rinse the neck of the flask and ensure that all the solution, and therefore all moles, are present.
- Two to three drops of indicator may be added at this point if the aliquot has been delivered for use in an acid–base titration.

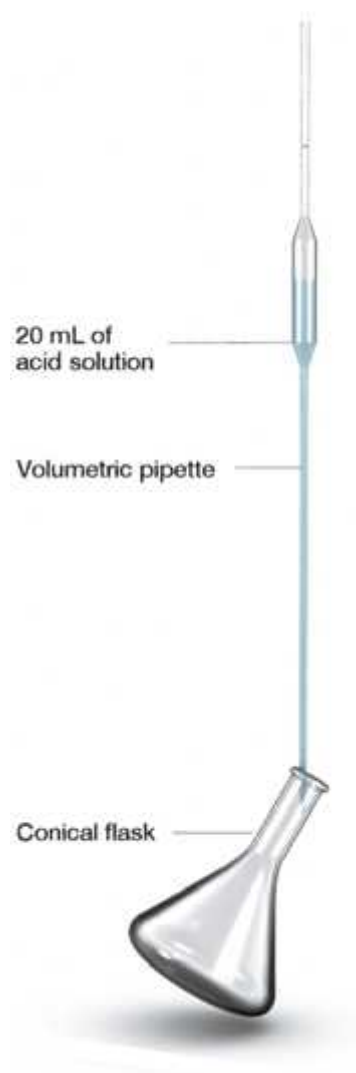


Figure 1.3.8:
Delivery from the
volumetric pipette.

The burette: preparation and use

Burettes are available in a range of volumes (typically 50 mL is chosen) and are used to accurately deliver **titres** (repeated volumes).

Prior to use, several important steps are undertaken to ensure their accuracy in delivering desired volumes (and therefore moles) of reactants.

Preparation

- Initially the burette should be checked to ensure it is free from defects.
- The burette is initially cleaned with distilled water to ensure that any remaining impurities from previous use have been removed.
- A small volume of distilled water is introduced to the burette through a clean funnel. The burette is held horizontally and the water run over the internal surfaces.
- On returning the burette to the vertical position, a small amount of distilled water is run through the tap assembly.
- This process may be repeated if there are signs of remaining contaminants.
- This entire cleaning process is then repeated with the solution to be delivered.

Delivery

- The burette is filled with the assistance of a clean funnel. A small volume of solution is run through the tap assembly until the tip is filled with solution (it is important to remove the air bubble).
- The burette is clamped vertically.
- The burette is filled to below the zero mark, with the meniscus read at eye level (Figure 1.3.9).
- The initial volume is read from the bottom of the meniscus at eye level and recorded.
- For a rough titration, with the tap wide open, swirling continuously, and then closed when an observable change in colour is first noted. (The purpose of a rough titration is to establish an approximate volume required for proceeding titrations.)
- Periodically during the titration, the sides of the conical flask are washed to ensure all reactants are present in the reacting solution.
- The equivalence point is established when the mole ratio of reacting quantities is met. The endpoint is recognised as a permanent observable change past the equivalence point (point where the stoichiometric ratio has been achieved) (Figure 1.3.10).
- Titration are typically repeated until three **concordant titres** are obtained. Concordant titres are generally recognised as being within 0.1 mL of one another, depending on the **titrant** (known reagent) and **analyte** (unknown reagent).

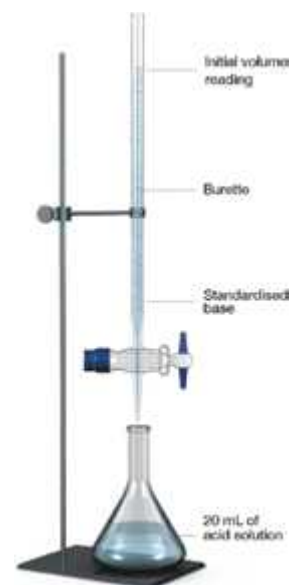


Figure 1.3.9:
Preparation of the burette.



Figure 1.3.10:
Reaching the endpoint
of the titration.



Science as a human endeavour

Biodiesel production

Biodiesel is produced by transesterification reactions that can be catalysed by acids or bases, but base-catalysed reactions are more common.

In the base-catalysed reaction, sodium hydroxide must be added to neutralise the acidity of the oils; further sodium hydroxide is required in the reaction to convert the oils to biodiesel. The oils used as raw materials vary in acidity, and achieving a successful yield of biodiesel requires a knowledge of how much sodium hydroxide must be added during the reaction. Titration is often used to determine the level of acidity present so the correct quantity of base can be added to optimise production.

If the feedstock oil used has a high acid content, acid-catalysed esterification can be used to react the fatty acids with alcohol to produce biodiesel. However, this method involves longer reaction times and higher costs.



Question

34. (a) The use of titration to determine oil acidity demonstrates the role of precise scientific procedures in optimising chemical industry. **Identify** and **explain** which 'Science as a Human Endeavour' concept this exemplifies.

(2 marks) **KA3**

- (b) **Describe** the economic and practical limitations of using acid-catalysed esterification compared to base-catalysed reactions. **Identify** and **explain** which 'Science as a Human Endeavour' concept this exemplifies.

(3 marks) **KA3**

? Science inquiry skills

Skills in context

Precision

Precision, with reference to a set of data, is determined by the degree of uniformity of the values. Precision is linked to the reproducibility and reliability of producing consistent data and is evaluated through the **range** evident in sets of data or the amount of **scatter** evident around a line of best fit if graphing the data.

Accuracy

Accuracy, with reference to a set of data, is evaluated through conformity with a true or accepted value. Accuracy is linked to the **validity** (how effectively the procedure generates valid conclusions) of the investigation. Accuracy is evaluated by obtaining an average for the data set and making comparisons with the accepted value.

Precision and accuracy may be visualised using a target (Figure 1.3.11).

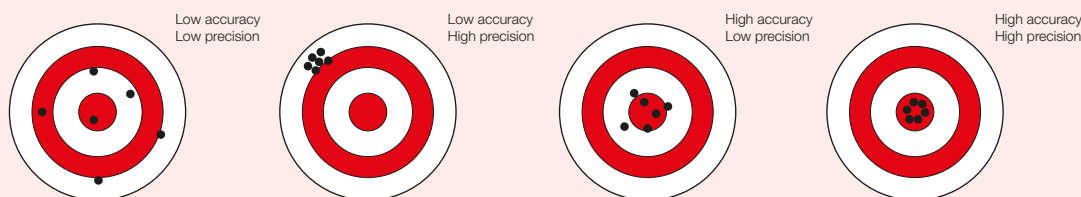


Figure 1.3.11: Visual representation of precision and accuracy.

Random errors

Random errors are variations in the measurements taken for experimental data due to limitations of the experimenter and the precision of the apparatus. Random errors are linked to the precision of the data obtained. When evaluating random errors, their significance and impact needs to be considered with respect to evidence of the variation in the data obtained.

Example

Variation in the colour and intensity of the indicator obtained at the endpoint when using acid–base indicators or self-indicating redox reactions is an example of random error in titration. Human perception of colour change and the ability of the experimenter to control flow from the tap during a titration results in colour differences. Depending on the skill and technique of the experimenter, this error will typically generate quite small variation in recorded volumes.

Systematic errors

Systematic errors are recurrent errors inherent in the apparatus or experimental method. As the name suggests, the errors are present in the system or procedure. When evaluating systematic errors, the significance and impact of this consistent difference needs to be considered with respect to the magnitude of the data obtained. Systematic errors are linked to the accuracy of the measurements.

Repeating the titration procedure using different glassware and fresh stock solutions will identify one or more systematic errors but will not eliminate the source(s) of error from the analysis and may even introduce error of greater magnitude.

Example 1

Glassware such as volumetric pipettes, volumetric flasks, and burettes have all been manufactured within the limits of manufacturing tolerances (Refer to Page 48) and therefore have inaccuracies associated with their use. The selection and use of different glassware will result in accumulated systematic error from the inherent differences in calibration of each piece of glassware. A volumetric pipette used with great skill may still have a calibration difference of up to 0.03 mL, delivering 20.03 mL instead of the stated 20.00 mL.

Example 2

Some chemical reagents degrade over time in storage. Hydrogen peroxide is stored at low temperatures in an opaque black plastic container, as it decomposes when exposed to sunlight. Solutions stored for extensive periods may have lower concentrations of peroxide available for reaction. Over the duration of a titration, fluctuations in recorded titres may also be evident as hydrogen peroxide decomposes over time.

Question

35. Dentists are interested in the impact of food acids and organic acids present in commonly consumed beverages on the degradation of tooth enamel. A series of titrations were undertaken to determine the presence of acids in white wine, orange juice and lemonade. The following data was obtained.

	Rough titre (mL)	Titre 1 (mL)	Titre 2 (mL)	Titre 3 (mL)	Titre 4 (mL)	Titre 5 (mL)	Titre 6 (mL)
White wine	12.05	11.90	11.85	11.90	11.95	11.75	11.90
	Rough titre (mL)	Titre 1 (mL)	Titre 2 (mL)	Titre 3 (mL)	Titre 4 (mL)	Titre 5 (mL)	Titre 6 (mL)
Orange juice	17.60	18.20	17.20	17.40	17.35	18.35	17.50
	Rough titre (mL)	Titre 1 (mL)	Titre 2 (mL)	Titre 3 (mL)	Titre 4 (mL)	Titre 5 (mL)	Titre 6 (mL)
Lemonade	12.05	9.70	9.65	9.50	9.25	9.20	8.90

- (a) **State** whether the average titre for the concordant values of white wine or lemonade offers a higher degree of precision.

(1 mark) IAE3

- (b) The same white wine was titrated by 10 other groups, with an average of 11.80 mL obtained.

- (i) **State** the reason for averaging the values obtained by 10 other investigations.

(1 mark) IAE4

- (ii) One group obtained an average titre of 11.75 mL. **State** and **explain** whether this value offers a higher or lower degree of accuracy compared to the concordant values stated for white wine above.

(2 marks) IAE3

- (c) The range in titre values for orange juice is 0.15 mL for the concordant titres, and 1.0 mL for all titre values, excluding the rough titre.

- (i) **State** whether this low precision is likely to be due to the presence of random or systematic error.

(1 mark) KA1

- (ii) **Suggest** one reason why there is such variance in the precision of values for the titration with orange juice.

(1 mark) IAE4

- (d) A supersaturated solution is present in lemonade, where a maximum concentration of carbon dioxide gas is dissolved at a given temperature. **Suggest** one reason why the titre values over the duration of the investigation are decreasing.

(1 mark) KA2

Science understanding

Determine the concentration of a solution of a reactant in a chemical reaction by using the results of a titration.

© SACE 2025

Direct titration (solution stoichiometry)

A **direct titration** is an analytical technique where a solution of unknown concentration is directly determined by applying the stoichiometric (mole) ratio from a known reaction equation.

Worked example

Salinity can be determined as a measure of the chloride ion concentration in solution. A direct titration with silver nitrate can be used to determine the chloride ion concentration.

A sample of water from the mouth of a river near the ocean was analysed. A 20 mL water sample was diluted in a 100 mL volumetric flask. A 20 mL aliquot of diluted sample was transferred to a conical flask using a volumetric pipette, with the addition of potassium chromate as an indicator.

A precipitate of silver(I) chloride was formed when silver(I) nitrate solution was transferred (dropwise) to the sample of river water. When all the chloride ions precipitated, the excess silver ions underwent reaction with chromate ions as an indicator to achieve a red-brown colour.

The diluted sample was titrated with 0.100 mol L⁻¹ silver nitrate (AgNO₃) until the first permanent colour was achieved. The process was repeated until concordant values were obtained.

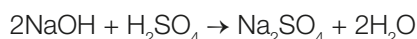
	Rough Titre	Titre 1	Titre 2	Titre 3	Titre 4
Volume (mL)	16.55	15.60	15.65	15.80	15.55



	Explanation	Calculation
STEP 1	Calculate the known number of moles of silver ions (Ag ⁺) from the average of the volume of the concordant titres and the stated concentration of silver nitrate solution.	$\text{Average titre} = \frac{15.60 + 15.65 + 15.55}{3}$ $n(\text{Ag}^+) = 0.01560 \times 0.100$ $= 0.001560 \text{ mol}$
STEP 2	Using the stoichiometric ratio from the equation provided, calculate the moles of the unknown, chloride ions (Cl ⁻).	$n(\text{Ag}^+) : n(\text{Cl}^-) = 1:1$ $\therefore n(\text{Cl}^-) = 0.00156 \text{ mol}$
STEP 3	Using the moles of chloride ions and the volume of the aliquot, calculate the concentration of chloride ions in mol L ⁻¹ .	$c = \frac{n}{V}$ $c(\text{Cl}^-) = \frac{0.00156}{0.0200}$ $= 0.0780 \text{ mol L}^{-1}$
STEP 4	Calculate the original concentration prior to dilution.	$c(\text{Cl}^-)_{\text{original}} = \frac{100}{20} \times 0.078$ $= 0.390 \text{ mol L}^{-1}$
STEP 5	Convert the original concentration to ppm by multiplying by the molar mass of chloride ions and then a factor of 10 ³ .	$\frac{\text{mol}}{\text{L}} \xrightarrow{\times M} \frac{\text{g}}{\text{L}} \xrightarrow{\times 10^3} \frac{\text{mg}}{\text{L}} = \text{ppm}$ $c(\text{Cl}^-)_{\text{original}} = 0.390 \times 35.45 \times 10^3$ $= 13825.5 \text{ mg L}^{-1}$ $= 13800 \text{ ppm}$

Question

36. A chemist wishes to determine the concentration of a dilute solution of sulfuric acid. A 20.00 mL sample of the sulfuric solution is analysed using titration. A standardised solution of sodium hydroxide with a concentration of $0.2074 \text{ mol.L}^{-1}$ is used as the titrant. The reaction is shown below.



The three concordant titres were 10.10 mL, 10.00 mL, and 10.10 mL.

- (a) Calculate the average titre.

(1 marks) **KA1**

- (b) Use $c = n/V$ to calculate the number of moles of NaOH in the average titre.

(2 marks) **KA4**

- (c) State the molar ratio of sodium hydroxide to sulfuric acid in the neutralisation reaction. Hence, determine the number of moles of sulfuric acid required to react with the average titre.

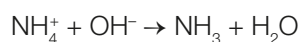
(2 marks) **KA4**

- (d) Calculate the molar concentration of sulfuric acid in the 20.00 mL analyte solution.

(2 marks) **KA4**

37. Most nitrogen fertilisers contain water-soluble ammonium ions, (NH_4^+). High concentrations of ammonium ions in bodies of water can indicate the presence of fertiliser runoff. The increased concentration of ammonium ions may lead to **eutrophication** (increased nutrient concentration) in the waterway.

A sample of water was analysed for the presence of ammonium ions through titration with a previously standardised $0.00200 \text{ mol L}^{-1}$ sodium hydroxide (OH^-) solution, according to the equation below:



A 20.0 mL sample of water required an average titre of 10.2 mL to achieve the endpoint.

- (a) **Calculate** the moles of sodium hydroxide required to reach the endpoint.

(2 marks) **KA4**

- (b) Hence, **determine** the moles of ammonium ions present.

(1 mark) **KA4**

- (c) **Calculate** the concentration of ammonium ions, in mol L⁻¹, in the sample of water.

1

(3 marks) KA4

Back titration

A **back titration** is a two-stage analytical technique, where a known amount of an excess of one reagent is added to a reagent of unknown concentration. The remaining excess reagent undergoes a secondary reaction with a differing reagent (Figure 1.3.12).

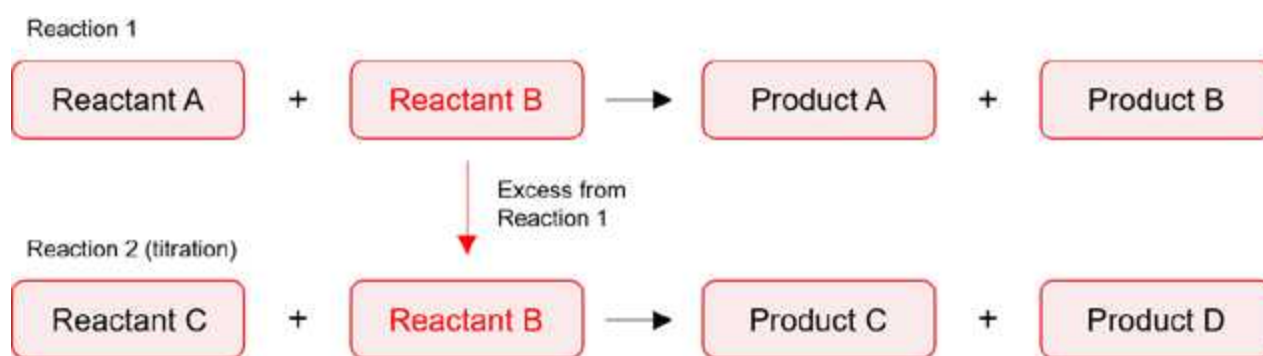


Figure 1.3.12: Mapping of quantities in a back titration.

Worked example

The concentration of carbon dioxide (CO₂) in air can be determined through an acid–base back titration. A 3.50 L sample of air was bubbled through 50.00 mL of 0.0200 mol L⁻¹ barium hydroxide (Ba(OH)₂) precipitating barium carbonate (BaCO₃).



The excess Ba(OH)₂ was titrated with 0.0316 mol L⁻¹ hydrochloric acid (HCl). An average titre of 38.58 mL was achieved in reaching the endpoint.

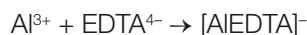
	Explanation	Calculation
STEP 1	Calculate the original number of moles of barium hydroxide, Ba(OH) ₂ , from the volume and concentration supplied prior to the reaction. Label the quantity as the <i>original</i> .	$n = c \times V$ $n(\text{Ba(OH)}_2)_{\text{original}} = 0.0200 \times 0.05000$ $= 0.00100 \text{ mol}$
STEP 2	Determine all quantities working ‘back’ from Equation 2 to Equation 1. Calculate the known number of moles of hydrochloric acid (HCl) by using the average volume of the concordant titres for Equation 2 and the concentration of aqueous HCl.	$n(\text{HCl}) = 0.0316 \times 0.03858$ $= 0.001219 \text{ mol}$

	Explanation	Calculation
STEP 3	Using the mole ratio from Equation 2, calculate the moles of the unknown, excess Ba(OH)_2 , from the calculated moles of HCl. Label the quantity as the <i>excess</i> .	$\frac{n(\text{Ba(OH)}_2)}{n(\text{HCl})} = \frac{1}{2}$ $n(\text{Ba(OH)}_2)_{\text{excess}} = \frac{n(\text{HCl})}{2}$ $n(\text{H}_2\text{SO}_4) = \frac{0.001219}{2}$ $= 0.0006096 \text{ mol}$
STEP 4	Ba(OH)_2 links Equation 2 to Equation 1. Calculate the reacted moles by subtracting the excess from the original number of moles of Ba(OH)_2 calculated prior. Label the quantity as the <i>reacted</i> . Note that when comparing amounts of substances between different equations/reactions, the number of moles is used directly. No consideration of stoichiometric ratio is necessary; this only applies within a reaction.	$n(\text{Ba(OH)}_2)_{\text{reacted}} = n(\text{Ba(OH)}_2)_{\text{original}} - n(\text{Ba(OH)}_2)_{\text{excess}}$ $n(\text{Ba(OH)}_2)_{\text{reacted}} = 0.00100 - 0.0006096$ $= 0.0003904 \text{ mol}$
STEP 5	Using the mole ratio from Equation 1, calculate the moles of the unknown carbon dioxide (CO_2) from the calculated moles of reacted Ba(OH)_2 .	$\frac{n(\text{CO}_2)}{n(\text{Ba(OH)}_2)} = \frac{1}{1}$ $\therefore n(\text{CO}_2) = 0.0003904 \text{ mol}$
STEP 6	Calculate the concentration of CO_2 in mol L^{-1} .	$c = \frac{n}{V}$ $c(\text{CO}_2) = \frac{0.0003904}{3.50} = 0.0001115 \text{ mol L}^{-1}$
STEP 7	Convert the concentration into ppm.	$\frac{\text{mol}}{\text{L}} \xrightarrow{\times M} \frac{\text{g}}{\text{L}} \xrightarrow{\times 10^3} \frac{\text{mg}}{\text{L}} = \text{ppm}$ $c(\text{CO}_2) = 0.0001115 \times 44.01 \times 10^3$ $= 4.91 \text{ mg L}^{-1}$ $= 4.91 \text{ ppm}$

Question

38. Aluminium sulfate (Alum) can be added to domestic water supplies as a coagulant/flocculant to remove fine clay particles. By using a back titration with EDTA and a suitable indicator, the concentration of aluminium ions can be determined.

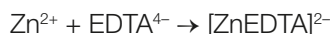
A 25 mL sample of water was transferred to a volumetric flask along with 30.0 mL of 0.010 mol L^{-1} EDTA.



- (a) **Calculate** the original number of moles of EDTA.

(2 marks) **KA4**

The excess EDTA was titrated with $0.0010 \text{ mol L}^{-1}$ zinc sulfate.



Concordant titres below were obtained.

	Rough titre	Titre 1	Titre 2	Titre 3
Volume (mL)	53.15	52.90	52.80	52.70

(b) (i) **Calculate** the number of moles of zinc ions (Zn^{2+}) that reacted with the excess EDTA.

(3 marks) **KA4**

(ii) Hence, **calculate** the moles of excess EDTA.

(1 mark) **KA4**

(iii) **Calculate** the moles of EDTA that reacted with the aluminium ions, Al^{3+} .

(2 marks) **KA4**

(iv) Hence, **calculate** the concentration, in mol L^{-1} , of Al^{3+} present in the water sample.

(3 marks) **KA4**

(v) **Express** the concentration of Al^{3+} , in ppm, present in the water sample.

(2 marks) **KA4**

39. Solutions of ammonia (1–10% w/v) are used as household cleaners, particularly for glass. The concentration of ammonia in a commercially available 'cloudy ammonia' solution can be determined by back titration with hydrochloric acid.

20.00 mL of the cloudy ammonia solution was pipetted into a 200.0 mL conical flask. 50.00 mL of $0.103 \text{ mol L}^{-1} \text{HCl}_{(\text{aq})}$ was immediately added to the conical flask and reacted with the ammonia in solution.



The excess HCl was titrated with $0.0507 \text{ mol L}^{-1} \text{Na}_2\text{CO}_{3(\text{aq})}$. The average titre was 20.35 mL of $\text{Na}_2\text{CO}_{3(\text{aq})}$. First, the amount of HCl that remained in excess after the reaction with ammonia is calculated.

(a) Write a balanced equation for the reaction of HCl with Na_2CO_3 .

(2 marks) **KA4**

(b) Calculate the moles of Na_2CO_3 that reacted in the titration.

(2 marks) **KA4**

- (c) Hence, determine the number of moles of HCl that reacted in the titration.

(2 marks) **KA4**

Next, the amount of ammonia in the cloudy ammonia solution is determined.

- (d) Calculate the total number of moles of HCl originally added to the cloudy ammonia solution.

(2 marks) **KA4**

- (e) Calculate the number of moles of HCl that reacted with ammonia in the cloudy ammonia solution.

(2 marks) **KA4**

- (f) Hence, determine the number of moles of NH_3 that reacted with HCl.

(2 marks) **KA4**

- (g) Calculate the ammonia concentration in the cloudy ammonia solution.

(3 marks) **KA4**

- (h) Express the ammonia concentration as a percentage weight by volume, %w/v.

(3 marks) **KA4**

Indirect titration

An **indirect titration** is a two-stage analytical technique whereby the product from an initial reaction undergoes a secondary reaction with a different reagent (Figure 1.3.13).

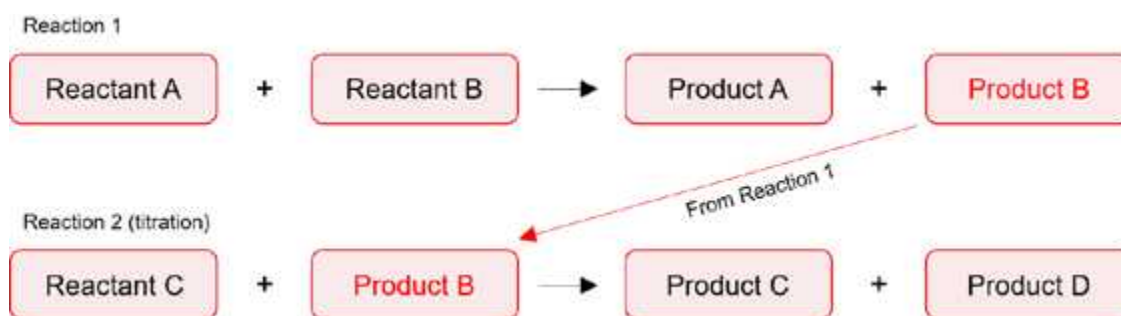
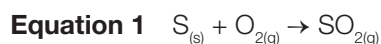


Figure 1.3.13: Flowchart of calculations in an indirect titration.

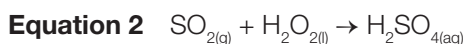
Worked example

The sulfur content of coal can be indirectly determined. The combustion of coal releases sulfur dioxide formed from the sulfur impurities present. The sulfur dioxide can be analysed on formation of sulfuric acid.

On the combustion of a sample of coal, of mass 8.06 g, the sulfur impurities were converted to sulfur dioxide gas (SO₂).



The sulfur dioxide gas produced was then bubbled through an aqueous solution of hydrogen peroxide (H₂O₂), forming sulfuric acid (H₂SO₄).



The sulfuric acid was then titrated against 0.100 mol L⁻¹ sodium hydroxide (NaOH).



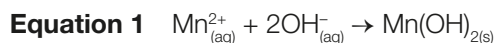
An average titre of 44.2 mL was obtained.

	Explanation	Calculation
STEP 1	The moles of sulfur dioxide (SO ₂) in Equation 2 are indirectly determined from Equation 3. Calculate the known number of moles of NaOH, using the average volume of the concordant titres for Equation 3 and the concentration of aqueous NaOH.	$n = c \times V$ $n(\text{NaOH}) = 0.100 \times 0.0442$ $= 0.00442 \text{ mol}$
STEP 2	Using the stoichiometric ratio from Equation 3, calculate the moles of the unknown H ₂ SO ₄ from the calculated moles of NaOH.	$\frac{n(\text{H}_2\text{SO}_4)}{n(\text{NaOH})} = \frac{1}{2}$ $n(\text{H}_2\text{SO}_4) = \frac{n(\text{NaOH})}{2}$ $n(\text{H}_2\text{SO}_4) = \frac{0.00442}{2}$ $= 0.00221 \text{ mol}$
STEP 3	The moles of H ₂ SO ₄ reacting in Equation 3 are the product of Equation 2. Hence, the two quantities can be equated. Note that when comparing amounts of substances between different equations/reactions, the number of moles is used directly. No consideration of stoichiometric ratio is necessary; this only applies within a reaction.	$\therefore n(\text{H}_2\text{SO}_4) = 0.00221 \text{ mol}$
STEP 4	Using the mole ratio from Equation 2, calculate the moles of the unknown SO ₂ from the moles of H ₂ SO ₄ .	$\frac{n(\text{SO}_2)}{n(\text{H}_2\text{SO}_4)} = \frac{1}{1}$ $\therefore n(\text{SO}_2) = 0.00221 \text{ mol}$
STEP 5	Equate the moles of elemental sulfur (S) with SO ₂ using the mole ratio from Equation 1.	$\therefore n(\text{S}) = n(\text{SO}_2) = 0.00221 \text{ mol}$
STEP 6	Calculate the mass of elemental sulfur.	$m = n \times M$ $m(\text{S}) = 0.00221 \times 32.06$ $= 0.0709 \text{ g}$
STEP 7	Calculate the percentage of S by mass in the original sample of coal. (Note: rounding occurs at the final stage.)	$\%m(\text{S}) = \frac{m(\text{S})}{m(\text{coal})} \times 100$ $= \frac{0.0709}{8.06} \times 100$ $= 0.879\%$

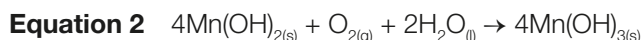
Question

40. The biochemical oxygen demand (BOD) can be used to determine the quality of a body of water. It is determined over a five-day period, at a controlled temperature, by measuring the amount of oxygen required to oxidise the organic components in the sample. A value of approximately 2–8 ppm would be expected for moderately polluted waters.

STAGE 1 A 100 mL water sample was collected in a sealed container with an equal volume of manganese(II) chloride and sodium iodide introduced. The manganese(II) ions were precipitated as manganese(III) hydroxide.



The precipitated manganese(II) hydroxide was oxidised by the dissolved oxygen, yielding manganese(III) hydroxide.



- (a) **Assign** oxidation numbers to manganese in Equation 2 and hence state whether manganese(II) hydroxide is the oxidising agent or reducing agent in this reaction.

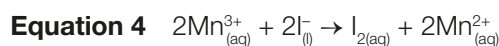
(2 marks) **KA4**

STAGE 2 Sulfuric acid was added to the manganese(III) hydroxide precipitate, releasing manganese ions (Mn^{3+}) in aqueous solution.

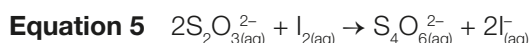
- (b) **Write an ionic equation (Equation 3)** to represent this stage.

(2 marks) **KA4**

STAGE 3 The Mn^{3+} ions oxidise the iodide ions (I^{-}) in solution.



- (c) The resulting volume of solution the solution was titrated with $0.0200 \text{ mol L}^{-1}$ sodium thiosulfate solution, using starch as an indicator. An average titre of 20.2 mL was achieved.



- (i) **Calculate** the number of moles of thiosulfate that reacted with iodine in Equation 5.

(2 marks) **KA4**

- (ii) Hence, **calculate** the number of moles of iodine that reacted in Equation 5.

(2 marks) **KA4**

- (iii) Hence, **determine** the number of moles of iodine that reacted in Equation 4.

(1 mark) **KA1**

- (iv) The mole ratio of the species linked from reactions represented in Equations 2–5 are summarised below:

	Equation 2	Equation 3	Equation 4	Equation 5
Ratio	1:4	1:1	2:1	2:1
Species	$\text{O}_2:\text{Mn}(\text{OH})_3$	$\text{Mn}^{3+}:\text{Mn}(\text{OH})_3$	$\text{Mn}^{3+}:\text{I}_2$	$\text{S}_2\text{O}_3^{2-}:\text{I}_2$

- (1) Using the information provided in the table, **calculate** the moles of oxygen present in the original water sample.

(3 marks) **KA4**

- (2) **Calculate** the concentration, in mol L^{-1} , of oxygen in the original water sample.

(2 marks) **KA4**

- (3) **Convert** this concentration to ppm of oxygen in the original water sample.

(3 marks) **KA4**

- (4) Hence, **state** whether the sample of water is likely to be polluted.

(1 mark) **IAE3**



Science as a human endeavour

Most Australians drink primarily tap water, but there is a significant minority of Australians who say they drink only bottled water. In 2021, Australia had the second-highest consumption rate per capita of bottled water, at 504 litres per person, behind only Singapore. A survey by Queensland Urban Utilities found that, of the Australians who prefer bottled water, most believed that it was “better quality” or “better for their health”. This might explain why people are willing to pay such a premium for bottled water, which is more than 2000x more expensive per litre than tap water.

Bottled water is considered a packaged food and is regulated by Food Standards Australia and New Zealand, enforced by state-level authorities. Voluntary industry codes require bottled water to be tested for safety once each year. Unlike state water authorities (e.g., SA Water), bottled water companies have less control over the catchment where they source their water. Most companies that sell bottled “spring” water do not disclose the precise location where they source their water, and most other companies use filtered tap water (usually labelled “pure Australian water”). Like most food products sold on Australian shelves, bottled water is almost certainly safe. However, little evidence shows it to be better in taste or quality than tap water.

Australia has some of the world’s most safe and well-monitored tap water. All tap water in Australia must comply with the Australian Drinking Water Guidelines, which are among the most stringent in the world. In South Australia, more than 1000 tests are conducted each day to continuously ensure the safety and taste of tap water. A selection of these tests is shown in the table below.

Table: Adelaide Central Metro Water Quality Report, August 1 2023 – July 31 2024 (average)

Component	Unit	National Guideline	Result
Aluminium*	mg/L	< 0.2	0.031
Antimony	mg/L	< 0.003	< 0.0003
Arsenic	mg/L	< 0.01	0.00043
Barium	mg/L	< 2	0.028
Beryllium	mg/L	< 0.06	< 0.0002
Boron	mg/L	< 4	0.054
Cadmium	mg/L	< 0.002	< 0.0001
Calcium	mg/L	No guideline	24.2
Chloral hydrate	µg/L	< 100	7.6
Chloride*	mg/L	< 250	90
Free chlorine	mg/L	< 5	0.3
Chloramine	mg/L	< 5	< 0.1
Chlorite	mg/L	< 0.8	0.01
Chloroacetic acid	µg/L	< 150	< 3
Chromium	mg/L	< 0.05	0.0002
Copper	mg/L	< 2	0.0598
Cyanide	mg/L	< 0.08	< 0.05
Dichloroacetic acid	µg/L	< 100	8
E. coli	cfu/100 mL	0	0
Fluoride	mg/L	< 1.5	0.9
Iodide	mg/L	< 0.5	< 0.01
Lead	mg/L	< 0.01	0.0029
Magnesium	mg/L	No guideline	12.97
Manganese	mg/L	< 0.5	0.0029
Mercury	mg/L	< 0.001	< 0.00003
Molybdenum	mg/L	< 0.05	0.0003
Nickel	mg/L	< 0.02	0.0006
Nitrate + Nitrite	mg/L	< 50	0.31
Potassium	mg/L	No guideline	4.82
Selenium	mg/L	< 0.01	< 0.0001



Science as a human endeavour

Component	Unit	National Guideline	Result
Silver	mg/L	< 0.1	< 0.00002
Sodium*	mg/L	< 180	51
Sulphate*	mg/L	< 250	46
Trihalomethanes	µg/L	< 250	146
Uranium	mg/L	< 0.02	< 0.0001

*Components marked with an asterisk are measured for aesthetic reasons; these guidelines reflect an acceptable taste rather than a health concern.

The monitoring programs used by SA Water are approved by SA Health. Across South Australia, a sample of tap water is taken for testing every three minutes by field workers. Laboratory analyses are carried out by the Australian Water Quality Centre in Adelaide in accordance with the requirements of the National Association of Testing Authorities.

Browne, K. (2018). *Is bottled water safer than tap water?* [online] CHOICE. Available at: <https://www.choice.com.au/food-and-drink/drinks/water/articles/is-bottled-water-safer-than-tap-water>.

SA Water (2022). *Your Drinking Water Profile*. [online] www.sawater.com.au. Available at: <https://www.sawater.com.au/water-and-the-environment/safe-and-clean-drinking-water/your-drinking-water-profile>.

Question

41. (a) **Explain** how the continuous testing of tap water enables scientists and public health authorities to ensure the availability of safe and affordable drinking water. **Identify** and **explain** which 'Science as a Human Endeavour' concept this exemplifies.

(3 marks) KA3

- (b) **Explain** how the perception of bottled water as "better quality" or "better for health," despite little evidence to support these claims, illustrates the influence of social, cultural, or economic factors on the acceptance of scientific knowledge.

(3 marks) KA3

- (c) **Discuss** how limitations in data collection might impact the reliability of scientific conclusions about bottled water safety.

(3 marks) KA3

- (d) **Identify** and **explain** an example of the importance of conventions and verification processes in scientific communication.

(3 marks) KA3

1.4 Chromatography

Science understanding

Chromatography techniques, including thin layer chromatography (TLC), gas chromatography (GC), high-performance liquid chromatography (HPLC), and ion chromatography (IC), involve the use of a stationary phase and a mobile phase to separate the components of a mixture.

The rate of movement of the components is caused by the differences between the strengths of the interactions between atoms, molecules, or ions in the mobile and stationary phases.

Predict the relative rates of movement of components along a stationary phase on the basis of their polarities and charge, given the structural formulae or relative polarities of the two phases.

© SACE 2025

Principles of chromatography

Chromatography is a crucial technique in analytical chemistry for the separation, identification, and quantification of components within complex mixtures. This technique relies on the fundamental principles of differential adsorption and solubility, where substances are separated based on their affinities for a stationary phase and a mobile phase.

Chromatographic methods are widely used in environmental analysis, forensic science, pharmaceutical testing, and food quality control.



Science as a human endeavour

Origins of chromatography

The term “chromatography” (from Greek: chromatos = colour, graphein = to write) was coined by Mikhail Tsvet, a Russian botanist who first developed the technique in the early 1900s. Tsvet’s groundbreaking work involved separating plant pigments by passing plant extracts through a glass column packed with calcium carbonate. The separated pigments formed coloured bands in the column, leading to the technique’s name. While modern chromatography has evolved far beyond separating coloured compounds, Tsvet’s fundamental principles remain at the core of all chromatographic methods.

Mikhail Tsvet is widely recognised as one of the first people to effectively develop the technique of chromatography “colour writing” in applications of early methods of both paper and column chromatography. Tsvet, a botanist, invented the principles of chromatography and used chromatographic methods to separate yellow, orange and green pigments from plants (xanthophylls, carotenes and chlorophylls).

While still using similar principles of adsorption applied to earlier methods, many of today’s modern applications of chromatography have shown significant advancements in sensitivity of analysis, and include environmental, food, forensic and pharmaceutical analysis.



Separation in chromatography is achieved by the extent of interaction between the individual components in the mixture and the **stationary phase**. In some applications of chromatography (TLC and column), interaction with the **mobile phase** also influences the separation. The stationary phase consists of a solid material on which components interact with the surface of the material through **adsorption**. The stationary phase is a fixed material that can be:

- A solid surface (adsorption chromatography)
- A liquid coating on a solid support (partition chromatography)
- An ion exchange resin (ion chromatography)

The **mobile phase** is a fluid (something that flows; gas or liquid) comprised of molecules of a chosen polarity that drive the separation. The polarity of the fluid selected may range from highly polar to non-polar. The mobile phase is a fluid that moves through or over the stationary phase.

The strength of interactions between phases determines the extent of the separation. Components separate due to their relative levels of adsorption to the stationary phase, and, in some techniques, **solubility** in the mobile phase. Components that are more strongly adsorbed to the stationary phase travel at a slower rate. Conversely, components that are less strongly adsorbed to the stationary phase travel at a faster rate.

The polarity, size, and charge of the mixture to be separated are all important factors in determining the level of interaction with each phase, and, therefore, the effectiveness of the separation.

Adsorption chromatography

Adsorption chromatography involves interactions on the surface of the adsorbent material used as the stationary phase (Figure 1.4.1). Some methods of chromatography also involve interactions within the structure of the stationary phase between liquid phases (referred to as **adsorption** or **partition** chromatography).

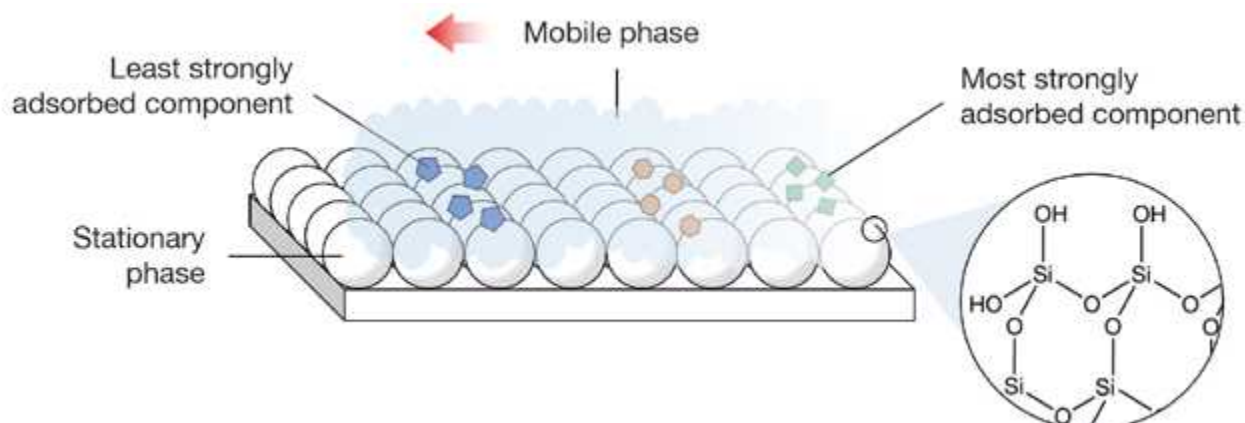


Figure 1.4.1: Adsorption of particles onto the surface of a stationary phase.

- **Normal phase** chromatography is where the polarity of the stationary phase is greater than that of the mobile phase
- **Reverse phase** chromatography, which is (ironically) more commonly used than normal phase, uses a stationary phase with a polarity that is less than the mobile phase.



Science as a human endeavour

Metabolomics and Personalised Medicine

Recent advances in chromatographic techniques, particularly LC-MS (Liquid Chromatography-Mass Spectrometry), have revolutionised the field of metabolomics - the study of small molecules produced during cellular processes. At the Mayo Clinic, researchers have developed a method using HPLC to analyse over 1,000 metabolites in blood samples within 15 minutes. This breakthrough has enabled the creation of individual metabolic profiles, allowing doctors to tailor medical treatments to each patient's unique biochemistry. For instance, by analysing metabolic profiles, doctors can predict how patients will respond to certain medications, potentially avoiding adverse reactions and improving treatment efficacy. This application demonstrates how improvements in chromatographic resolution and detection sensitivity have directly impacted patient care.

Question

42. One of the key concepts of science as a human endeavour is 'Application and Limitation'. Discuss examples in the text above that illustrate this key concept.

(2 marks) **KA3**

Chromatographic methods – including thin-layer chromatography (TLC), gas chromatography (GC), high-performance liquid chromatography (HPLC) and ion-exchange chromatography (IC) may all utilise the principle of adsorption, depending upon the materials chosen as the stationary phase.

Thin-layer chromatography (TLC)

Thin-layer chromatography (TLC) is a technique used to separate components of a mixture on the thin surface of a stationary phase (Figure 1.4.2). A thin layer of adsorbent material (examples include silica or alumina) is bonded to the surface of an inert sheet of material (glass, aluminium or polymer) as the stationary phase.

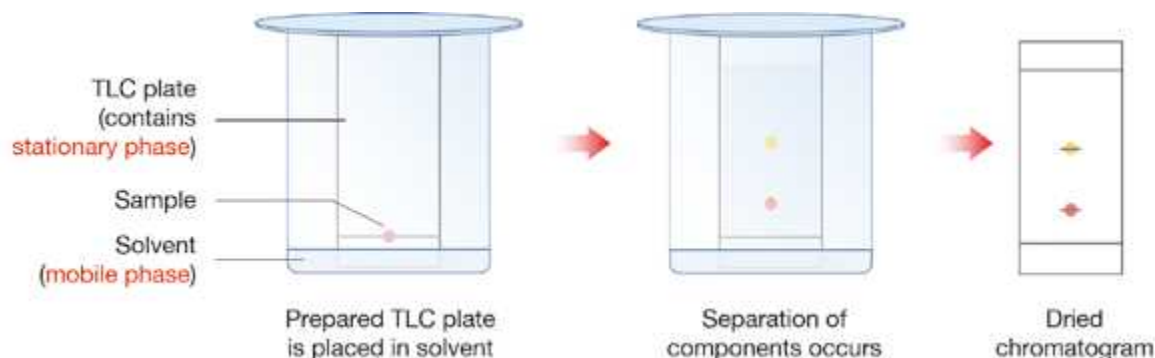


Figure 1.4.2: Chromatographic separation using thin layer chromatography

A pencil line is drawn near the bottom of the plate to indicate the **origin** (the point where the mixture is introduced) of the separation. A sample mixture (or series of mixtures) is spotted onto the line using a micropipette drawn from a fine capillary. The spotted mixture is allowed to dry and the plate is carefully lowered into a beaker or cell that contains a small volume of solvent as the mobile phase. Care is taken to ensure that the solvent sits below the origin. A watch glass or lid is placed on top to generate a saturated environment and reduce evaporation. The solvent moves up the plate, past the mixture, due to **capillary action** (upward force due to adhesion) formed by the tiny gaps between grains of adsorbent material.

As the solvent moves up the plate, components travel with the mobile phase and experience different levels of adsorption to the stationary phase. The level of interaction of each component with the stationary and mobile phases determines the rate of movement.

Once the components on the **chromatogram** (separated components on the stationary phase) have been resolved, the plate is removed from the solvent before the **solvent front** (the furthest point the solvent has travelled) reaches the top of the plate. The distance that the solvent and components have travelled is recorded. The varying rates of movement of the components allow for, in most cases, separation based on the distance travelled.

A different solvent may be chosen as the mobile phase when separation is minimal or one or more components of the mixture cannot be resolved. The polarity of the phases may also be reversed by changing the type of stationary phase (non-polar or polar) and solvent chosen.

Colourless components may be identified through reactions with additional reagents (such as ninhydrin, in the case of amino acids) in conjunction with the use of alternative light sources (such as ultraviolet for plates that have been treated with a fluorescing agent).

Science understanding

Data from chromatography techniques can be used to determine the composition and purity of substances.

Calculate and apply R_f values and retention times in the identification of components in a mixture.

© SACE 2025

R_f retardation factor

The distance each component has travelled can be measured and compared to the distance the solvent has travelled to establish a ratio referred to as the R_f , **retardation factor** (Figure 1.4.3). This can be applied in the identification of components in a mixture.

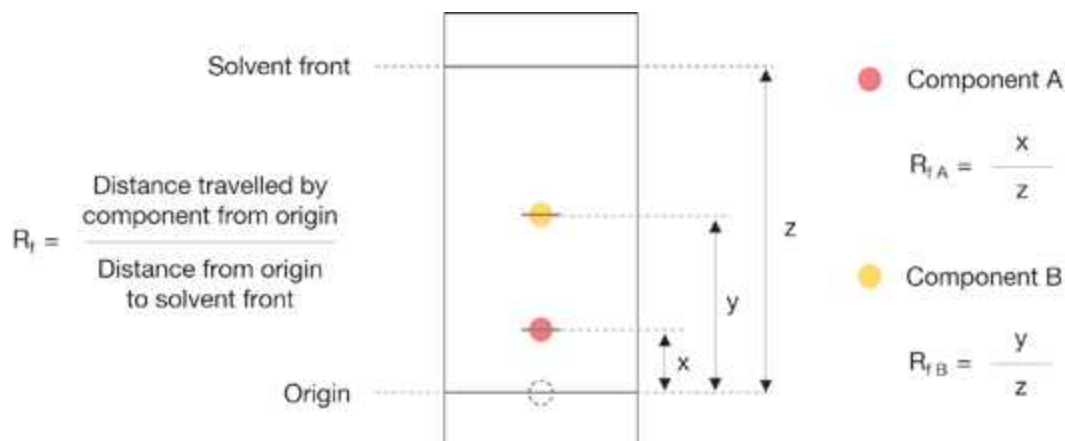


Figure 1.4.3: Determination of R_f .

$$R_f = \frac{\text{distance from the origin to the centre of the component}}{\text{distance from the origin to the solvent front}}$$

As evident in Figure 1.4.3, an R_f value closer to one indicates that the component has travelled to a position close to the solvent front at the top of the chromatogram. An R_f value closer to 0.1 would indicate that the component remained close to the origin at the bottom of the chromatogram.

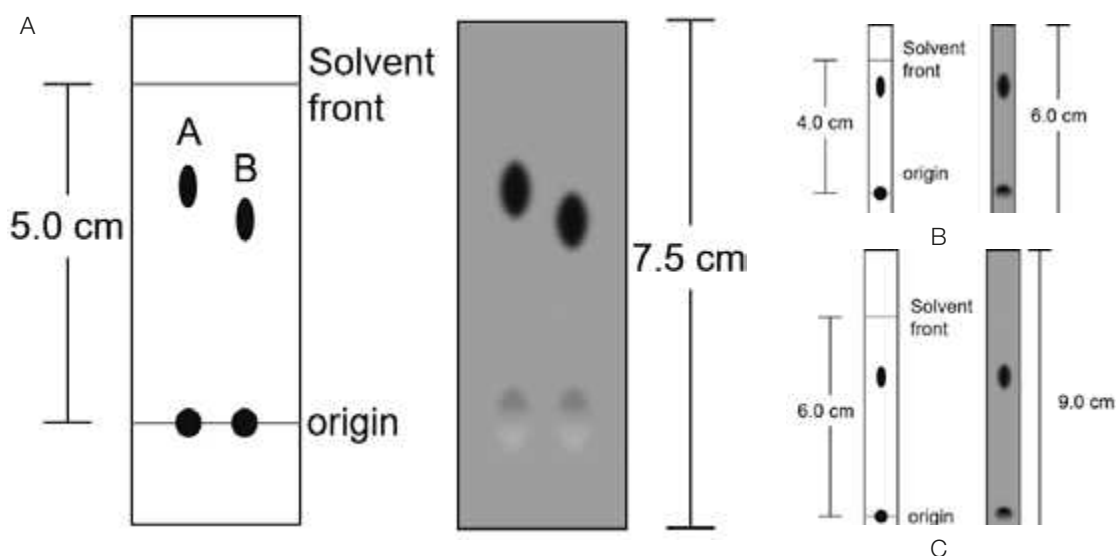
Question

43. Technetium-99m (Tc) is the most common radiopharmaceutical used in medical diagnostic procedures. It is used as a radioactive tracer that can be detected within the human body.

Different oxidation states of technetium target different areas of the human body. Technetium is generated as TcO_4^- (pertechnetate ion) with an oxidation state of +7. A reducing agent can be added to generate a +3, or +4, TcO_2 (technetium dioxide), oxidation state.

Thin-layer chromatography is employed to detect which species have been successfully generated. A radio chromatogram is produced.

- (a) TLC, using silica as a stationary phase, was used to analyse the effectiveness of the production of TcO_2 from TcO_4^- . A chromatogram was prepared as a reference from samples of TcO_2 and TcO_4^- .



Component	R_f
TcO_4^-	0.68
TcO_2	0.58

- (i) **Calculate** the R_f of each component in chromatogram A.

(4 marks) **KA4**

- (ii) Using the data provided in the table, **identify** the components as TcO_2 and TcO_4^- .

(2 marks) **KA4**

- (b) A study was undertaken to determine the effectiveness of the separation using a shorter (B) or longer (C) stationary phase. **Explain** what can be concluded from the findings in terms of the duration and validity of the separation.

(4 marks) **IAE3**

Column chromatography

Column chromatography is a form of liquid chromatography. It uses a column, which is not dissimilar to a burette. In this column, a solid adsorbent (stationary phase) is packed. The adsorbent can either be used dry or saturated with eluent (the solvent used as the mobile phase). The **eluent** is added from a reservoir above the column. Due to gravity the eluent then passes through the column (Figure 1.4.4).

Components in the mixture have varying levels of adsorption to the stationary phase and solubility in the mobile phase. As the solvent travels through the column, components in the mixture are carried at different rates. Components that are more strongly adsorbed to the stationary phase travel at a slower rate compared to components that are less strongly adsorbed. The components separate into bands in the column.

Unlike in thin-layer chromatography, the separation in column chromatography is not halted. Instead, the components **elute** (leave) the column. The advantage of this process is that the components can then be isolated for later use or for further analysis and identification.

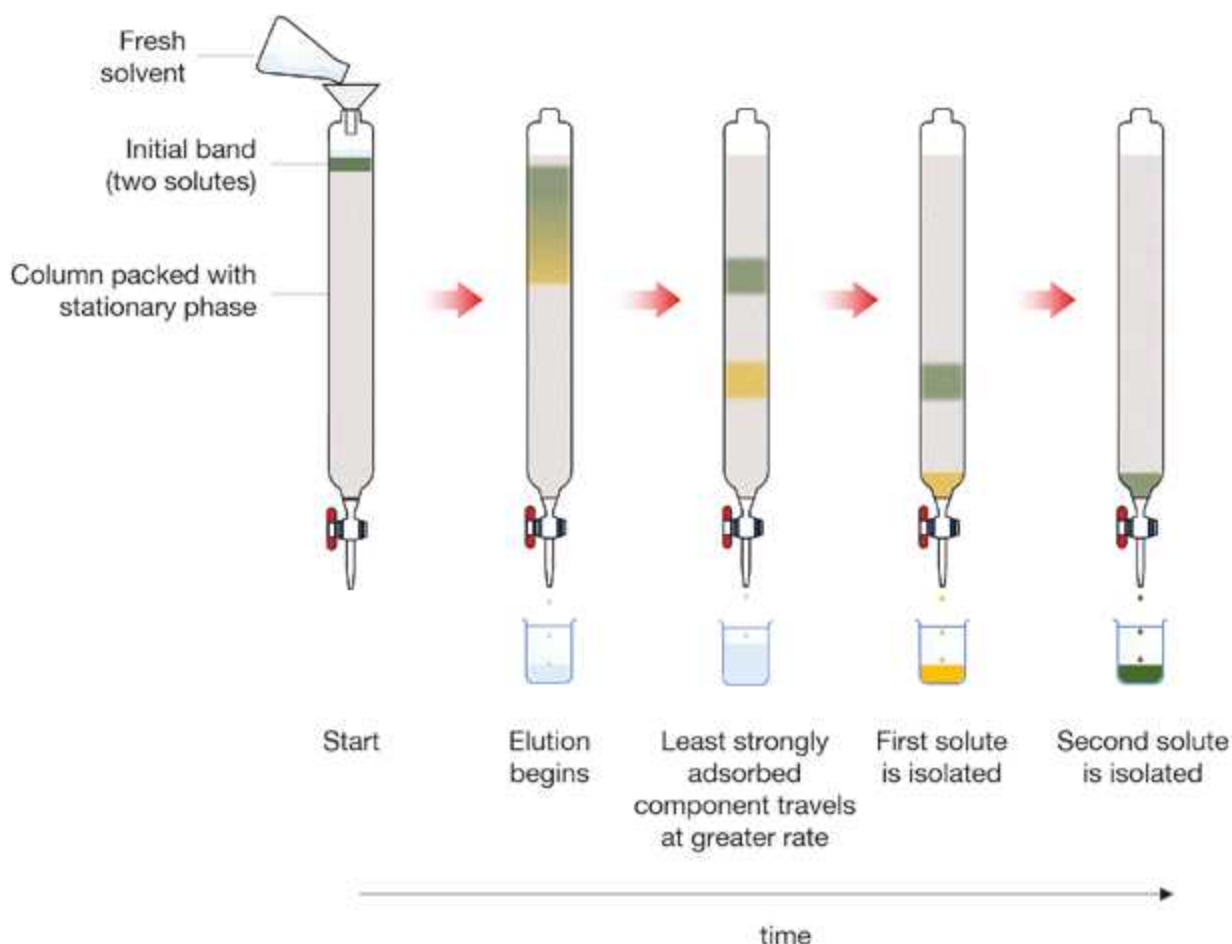


Figure 1.4.4: Separation of bands of components using column chromatography.



Science as a human endeavour

Space Exploration Chromatography

NASA's Mars Organic Molecule Analyzer (MOMA) represents a remarkable adaptation of chromatographic technology for space exploration. The instrument, aboard the ExoMars rover, combines miniaturized GC-MS with laser desorption mass spectrometry to search for organic molecules on Mars. Engineers had to overcome significant challenges to create a chromatograph that could operate in Mars' extreme conditions (-90°C to 20°C) while being compact enough for space travel. The system uses helium as a carrier gas stored in tiny tanks and employs multiple columns for redundancy in case of failure. This innovation has allowed for the first detailed organic analysis of Martian soil, providing insights into potential past life on Mars.

Question

44. Consider the key concepts of science as a human endeavour.

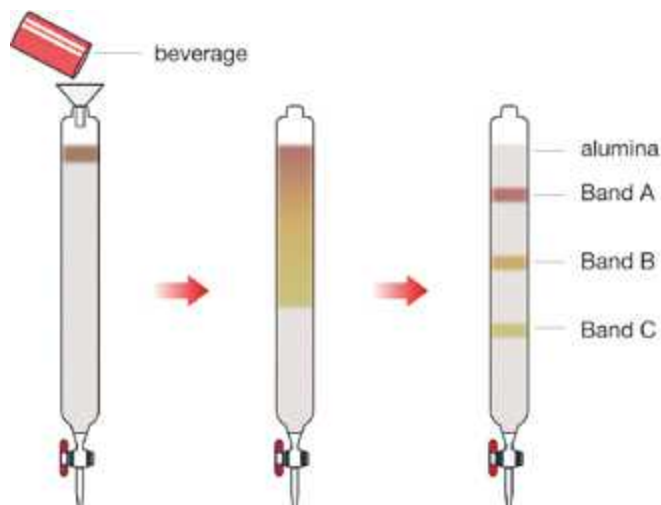
Using *one* of these key concepts, describe how MOMA technology is an example of science as a human endeavour.

(2 marks) **KA3**

Question

45. Artificial colours are added to many foods and beverages. Column chromatography was used to analyse artificial food colours in a beverage. The column was packed with alumina as a polar stationary phase; separation occurred using a non-polar solvent.

(a) **Consider** the diagram of the separation below.



- (i) **State** and **explain** which component was least polar.

(3 marks) IAE3

- (ii) At a later stage during the separation, Band A appeared to be separating into two components. **Suggest** one change that could be made to the procedure to separate these components more effectively.

(1 mark) IAE4

- (b) Consider the same separation performed as thin-layer chromatography. **State** and **explain** which component would produce the largest R_f value.

(3 marks) IAE3

Gas chromatography

Gas chromatography (GC) is effective at separating gaseous or volatile (low boiling-point) mixtures. Mixtures that are susceptible to degradation at high temperature are not suitable for gas chromatography. The mixture is introduced in very small quantities via a microlitre pipette. The sample is injected through a diaphragm into one end of a coiled chromatography column. The column is housed in a thermostatically controlled oven to ensure the mixture, if not already a gas, is converted to a gaseous state. On entering the column, the components are transported through the column by an inert **carrier gas** (usually hydrogen, nitrogen or helium) as the mobile phase (Figure 1.4.5). The flow rate of the gas and temperature of the oven can both be controlled to assist in the separation.

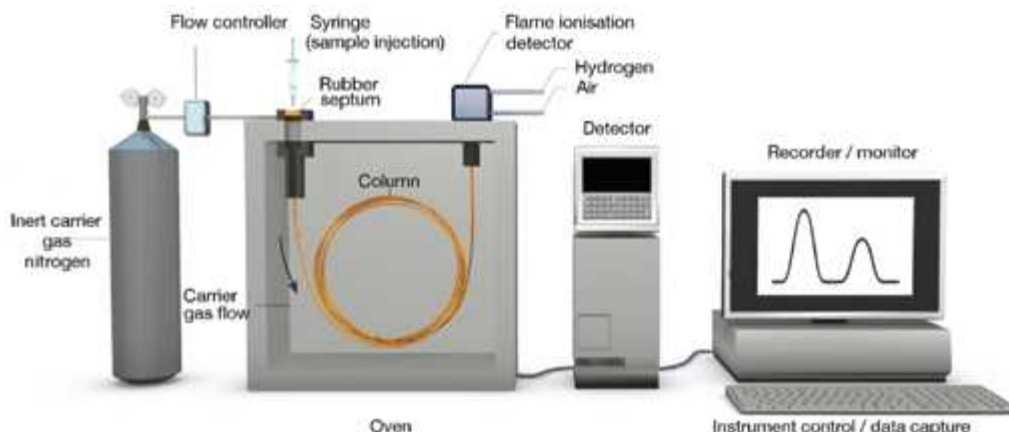


Figure 1.4.5: Schematic of gas chromatography.

The column contains the stationary phase. There are two commonly used types of columns; **capillary columns** (Figure 1.4.6) where the stationary phase coats the internal surface of the column, and **packed columns** where the column is completely packed with adsorbent material.

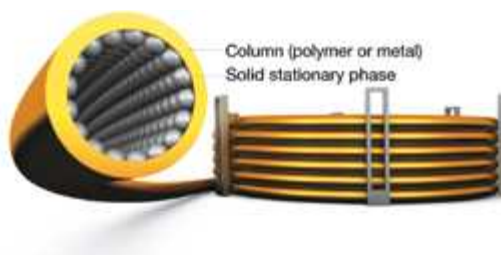


Figure 1.4.6: Capillary column.

While the gaseous components travel with the carrier gas, they interact to varying extents with the stationary phase inside the column. Components that are more strongly adsorbed to the stationary phase travel at a slower rate and are retained in the column for longer periods of time before **eluting** (leaving the column). Conversely, components that are less strongly adsorbed to the stationary phase are retained for a shorter period of time. The components may then be sent to a **flame-ionisation detector** to assist in identification. GC is widely used in environmental monitoring, particularly for analysing air samples and detecting pollutants.



Science as a human endeavour

Environmental forensics

In 2023, environmental scientists at the University of California developed a novel application of two-dimensional gas chromatography (GC×GC) to track microplastic pollution in oceans. This technique can identify not only the type of plastic but also its manufacturer based on unique chemical signatures from the manufacturing process. By analyzing ocean samples, researchers created a global “plastic fingerprint” database that has helped identify major sources of ocean pollution and hold companies accountable. The technique separates plastics based on both volatility and polarity, providing a level of detail previously impossible with conventional GC.

Question

46. (a) Identify the key SHE descriptor that best aligns with the application of two-dimensional gas chromatography (GC×GC) in tracking microplastic pollution in oceans. Explain your choice with reference to the development and use of the “plastic fingerprint” database.

(2 marks) **KA3**

- (b) Discuss the potential impact of GC×GC technology on addressing global plastic pollution and the challenges that need to be overcome for its widespread adoption in environmental monitoring.

(3 marks) **KA3**

Retention time

The chromatogram produced by quantitative methods of analysis conveys a record of the time taken for each component to elute the column, as well as a measure of relative concentration of that component in the mixture.

A chromatogram can be used for qualitative analysis through the identification of the peaks generated in a graph of **retention time**. The time taken from the injection of the sample to detection after eluting the column is recorded as retention time. Retention times can be compared with known standards, under the same set of conditions, to allow positive identification of components (Figure 1.4.7).

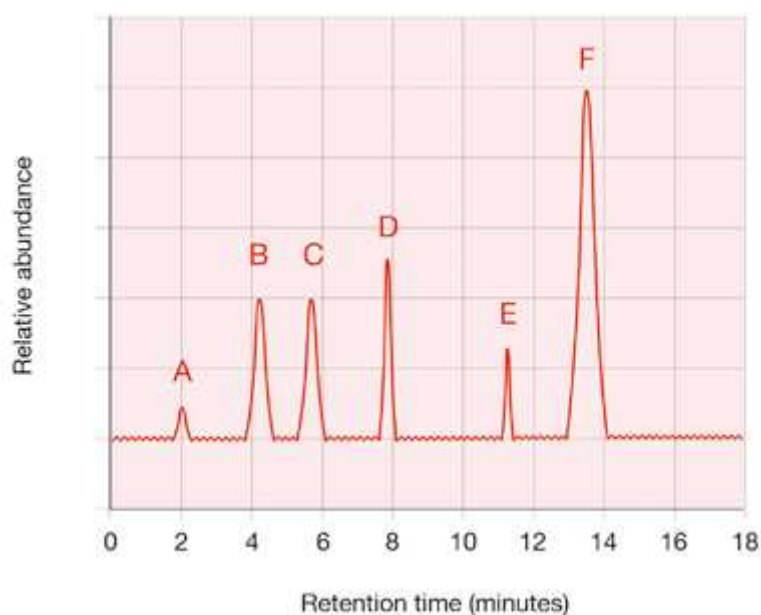


Figure 1.4.7: Quantitative chromatogram with retention times.

Figure 1.4.7 shows the retention times of six components of a mixture. Component F has the longest retention time. Component F experienced the strongest adsorption to the stationary phase and took the longest time to elute.

Quantitatively, component A is present at the lowest concentration and component F at the highest concentration. Component B and C are present in equal concentrations.



Science as a human endeavour

Identifying the origin of oil spills

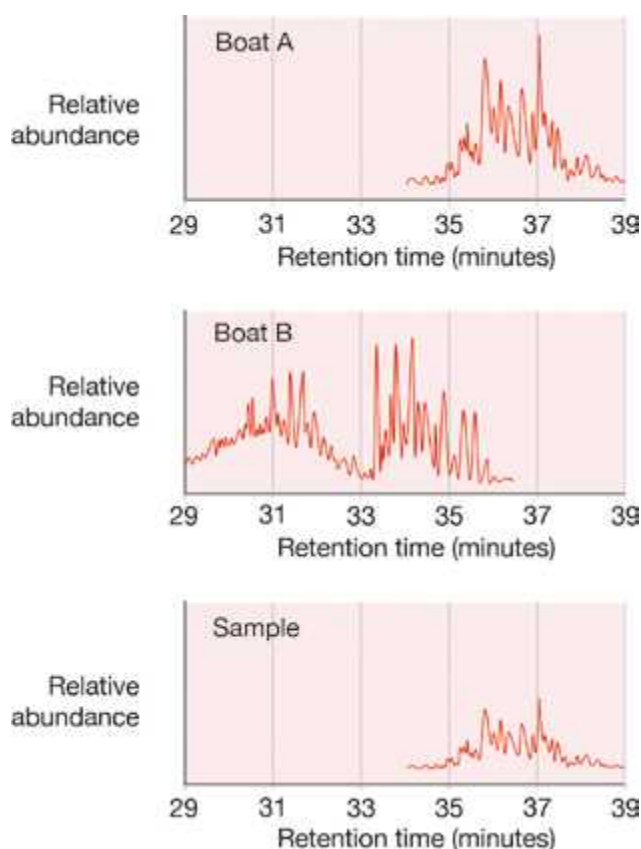
One challenging application of gas chromatography (GC) is in the identification of components in oil from oil spills. This may be due to accidental or deliberate discharges of oil from ships.

Environmental analysis of oils can be used to determine their point of origin for both the offending ship and even the company or region responsible for supply. GC can identify the components remaining in the oil spill (highly volatile components will be lost in the environment) as well as identifying biomarkers. The organisms and even geology present in specific locations where the oil has formed over millions of years, leaves traces of organic molecules as unique indicators. These indicators can be traced to oil supplies and specific geographical locations where the oil originated from.

Question

47. Gas chromatography was used to compare the bilge oil of a number of docked tankers with a small spill of oil found in the ocean in the vicinity of the tankers.

The chromatograms below were produced from the spill and from the bilge of two of the tankers present.



- (a) **State** and **explain**, from the chromatograms provided, which tanker is most likely to have generated the spill.

(3 marks) IAE3

- (b) **Suggest** one reason why the evidence supplied may not be conclusive.

(1 mark) IAE3

High-performance liquid chromatography

High-performance liquid chromatography (HPLC, also known as high-pressure liquid chromatography) is an alternative quantitative technique to gas chromatography. The separation of a mixture can be made more efficient if smaller adsorbent particles are used as the stationary phase and packed into a shorter column. Due to the stronger capillary forces experienced, the solvent must be forced through the column under pressure.

The column is packed with an adsorbent material of small particle size, hence very large surface area. The mobile phase, referred to as an eluent in this technique, is pumped through the column under high pressure and at a constant flow rate. The sample is once again injected into the system, with components transported by the liquid solvent (Figure 1.4.8).

Components that are more strongly adsorbed to the stationary phase travel at a slower rate. Components that are less strongly adsorbed to the stationary phase travel at a faster rate. Components elute the column at different times. The detector registers the retention time and intensity of each component, which can then be compared to known standards. HPLC is effective for mixtures that may breakdown at the higher temperatures experienced in the oven during GC. Components with a higher affinity for the stationary phase elute more slowly, providing precise, high-resolution separation.

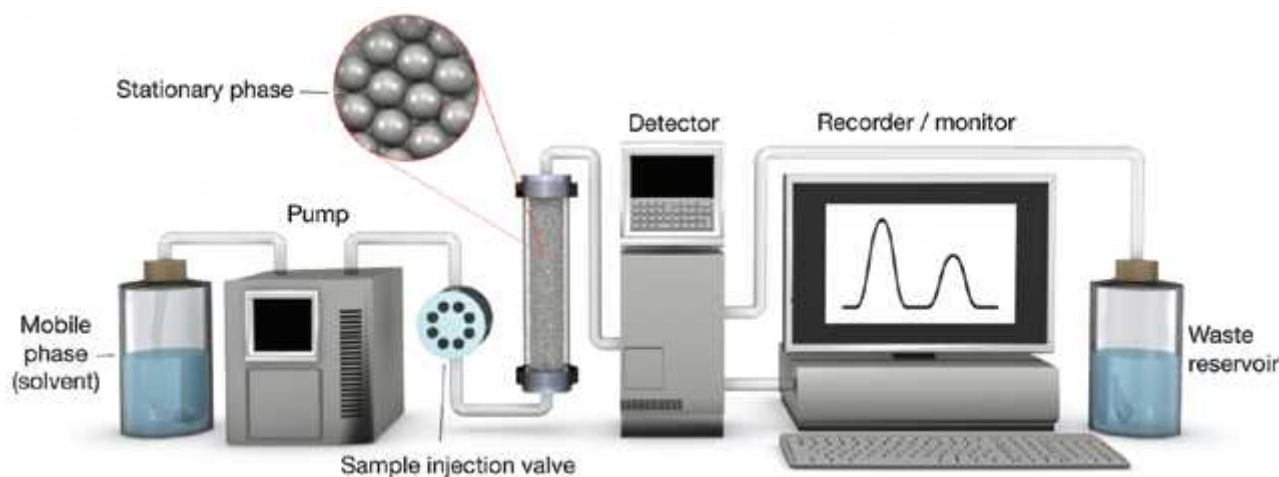


Figure 1.4.8: Schematic of high-performance liquid chromatography.



Science as a human endeavour

Wastewater analysis and drugs: a European multi-city study

The 2015 SCORE Wastewater Monitoring Campaign analysed wastewater in over 60 European cities and towns. In some instances, similar analysis had occurred over a four- to five-year period. Samples from water treatment plants were analysed for urinary biomarkers of the target drug or metabolic products (products formed when the body breaks down a drug) these included analysis of the residues for amphetamine, methamphetamine, MDMA, cocaine, and cannabis. The studies revealed patterns of illicit drug use linked to geographical location and population demographic.

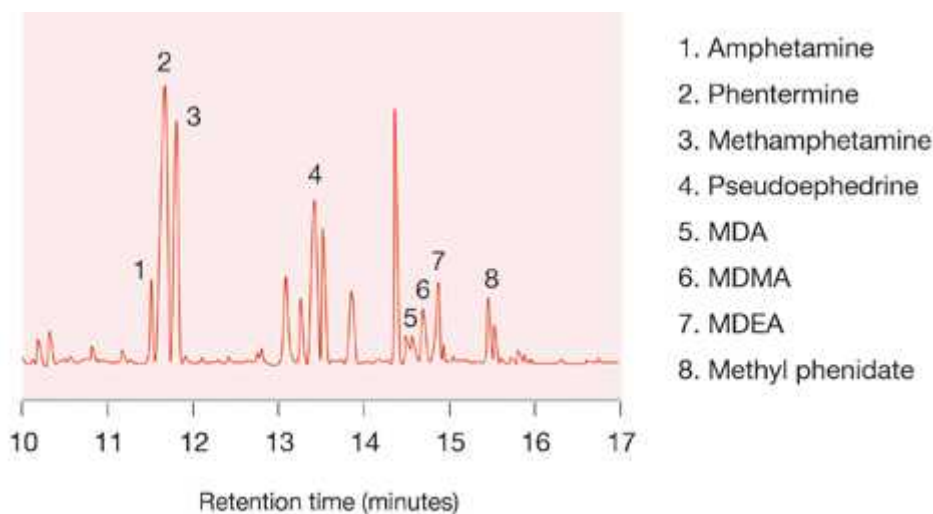
High-performance liquid chromatography and mass spectrometry (ions identified on mass-charge ratio) were used in the separation and measurement of the residual drugs. Based on the level of residual drug entering wastewater, researchers were able to back-calculate the consumption of illicit drugs in populations. Subsequently similar studies have been undertaken in Australia.

Question

1

48. Wastewater in Adelaide, South Australia, was analysed using high-performance liquid chromatography (HPLC) over a two-week period. Researchers tested for residues of cocaine, amphetamine, methamphetamine and MDMA.

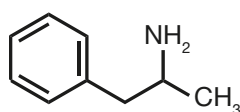
(a) The chromatogram below was used in the identification of the targeted drugs.



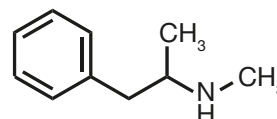
Determine the retention time of MDMA, to three significant figures.

(2 marks) **KA1**

(b) Amphetamine and methamphetamine have very similar chemical structures shown below:



Amphetamine



Methamphetamine

(i) **Identify** the structural difference between the two molecules.

(1 mark) **KA1**

(ii) Using the chromatogram and structure of the molecules above, **explain** whether the stationary phase used for the separation is more likely to be polar or non-polar.

(3 marks) **IAE3**

Science understanding

Ion chromatography (also known as ion exchange chromatography) is used to remove either cations or anions from a mixture by replacing them with ions of another type.

Explain, using equilibrium principles, how ions attached to the surface of a resin can be exchanged with ions in aqueous solution.

© SACE 2025

Ion chromatography

Ion chromatography (IC) relies upon the principle of ion-exchange in an **equilibrium system** (reactions that proceed in both the forward and backward directions). IC is effective in water quality analysis, where it is used to detect contaminants such as sulfate and chloride ions.

Ion-exchange chromatography utilises a solid **ion-exchange resin** as the stationary phase. The column is packed with porous beads. The resin can be prepared with either a positively or negatively charged surface. Ions of opposite charge bond to the surface of the resin from solution. These ions are exchangeable with ions from the sample mixture, depending upon their type, magnitude of charge, charge distribution and charge density.

Exchange resin	Exchange group	Example	Structure
Anion exchange column (positive resin surface)	Anions	Diethylaminoethyl (DEAE)	$\text{---O---C---C---N}^+\text{---H}$ $\text{H}_2\text{C---CH}_3$ $\text{H}_2\text{C---CH}_3$
Cation exchange column (negative resin surface)	Cations	Carboxymethyl (CM)	$\text{---O---C---C---O}^-$ O

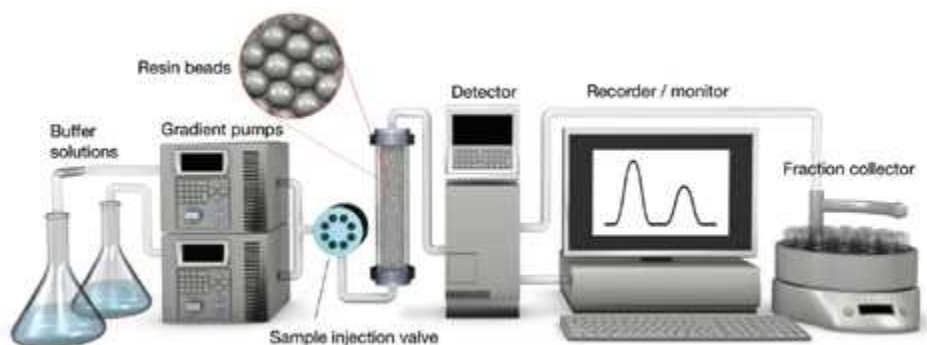


Figure 1.4.9: Schematic of ion-exchange chromatography.

As the liquid mobile phase passes through the resin, exchangeable ions take up binding sites (Figure 1.4.9). Ions with greater charge-density generate stronger electrostatic attraction or repulsion with the stationary phase. For example, if using a negatively charged resin surface, highly positive ions would be strongly attracted, slight positive ions less. Slightly negatively charged ions would undergo weak repulsion, and highly negative, strong repulsion.

An equilibrium is established between ions bound to the resin surface and ions in solution (Figure 1.4.10).

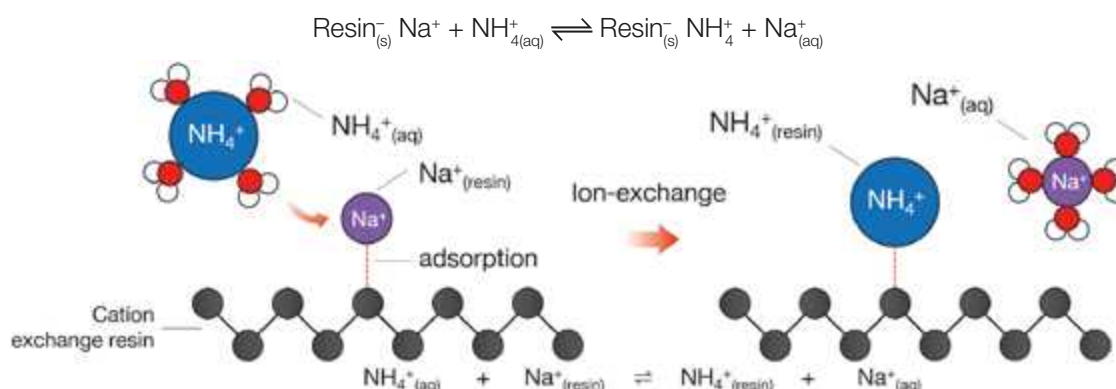


Figure 1.4.10: Ion exchange on the resin surface.

Only strongly interacting species remain attached to the resin after the solvent has been eluted from the column. Species strongly bound to the surface may then need to be removed. To achieve this removal from the resin surface, ion concentration or pH may be altered to weaken the **electrostatic interactions** (attraction of positive and negative charges).

Flooding the resin column with a high concentration of aqueous sodium ions will place a stress on the equilibrium system. According to **Le Châtelier's Principle** (refer to Page 119), the equilibrium system will counteract the introduced change by shifting the position of equilibrium to the left, favouring the backward reaction. Sodium ions will bind to the surface of the resin and exchangeable ions on the surface will be released into aqueous solution and elute.

Ion-exchange chromatography is effective at separating amino acids and proteins that are susceptible to changes in functional groups due to altered pH. Amino groups may become protonated at low pH or returned to molecular species as higher pH (refer to pages 217 and 218).

Question

49. Ammonium nitrate is a fertiliser added by farmers to increase crop yield in nitrogen-deficient soils. Fertiliser run-off from soils may enter local waterways and lead to **eutrophication** (increased nutrient concentrations).

(a) Ammonium nitrate fertilisers were applied on farming land near a creek. The creek was analysed to determine nitrate levels.

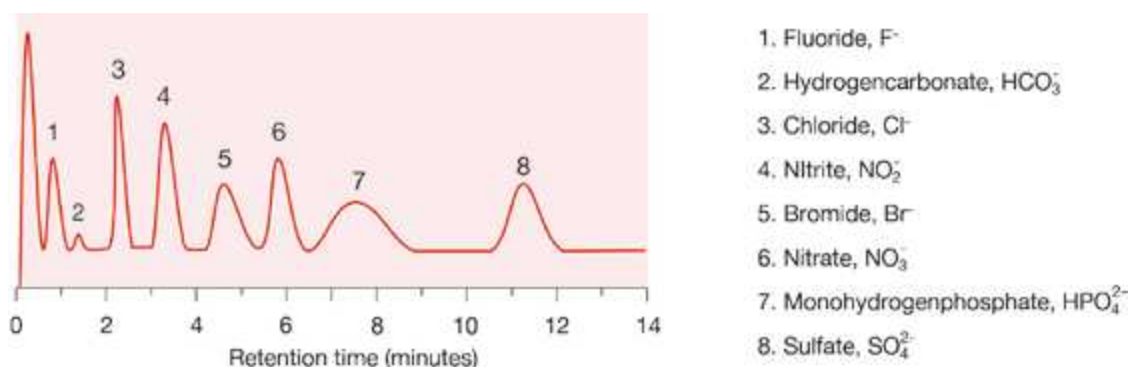
(i) **State** the property of nitrate and ammonium ions that allows them to be absorbed by plants.

(1 mark) **KA1**

(ii) **State** whether an anion or cation exchange column would be used for the analysis of nitrate ions.

(1 mark) **KA1**

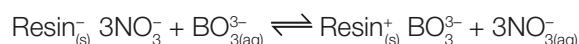
(b) The chromatogram below was obtained for a range of anions present in the creek water.



Explain why the retention time of nitrate ions present in the water is shorter compared to that of sulfate ions.

(3 marks) **IAE3**

(c) To regenerate the resin in the column for future use, the column is flooded with a solution containing a high concentration of sodium borate (Na_3BO_3).



Explain, using equilibrium principles, how the resin is regenerated.

(3 marks) **IAE3**

1.5 Atomic spectroscopy

Science understanding

Flame tests and atomic absorption spectroscopy (AAS) are analytical techniques that can be used to identify elements; these methods rely on electron transfer between atomic energy levels

© SACE 2025

Principles of spectroscopy

Chemicals can be analysed qualitatively and quantitatively.

Qualitative analysis involves finding the chemical composition of a sample based on its physical and chemical properties. These can include colour, melting point, boiling point, conductivity, solubility, and reactivity.

Flame tests are one type of qualitative analytical technique used to identify the presence of certain metal ions in a sample. A wire loop is dipped in a salt or solution containing the metal ion to be tested and then placed in a Bunsen flame.

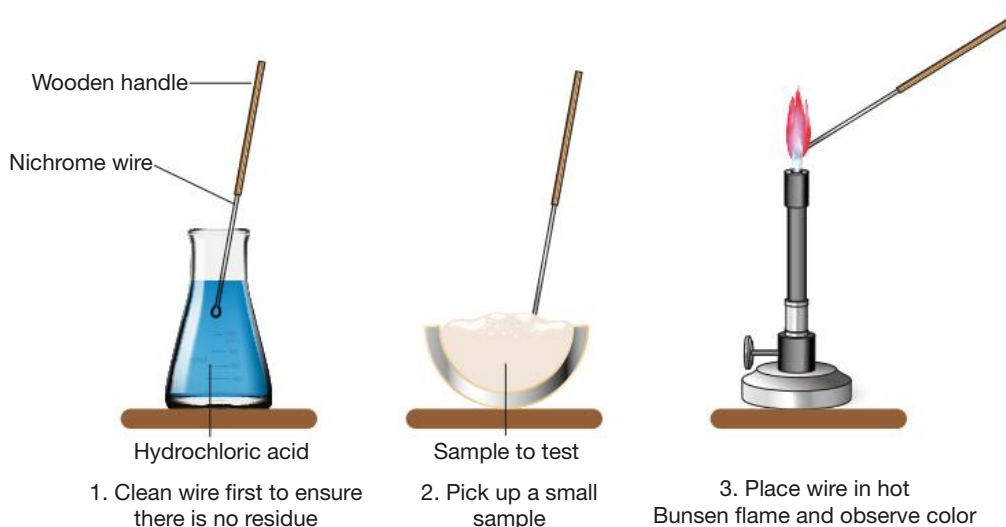


Figure 1.5.1: Testing a sample of a salt in a Bunsen flame

The colour of the flame that is produced is unique to that metal ion. For example, a salt that produces a bright green flame will most likely contain the copper (II) ion, Cu^{2+} .

The following table shows the flame colours produced by some metal ions.

Li^+	Na^+	K^+	Ca^{2+}	Ba^{2+}	Sr^{2+}	Rb^+	Cu^{2+}
							
LITHIUM Li^+	SODIUM Na^+	POTASSIUM K^+	CALCIUM Ca^{2+}	BARIUM Ba^{2+}	STRONTIUM Sr^{2+}	RUBIDIUM Rb^+	COPPER Cu^{2+}
Crimson red	Yellow	Lilac	Orange-red	Yellow-green	Red	Purple	Green

Table 1.5.1: Colours produced by atomic emission in a flame.

Flame tests illustrate the emission of energy as light when electrons return to their ground state. The different flame colours in flame tests are due to electron transitions. When a metal ion is heated, its electrons absorb energy and move to higher energy levels. As they return to their original levels, they release energy in the form of light. The wavelength (colour) of this light is unique to each element because each metal ion has distinct electron energy levels.

Flame tests have limitations; they are not very sensitive and can only detect relatively high concentrations of ions. Additionally, some metal ions produce similar flame colours, making it hard to distinguish them – for instance, rubidium and potassium salts produce a purple flame, and both lithium and strontium produce a red flame. These limitations make flame tests unsuitable for precise or low-concentration analyses. Hence, a more sophisticated analytical technique, like **spectroscopy**, is required.

Science understanding

Write the electron configuration using subshell notation of an atom or monatomic ion of any of the first 38 elements in the periodic table.

© SACE 2025

Electron configuration

Niels Bohr, a Danish physicist, conducted experiments involving the analysis of light emitted from heated gases. It was through these experiments that he concluded that electrons can only exist in set energy levels around the nucleus of an atom.

The Bohr three-dimensional model of the atom and a cross-section are shown below. The cross-section provides a simple model for the energy levels and the distribution of electrons in an atom.

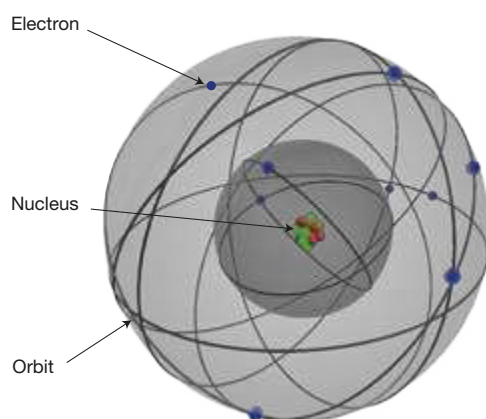
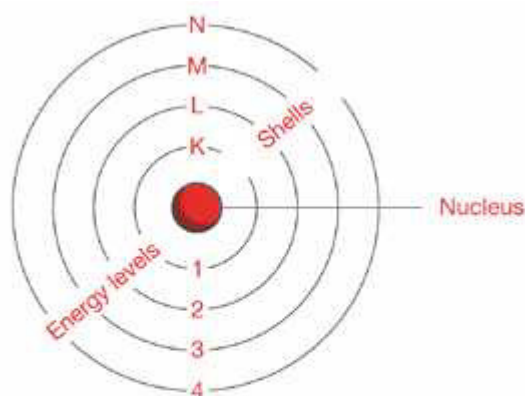


Figure 1.5.2: 3D Bohr model



In order from highest to lowest energy level (n):

$$n = 4 > n = 3 > n = 2 > n = 1$$

Figure 1.5.3: Cross-section of the 3D shells

Each shell has a maximum limit to the number of electrons it can contain. As the shell becomes larger, it can hold more electrons.

Shell/Principal quantum number (n)	Maximum number of electrons it can contain
K (n=1)	2
L (n=2)	8
M (n=3)	18
N (n=4)	32

Electron shells are divided into **subshells** – regions within a shell in which electrons have the same energy.

The number of the shell, ***n***, equals the number of subshells present. For instance, the first shell only has one subshell, the second shell has two subshells, the third shell has three subshells, and the fourth shell has four subshells.

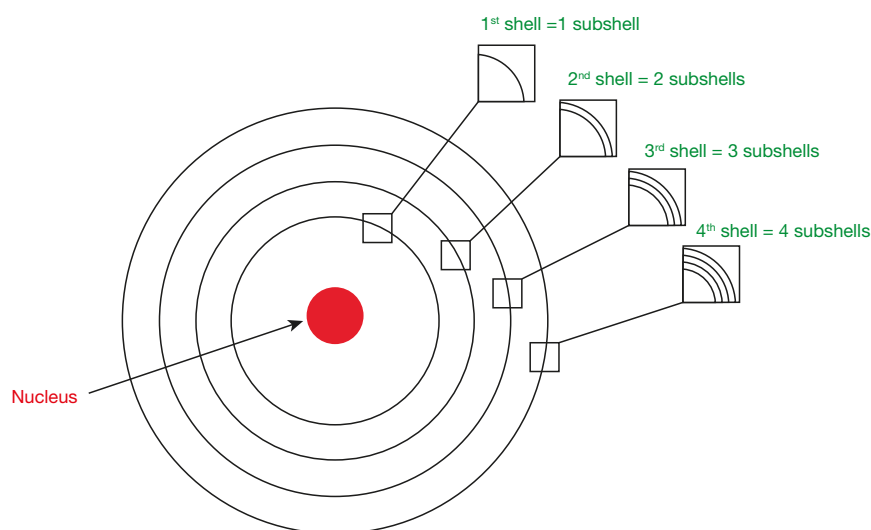


Figure 1.5.4: Representation of subshells within shells in an atom.

The subshells are labelled “***s***”, “***p***”, “***d***”, and “***f***”. The number of electrons that each subshell can hold is shown in the table below.

Subshell	Electron Capacity
s	2
p	6
d	10
f	14

Extra understanding

The letters used to label the subshells come from spectroscopy and the appearance of lines in the spectra:
s = sharp, p = principal, d = diffuse, and f = fine

Putting it all together looks like this:

Shell/Principal quantum number (<i>n</i>)	Names of subshells	Maximum number of electrons in the subshell	Maximum number of electrons in the shell
K (<i>n</i> =1)	1s	2	2
L (<i>n</i> =2)	2s	2	8
	2p	6	
M (<i>n</i> =3)	3s	2	18
	3p	6	
	3d	10	
N (<i>n</i> =4)	4s	2	32
	4p	6	
	4d	10	
	4f	14	
			$2n^2$

For any given shell, the energies of electrons in the subshells increases from **s** to **p** to **d** to **f**.

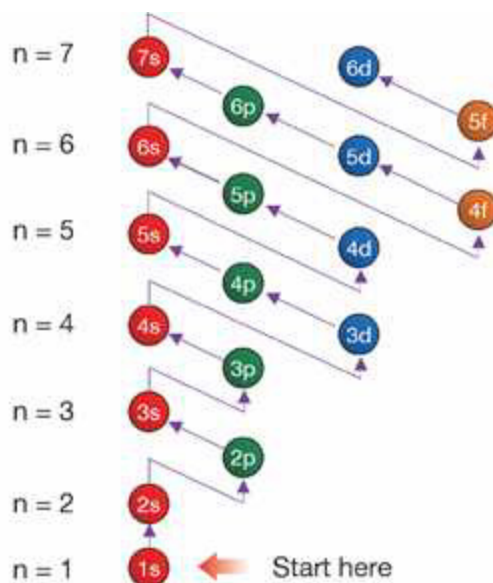


Figure 1.5.5: Energy sequence.

Lower energy subshells are filled first. Electrons fill higher subshells in order of increasing energy. This is referred to as the **Aufbau principle** (Figure 1.5.).

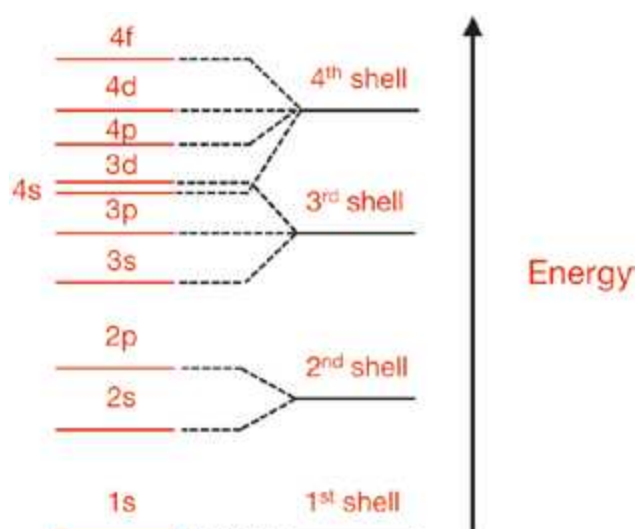


Figure 1.5.6: The Aufbau principle.

Notice how, beginning with the third shell, the subshells of different main shells begin to overlap.

Writing electron configurations using subshell notation

Electron configuration in subshells can be represented using **subshell notation**.

The shell number is written first, followed by the subshell (**s**, **p**, **d**, **f**). Finally, the number of electrons is written as a superscript to the right of the subshell (Figure 1.5.7).

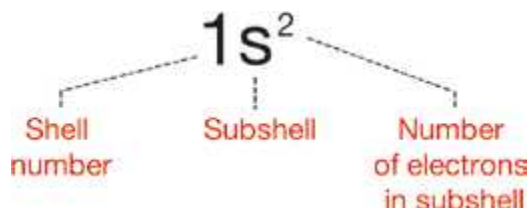


Figure 1.5.7: Electron configuration using subshell notation.

There are two straightforward methods for remembering the sequence in which subshells are filled, and hence how to write electron configurations.

Method 1: Subshells Columns with Diagonal Lines

If the subshells are written in columns corresponding to their **s**, **p**, **d**, or **f** character, descending diagonal lines show the correct order for filling.

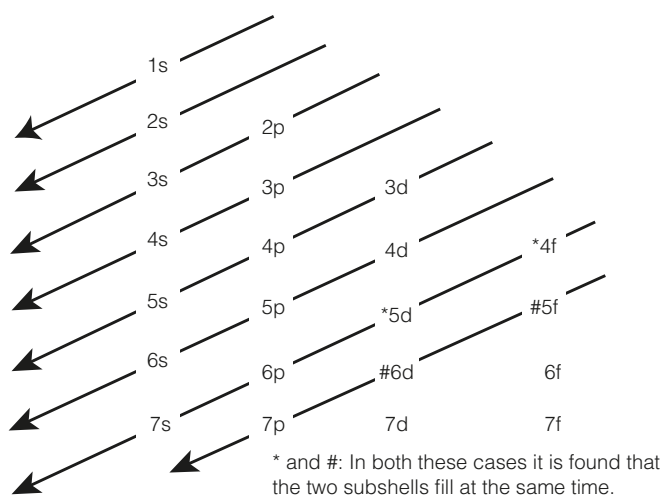


Figure 1.5.8: Diagonal method for determining fill order for electron subshells

Method 2: Reading Subshells from the Periodic Table

The periodic table is arranged such that the elements with s electrons in their highest energy subshell are grouped together in the s-block, elements with p electrons in their highest energy subshell are grouped in the p-block, and so on. The order of subshells can be read left-to-right, top-to-bottom, directly from the table.

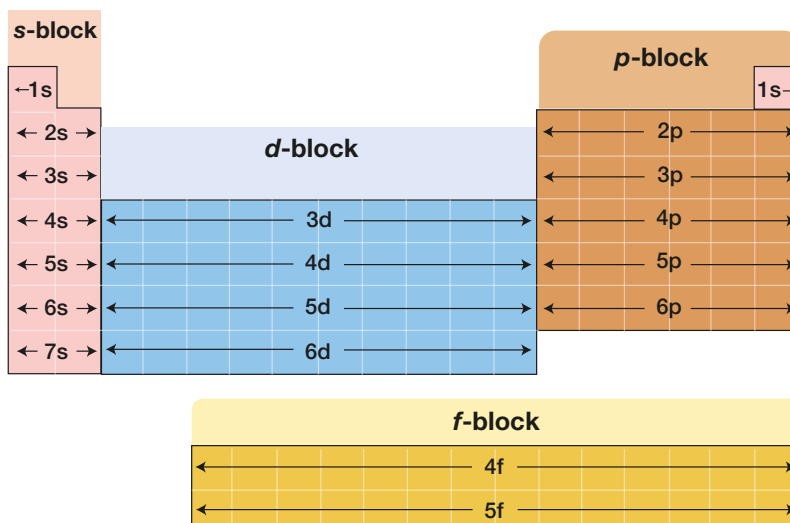


Figure 1.5.9 Periodic Table method for determining fill order for electron subshells.

For example, consider element 17, chlorine ($_{17}\text{Cl}$). It is:

- In the p -block
- In the '3p' row,
- The fifth element in its row

So, its configuration is expected to end with '3p⁵'.

Using either method above for determining the order in which subshells are filled, the electron configuration for chlorine is $1s^2 2s^2 2p^6 3s^2 3p^5$

Electron configuration of the first 20 elements

Question

50. The electron configurations for the first 20 elements are considered below.

Element	Symbol	Atomic number	Subshell electron configuration	Block
hydrogen	H	1	$1s^1$	s
helium	He	2	$1s^2$	s
lithium	Li	3	$1s^2 2s^1$	s
beryllium	Be	4		s
boron	B	5	$1s^2 2s^2 2p^1$	p
carbon	C	6		p
nitrogen	N	7	$1s^2 2s^2 2p^3$	p
oxygen	O	8		p
fluorine	F	9		p
neon	Ne	10	$1s^2 2s^2 2p^6$	p
sodium	Na	11		s
magnesium	Mg	12	$1s^2 2s^2 2p^6 3s^2$	s
aluminium	Al	13		p
silicon	Si	14		p
phosphorous	P	15		p
sulfur	S	16	$1s^2 2s^2 2p^6 3s^2 3p^4$	p
chlorine	Cl	17	$1s^2 2s^2 2p^6 3s^2 3p^5$	p
argon	Ar	18		p
potassium	K	19		s
calcium	Ca	20	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2$	s

(a) **Complete** the table of electronic configuration, using subshell notation, for the remaining elements.

(10 marks) **KA4**

(b) **Identify** one trend in the table above, evident in the electronic configuration.

(1 mark) **KA1**

Electron configuration of the transition elements and beyond

The third, fourth, and fifth main shells overlap significantly, so the order in which subshells are filled as further electrons are added continues to be complex.



As can be seen in Figure 1.5.9 (periodic table image), elements 21-30 have one or more electrons in the 3d subshell, elements 31-36 have electrons in the 4p subshell, and elements 37 and 38 have electrons in the 5s subshell.

Consider element 30, zinc ($_{30}\text{Zn}$). It is:

- In the *d*-block
- In the '3d' row,
- The tenth element in its row

So, its configuration is expected to end with ' $3d^{10}$ '.

Using either method for determining the order in which subshells are filled, the electron configuration for zinc is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}$.

Exceptions – chromium and copper

An atom has greater stability if (the orbitals in) its subshells are filled, half-filled, or empty. It is for this reason that chromium and copper are exceptions to the sequence. In chromium atoms and copper atoms, one electron moves from the 4s subshell to the 3d shell, giving electron configurations ending in $4s^1 3d^5$ and $4s^1 3d^{10}$, respectively.



The electron configurations for elements 21-38 are shown below:

Element	Symbol	Atomic number	Subshell electron configuration	Block
Scandium	Sc	21	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^1$	d
Titanium	Ti	22	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^2$	d
Vanadium	V	23	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^3$	d
Chromium*	Cr	24	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^5$	d
Manganese	Mn	25	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^5$	d
Iron	Fe	26	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^6$	d
Cobalt	Co	27	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^7$	d
Nickel	Ni	28	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^8$	d
Copper*	Cu	29	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^{10}$	d
Zinc	Zn	30	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10}$	d
Gallium	Ga	31	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^1$	p
Germanium	Ge	32	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^2$	p
Arsenic	As	33	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^3$	p
Selenium	Se	34	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^4$	p
Bromine	Br	35	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^5$	p
Krypton	Kr	36	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6$	p
Rubidium	Rb	37	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^1$	s
Strontium	Sr	38	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2$	s

Question

1

51. Gold, silver, copper, platinum and palladium are all precious metals that are found in e-waste from discarded computers, televisions and mobile phones.

(a) Gold, silver, copper, platinum and palladium are all found in the d-block

(i) **State** what is common to the subshell electronic configuration of these elements.

(1 mark) **KA1**

(ii) Copper can be extracted from copper ores containing the mineral covellite (CuS).

Identify the charge on the copper ion present in the mineral covellite.

(1 mark) **KA1**

(iii) **Write** the electronic configuration of copper, using subshell notation.

(2 marks) **KA4**

(iv) Copper can exist as Cu^+ and Cu^{2+} ions.

Write the electronic configuration of copper in these species, using subshell notation.

Cu^+

Cu^{2+}

(4 marks) **KA4**

(b) The expected and actual electronic configurations of copper and palladium are shown below.

Cu	Expected	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^9$	Pd	Expected	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 4d^8 5s^2$
	Actual	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^{10}$		Actual	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 4d^{10}$

Suggest why these elements exhibit the actual subshell electronic configuration rather than the expected.

(1 mark) **IAE3**

(c) Silver is used in electronic circuitry due to its low electrical resistance. When exposed to hydrogen sulfide in air, silver is oxidised and loses conductivity, forming silver sulfide (Ag_2S) and hydrogen gas.

(i) **Write** a balanced equation for the reaction.

(2 marks) **KA4**

(ii) **Identify** the oxidising agent.

(1 mark) **KA1**

Electron configuration of ions

Ions are charged atoms formed by the gain or loss of electrons. Metals tend to release electrons and form positive **cations**, while non-metals tend to gain electrons to form negative **anions**. Electrons are mostly gained or lost in the same order as the shells are filled.

Example 1: anion

A chlorine atom (Cl) can gain one electron to become a chloride anion (Cl^-). The additional electron is added to the lowest energy subshell that is available, which is 3p.

Chlorine Atom (Cl)	Chloride Ion (Cl^-)
$1s^2 2s^2 2p^6 3s^2 3p^5$	$1s^2 2s^2 2p^6 3s^2 3p^6$

Example 2: cation

A beryllium atom (Be) can lose two electrons to become a beryllium cation (Be^{2+}). The two electrons are lost from the highest energy subshell that already contains electrons, which is $2s$.

Beryllium Atom (Be)	Beryllium Ion (Be^{2+})
$1s^2 2s^2$	$1s^2$

Ions of Transition Metals

There is one significant exception to the method of determining the electron configurations of ions. Metals with their highest energy electrons in the d -block (transition metals) prefer to **lose electrons from the highest quantum number (n) first**; ie, the ns subshell before the $(n-1) d$ subshell.

Example

Nickel (Ni) can lose two electrons to become a nickel cation (Ni^{2+}). The two electrons are removed from the $4s$ subshell, rather than the $3d$ subshell.

Nickel atom (Ni)



Nickel ion (Ni^{2+})



Remove electrons from highest quantum number first

Ions take on the stable electron configuration of Group 8 noble gases.

Question

52. Iodine deficiency leads to intellectual and developmental disabilities.

- (a) Historically, dairy foods have contained high levels of iodine from the sterilisation of udders and dairy equipment. These techniques have been phased out, limiting iodine intake in the population. The World Health Organization recommends an average daily intake of $150 \mu\text{g}$ of iodine for an adult.
- (i) Analysis of Australian cow's milk showed an average content of $13 \mu\text{g}$ per 100 mL .
Calculate the daily consumption of cow's milk, in L, required to achieve the recommended daily intake of iodine.

(2 marks) **KA4**

- (ii) **Suggest** why this level may still be achieved without a high daily consumption of cow's milk.

(1 mark) **KA3**

- (b) Since 2009, bakers in Australia have been required to replace regular salt (NaCl) with iodised salt (NaI) to increase iodine intake in the general population.

- (i) **Write**, using subshell notation, the electronic configuration of sodium.

(2 marks) **KA4**

- (ii) **Write**, using subshell notation, the electronic configuration of the sodium ion.

(2 marks) **KA4**

- (iii) **Write**, using subshell notation, the electronic configuration of the chloride ion.

(2 marks) **KA4**

- (iv) **State** one similarity that would be expected between the configuration of the chloride and iodide ion.

(2 marks) **KA4**



Science as a human endeavour

e-waste

As consumer electronics become cheaper and more abundant, they are increasingly viewed as disposable. Mobile phones, computers, and televisions are either shredded and added to landfill waste in Australia or shipped to countries like China for processing.

In landfill, electronics have the potential to leach toxic products from the range of polymers used in their production. There is also the possibility that potentially hazardous metals may be released into the environment. While electronics may only represent a small component of household waste, they represent a large proportion of toxic waste.

Economically, it means that by dumping or exporting this waste, Australia is potentially losing precious metals that could be recycled and reused. It is estimated that from one tonne of mobile phones, 100 kilograms of copper, three kilograms of silver, and 200 grams of gold can be extracted.

These metals are usually extracted from ores in very energy-intensive processes. Ironically the percentage of these metals present in consumer devices is often much higher than that found naturally in the ore they are extracted from.

Many countries, including Australia, are researching methods for the extraction and recycling of the precious metals in electronic devices. Some methods have been highly effective, yielding greater than 95% of the metal present in the product. In South Australia, one project aims to grind the e-waste to a powder and use froth flotation, a technique common to the mining industry, to float the precious metals off on the surface of bubbles.

Question

53. Consider the information above, which outlines the impact of e-waste.

- (a) **Discuss** how the production and disposal of local e-waste is a global issue.

(2 marks) **KA3**

- (b) **State** how metal production techniques have been beneficial to the recycling of precious metals.

(1 mark) **IAE3**

Science understanding

- Explain the effect of the absorption or emission of radiation on the electron configuration of electrons in atoms or ions.
The wavelengths of radiation emitted and absorbed by an element are unique to that element and can be used to identify its presence in a sample.
- Explain why some wavelengths of radiation emitted and absorbed by an element are unique to that element.

© SACE 2025

Analysing the light – or *electromagnetic radiation* – emitted by atoms and ions is the most effective way to deduce their electronic structure.

Energy levels in atoms are quantised, meaning electrons absorb or emit specific energy amounts when they transition between levels. These transitions are associated with particular wavelengths of light, making each element's absorption and emission spectrum unique. An electron's lowest energy level is called its **ground state**.

When an atom or ion is given energy in the form of heat, light, or electricity, it becomes “excited”. Its electrons **absorb** the energy and move to a higher energy level – an **excited state**. The energy absorbed corresponds with a particular wavelength.

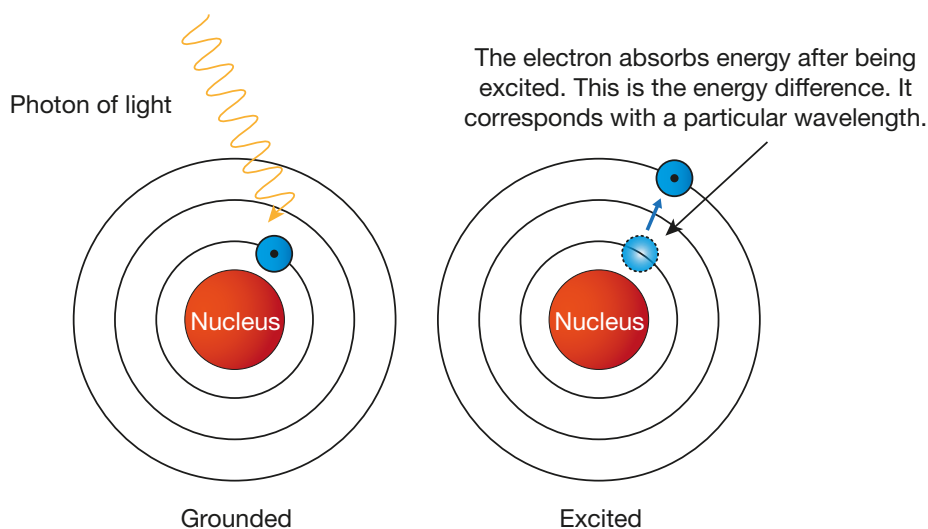


Figure 1.5.10: Electron absorbing energy and moving to a higher energy level.

Electrons are unstable in the excited state, so they fall back down to their ground state. In doing so, they release, or **emit**, energy. The energy that is emitted corresponds to a particular wavelength, many of which can be seen as visible light.

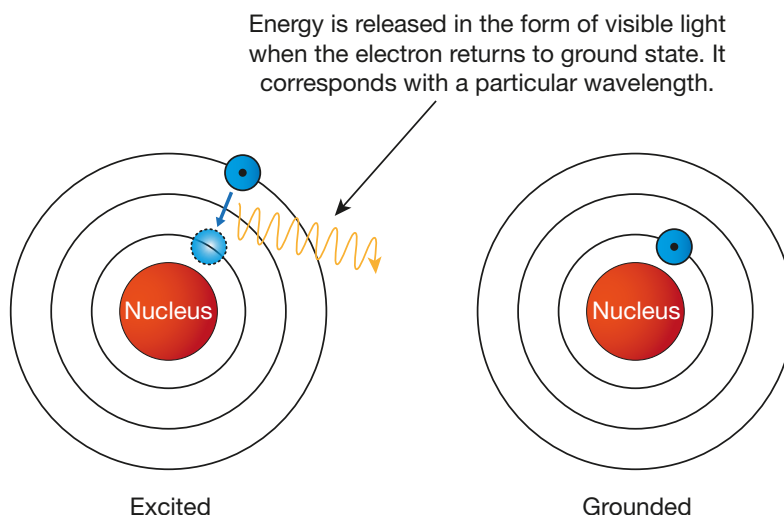


Figure 1.5.11: Electron releasing energy in the form of visible light when returning to ground state.

The uniqueness of wavelengths for each element is due to its distinct atomic structure, which defines the specific energy levels available to its electrons. As a result, each element emits or absorbs radiation at characteristic wavelengths. For example, the way lithium's electrons move between energy levels is different from the way helium's electrons move between energy levels, so they will absorb and emit different wavelengths of light.

The energy that is emitted and absorbed by each element can be measured on a **spectrum**.

An element can be identified by the light it absorbs or the light it emits. Because each element absorbs and emits wavelengths differently, each element can be identified by its own characteristic line absorption or line emission spectrum.

Line Emission Spectrum

An emission spectrum is produced when excited electrons return to their ground state.

If a high voltage is applied to atoms of an element, these atoms will give off light. The light emitted by these atoms is passed through a prism. The prism causes the different wavelengths of light to be separated, as shown in the image below.

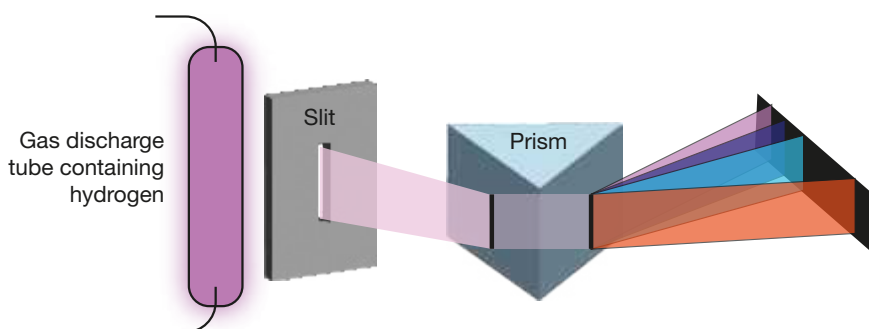


Figure 1.5.12: Light emitted from a gas discharge tube containing hydrogen dispersed through a glass prism



The lines that appear here correspond to the specific frequencies of light for that atom; in this case, hydrogen.

Figure 1.5.13: The emission spectrum of hydrogen.

The lines that appear represent electrons returning from a higher energy level to a lower energy level, and hence, the frequencies of light that correspond to these transitions.

Line Absorption Spectrum

An absorption spectrum is produced when ground state electrons move to an excited state.

The energy that is absorbed when an electron moves to a higher energy level corresponds to a particular wavelength, and this wavelength can be measured using an **absorption spectrometer**. This absorbed energy leaves a black line on the continuous spectrum of light because the wavelength has been absorbed and hence will not show up.

The line absorption spectrum is the inverse of the line emission spectrum, as seen below:

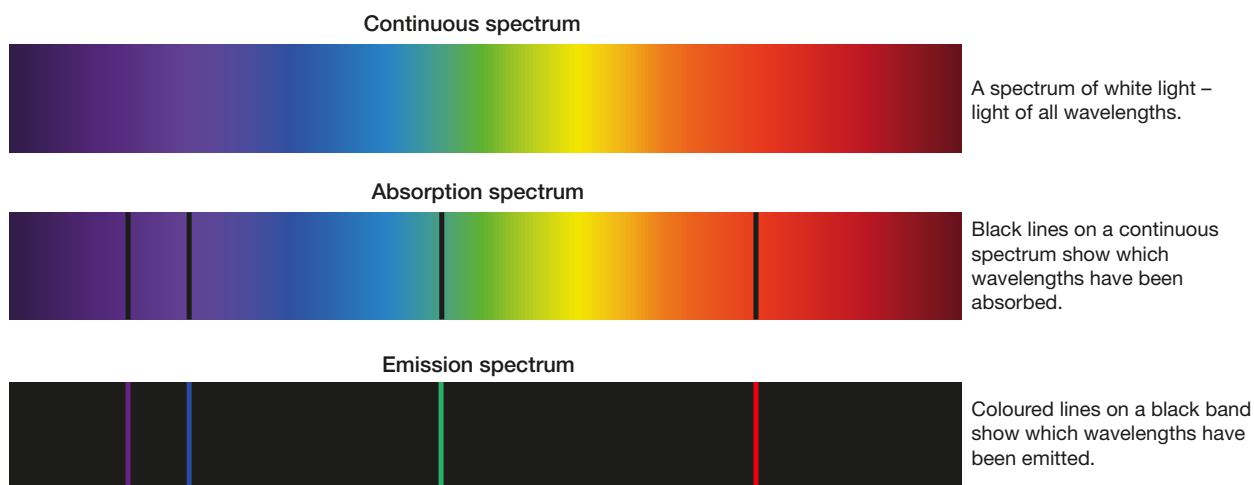


Figure 1.5.14: Absorption and emission spectra in relation to the continuous spectrum of light.

The line absorption spectrum is the basis of **Atomic Absorption Spectroscopy**, which is a very sensitive technique that allows scientists to determine the concentration of metallic elements in unknown samples.

Science understanding

Atomic absorption spectroscopy is used for quantitative analysis.

- Explain the principles of atomic absorption spectroscopy in identifying elements in a sample.
- Describe the construction and use of calibration graphs in determining the concentration of an element in a sample.

© SACE 2025

By applying the atomic absorption characteristics of metallic elements, Sir Alan Walsh developed a ground-breaking analytical technique: the **atomic absorption spectrometer**. Using the principle that atoms can absorb light at unique, specific wavelengths, this technique allows scientists to determine the concentrations of metal ions in aqueous solutions.

Using the atomic absorption spectrometer

To determine the concentration of a certain metal in a sample, the following steps occur within an atomic absorption spectrometer:

1. A **hollow cathode lamp** made of the element being tested emits light at a specific wavelength. This ensures that only atoms of that element in the sample absorb the light, minimising interference and increasing the accuracy of the measurement.

For example, if magnesium were being tested, a magnesium cathode lamp would be used. It emits a wavelength of light of 285.2 nm, which is specific to magnesium.

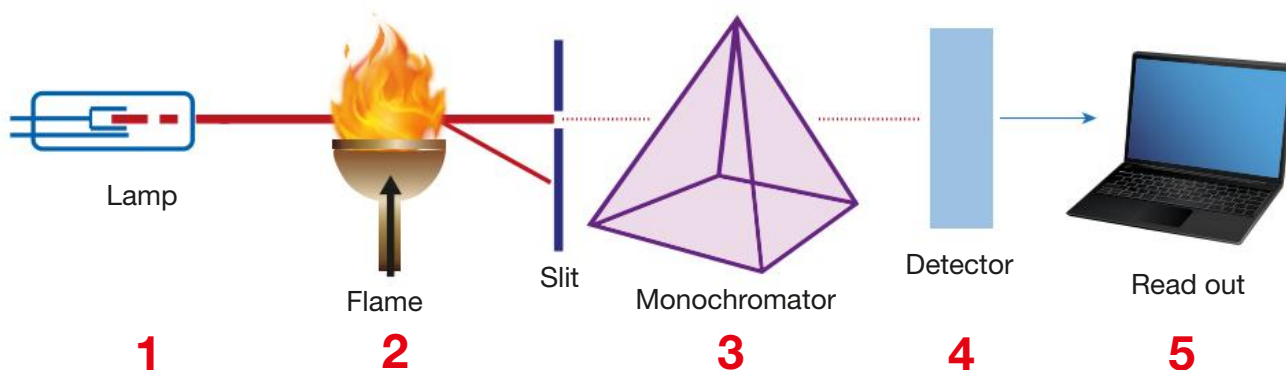


Figure 1.5.15: The processes of atomic absorption spectrometry.

The flame in AAS atomises the sample, breaking it down into individual atoms. This step is crucial because **only free atoms, not ions or compounds**, can absorb light in AAS, enabling accurate concentration measurements

2. The sample is introduced into the flame. The flame atomises the sample, breaking it down into individual atoms. This step is crucial because only free atoms, not ions or compounds, can absorb light in AAS, enabling accurate concentration measurements. If the sample contains the element being tested, the light energy will be absorbed in proportion to the concentration of the element in that sample.

If the sample contained magnesium, magnesium's atoms would become excited by absorbing the specific wavelength of light. The more magnesium atoms present in the sample, the more light is absorbed.

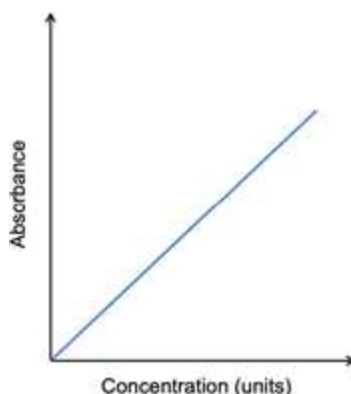
3. The remaining light travels into the **monochromator**. This filters the light beam, allowing only the wavelength specific to the element being tested to reach the detector. This isolation of wavelengths prevents interference from other elements, enhancing accuracy.
4. The beam strikes an electronic detector – the **photomultiplier** – which converts light energy into electrical energy.
5. The detector results are amplified, and the absorbance value is displayed on a computer or readout.

To convert an absorbance value to a concentration, a calibration curve must be used. A calibration curve correlates absorbance with concentration, allowing unknown sample concentrations to be interpolated.

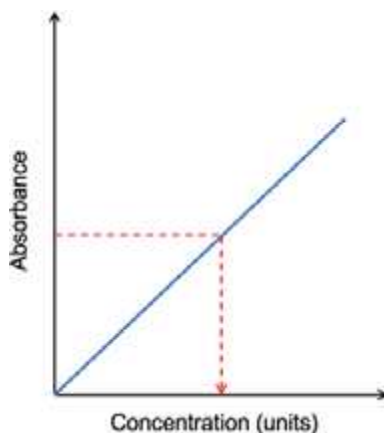
Constructing a calibration curve

An AAS machine is calibrated by measuring solutions of known concentrations (standard solutions) of the element to be tested.

- A hollow cathode lamp, with the cathode made of the metal to be tested, is selected. As mentioned earlier, this emits light of a certain wavelength. This wavelength only excites the electrons in the metal to be tested, without interference from other elements.
- A series of standard solutions of the metal being tested are made up. Distilled water is used to make a solution of concentration zero [units].
- The light is passed through these standard solutions. The degree of light absorbed is proportional to the concentration of the metal in the sample.
- The intensity of the light that is **transmitted** through the flame is measured by the detector.
- Plotting absorbance (y-axis) versus concentration (x-axis) produces a linear calibration curve. This linear relationship allows for determining unknown concentrations by finding the absorbance of the sample and comparing it to the curve.



- When light is passed through the unknown sample, only the element being tested will be detected, without interference from other elements, as only those atoms will absorb the wavelength of light being produced by the hollow cathode lamp.
- A horizontal line is drawn across to the calibration curve, and then down to the x-axis, to give the concentration of the element in the sample. This enables its concentration to be determined.



- To test for another metal, the appropriate lamp would need to be installed, and a new calibration curve using standard solutions of that metal would need to be prepared.

Atomic Absorption Spectroscopy is one of the world's most valuable analytical techniques. It is used in forensics, environmental science, pharmacology, agriculture, and mining – to name a few! Some applications include:

- Determining the concentration of metal ions in soil, drinking water, and wine
- Determining the concentration of toxic metals in e-liquids
- Toxicology examinations where poisoning is suspected

Furthermore, unlike atomic emission, which needs samples to be heated to high temperatures, there is no need for high temperatures in atomic absorption spectroscopy because most atoms absorb light in their ground state.



Science as a human endeavour

Evolution of AAS

The development of atomic absorption spectroscopy (AAS) represents one of the most significant advancements in analytical chemistry of the 20th century. In the 1950s, Australian scientist Sir Alan Walsh pioneered this revolutionary technology at CSIRO, fundamentally changing how scientists detect and measure metals in various samples. Walsh's breakthrough came from his innovative approach to measuring absorption rather than emission spectra, overcoming the significant limitations of traditional flame tests that had constrained analytical chemistry for decades. From its early prototypes, AAS technology has evolved into a sophisticated analytical method that has transformed multiple scientific fields.

In environmental science, it serves as a crucial tool for monitoring water quality and detecting soil contamination, enabling scientists to track pollution levels with unprecedented accuracy. The forensic science community has embraced AAS as an invaluable technique for analysing trace metals in evidence, while the food industry relies on it to ensure product safety through precise heavy metal analysis. In the mining sector, AAS has revolutionised mineral prospecting and ore analysis, providing mining companies with detailed compositional data that guides exploration and extraction decisions.

The evolution of AAS technology continues through ongoing scientific innovation. Modern instruments incorporate advanced computer systems for automated analysis, achieving sensitivity levels that can detect metals at concentrations of parts per billion. The development of graphite furnace AAS has further enhanced precision, while integration with other analytical techniques has created comprehensive analytical platforms. This continuous advancement illustrates how scientific innovation drives improvements in analytical capabilities, creating tools that serve both research and practical applications across diverse industries.

Question

54. Arsenic levels in the environment have been increasing due to pollution from industry. Inorganic arsenic has been detected in rice at concerning concentrations. Rice typically contains approximately ten times more arsenic than any other grain. Rice is highly efficient at taking arsenic out of soils, as it is grown in an anaerobic environment.

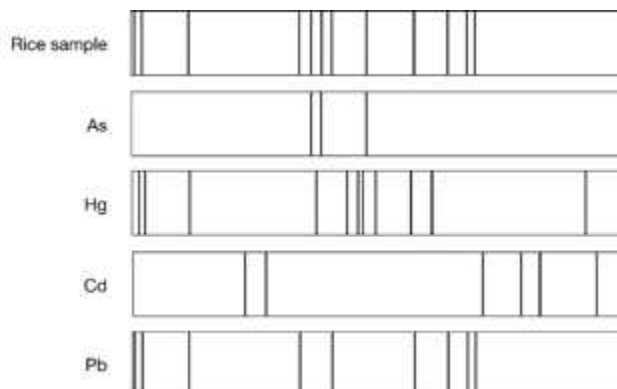
(a) (i) **State** which block of the periodic table where arsenic is found.

(1 mark) **KA1**

(ii) **Write** the electronic configuration of arsenic, using subshell notation.

(2 marks) **KA4**

- (b) Flame emission spectroscopy was used to determine the presence of arsenic and other potential harmful elements in a rice sample. The line emission spectra produced for the rice sample and identifiable elements are shown below:



(i) **State** and **explain** whether arsenic was present in the rice sample.

(2 marks) **IAE3**

(ii) **Identify** one other element of concern that is present in the rice sample.

(1 mark) **IAE3**

- (c) A particular brand of rice cakes was analysed and the arsenic concentration was determined to be 606 ppb. **Calculate** the mass of arsenic, in mg, consumed from a single rice cake of 1.02 g.

1

(3 marks) **KA4**

55. Compounds containing the cobalt cation, Co^{2+} , and the chromium cation, Cr^{3+} , can be added to glass to give it some colour.

(a) **Write** the electron configuration of:

(i) Co^{2+}

(2 marks) **KA4**

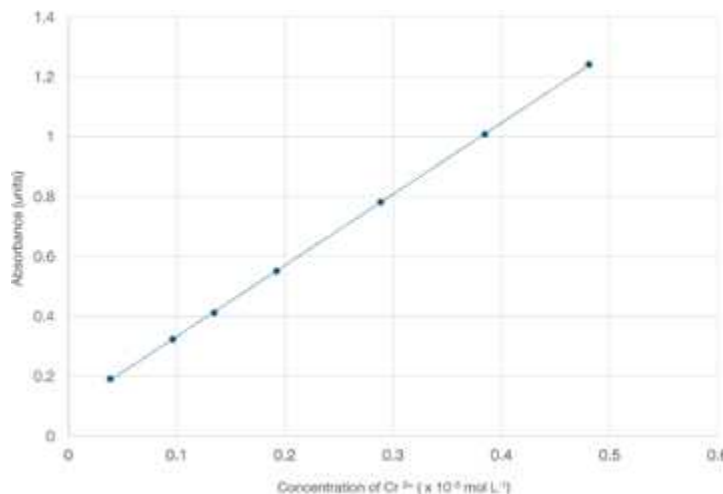
(ii) Cr^{3+}

(2 marks) **KA4**

- (b) By referring to their electron configurations, **explain** why the elements cobalt and chromium are placed in the same block of the periodic table.

(2 marks) **KA1**

- (c) To find the concentration of chromium ions in a sample, the absorbance of different solutions containing low concentrations of chromium ions was also measured. The results are shown on the calibration graph below:



- (i) **State** the relationship between the absorbance of chromium ions and the absorbance of light.

(1 mark) **IAE3**

- (ii) Analysis of the sample shows the absorbance value at 0.75. Use the calibration curve to **determine** the concentration of Cr^{3+} in the sample in mol L^{-1} .

(1 mark) **IAE3**

- (iii) **Convert** the concentration in (ii) above from mol L^{-1} to ppm.

(2 marks) **KA4**

(iv) By referring to the calibration graph, **determine**:

(1) the type of error that occurred during this analysis,

(1 mark) **KA4**

(2) the evidence from the graph that indicates this error, and

(1 mark) **IAE3**

(3) how this error may have occurred.

(1 mark) **IAE3**

(v) Manganese ions, Mn^{2+} , are also used to make coloured glass. **Explain** why manganese was not detected during the analysis.

(2 marks) **KA1**

(vi) **Describe** two changes that would be made if manganese needed to be detected.

(2 marks) **KA1**

56. The World Health Organisation has stated that the acceptable maximum concentration of iron (III) ions in drinking water is 3 ppm.

An atomic absorption spectrometer was used to determine the concentration of iron (III) compounds in a sample of water by first using a series of iron (III) solutions of known concentrations.

(a) The results of the calibration tests are shown in the table below.

Concentration of iron (III) ($\mu\text{g}/100\text{ mL}$)	Absorbance
0	0.00
50	0.15
100	0.31
175	0.51
200	0.60

Draw the calibration curve for the concentration of iron (III).



(3 marks) **IAE2**

- (b) The sample of water was analysed three times by three chemists to determine the concentration of iron (III). Their results are shown below, in .

	Analysis 1	Analysis 2	Analysis 3
Chemist A	263	266	266
Chemist B	269	269	270
Chemist C	266	268	267

- (i) **Identify** the chemist whose results are the most precise.

(1 mark) **IAE3**

- (ii) Given that this sample of water had an iron (III) concentration of exactly 265 $\mu\text{g}/100\text{ mL}$:

- (1) **Identify** the chemist whose results were the most accurate.

(1 mark) **IAE3**

- (2) **Determine** whether the water is safe for human consumption according to the World Health Organisation.

(1 mark) **IAE3**

- (c) **State** the function of the following parts of the atomic absorption spectrometer:

- (i) The flame

(1 mark) **KA1**

- (ii) The monochromator

(1 mark) **KA1**

57. Oils used in commercial aircraft are regularly analysed for traces of silicon, tin and titanium in the early detection of machine component failure.

- (a) Increases in the concentration of silicon may indicate sand deposits passing through the turbines of the engines, which may cause excessive wear. Sand is predominantly silicon dioxide (SiO_2).

- (i) **Identify** the block of the periodic table in which silicon is found.

(1 mark) **KA1**

- (ii) Using subshell notation, **write** the electronic configuration of silicon.

(2 marks) **KA4**

- (iii) **State** the type of bonding present in SiO_2 .

(1 mark) **KA1**

- (iv) **Explain**, in terms of bonding, why sand is a hard-abrasive substance with a high melting point.

(2 marks) **KA4**

- (b) Deposits of silicon dioxide can be removed from components by immersion in hot concentrated sodium hydroxide (NaOH), which forms sodium silicate (Na_2SiO_3) in aqueous solution.

- (i) **Write a balanced equation** for the reaction described above.

(2 marks) **KA4**

- (ii) **State** whether the silicon dioxide is demonstrating properties of an acidic or basic oxide in this reaction.

(1 mark) **KA1**

- (c) Lubricating oil in a jet engine was analysed for the presence of tin from solder in cooling systems. AAS was performed with the use of a graphite furnace. A concentration of $0.326 \mu\text{g mL}^{-1}$ was recorded.

(i) **Determine** the concentration of tin in ppb.

(2 marks) **KA4**

(ii) **State** whether titanium is a metal, non-metal or metalloid.

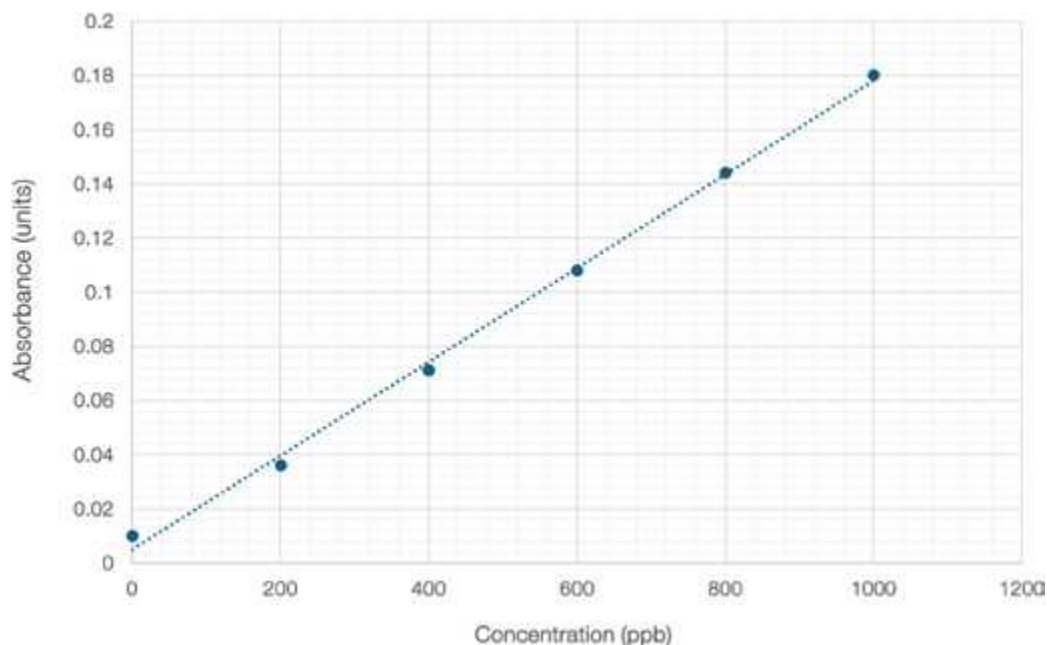
(1 mark) **KA1**

(iii) Titanium oxidises in air to form titanium dioxide, TiO_2 .

Write the electronic configuration of titanium in TiO_2 .

(2 marks) **KA4**

The calibration graph for the analysis of titanium in lubricating oils is shown below.



(iv) (1) **State** the feature of the graph that indicates high precision.

(1 mark) **KA1**

(2) With reference to the graph, **state** the type of error that occurred.

(2 marks) **IAE3**

? Science inquiry skills

Skills in context

Graphing in atomic absorption spectroscopy

Constructing a calibration graph requires the inclusion of a number of the following features (Figure 1.5.14).

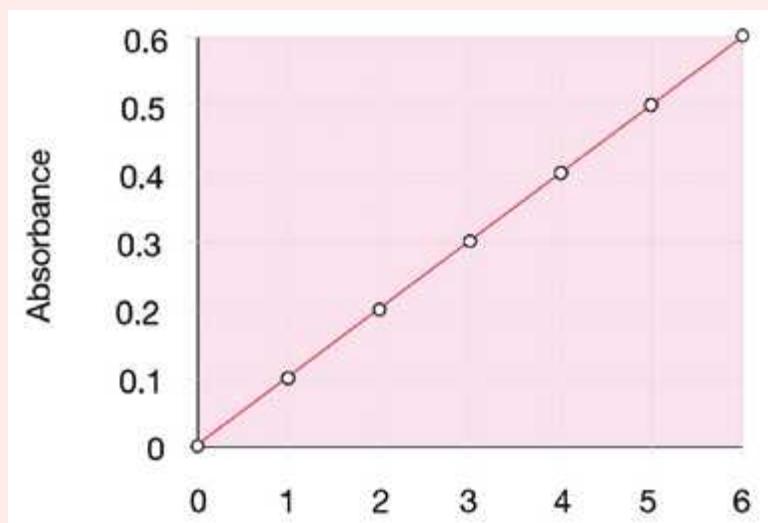


Figure 1.5.14: Features of a typical AAS graph.

Feature		Explanation
(1)	Identified variables	The concentration is altered in AAS, and therefore it represents the independent variable. The absorbance is measured, and therefore it is the dependent variable.
(2)	Labelled axes	Quantities need to be identified and attributed to each axis. Variables are generally plotted with the dependent variable on the y-axis and the independent variable on the x-axis. Absorbance is plotted on the y-axis and concentration on the x-axis.
(3)	Identified units	If applicable, units and prefixes show range and scale. Absorbance is measured in arbitrary units, so units are not required (some graphs may express the value as a percentage). Concentration is typically expressed in ppm, ppb, g L⁻¹ or mol L⁻¹ (with appropriate prefixes applied).
(4)	Application of an appropriate scale	Appropriate scale and size assists in plotting and conveying the data. The data should use the majority of the space provided. The scale used for AAS data would include the range for the prepared standard solutions.
(5)	Plotted data points	Data points need to be recorded clearly and accurately to allow interpretation of the line of best fit and an evaluation of the degree of scatter and hence precision. At least three data points are used to reduce the effect of random errors and establish trends. A line graph is applied to the AAS data.
(6)	Construction of a line of best fit	The line of best fit is applied to allow interpretation of the correlation with expected or established trends. AAS will typically produce a linear relationship, where absorbance is proportional to concentration.

Analysis of spectroscopy graphs

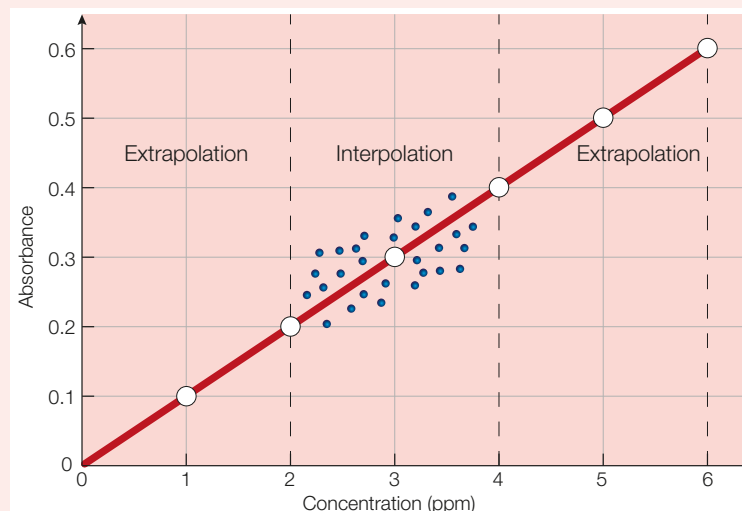


Figure 1.5.15: Interpretation of a graph.

Interpolation and extrapolation

Interpolation requires the determination of data points derived from the range of data provided. In AAS, concentrations for unknown samples are interpolated from the calibration line within the data. **Extrapolation** requires extension beyond the provided data based on an established trend (Figure 1.5.15). If the unknown values sit outside of the data, a new calibration graph would be produced or the samples diluted further to fit within the range of standards.

Applying a line of best fit

A **line of best fit** is applied in AAS. Typically, a linear relationship is established, producing a straight line. The line is drawn to leave an equal residual distribution of data points above and below the line of best fit (Figure 1.5.15).

Scatter and precision

Scatter is evident in the distribution of data points around an applied line of best fit. Scatter can also be evident in the calculated range of data collated in a table. In AAS, scatter can be seen in absorbance values if more than one reading is taken at each concentration. However, scatter is more commonly identified in the agreement of the data points around the line of best fit (Figure 1.5.15).

As considered in Page 53, scatter results from **random error**. The greater the degree of scatter, the greater the impact of random errors. Random errors affect the **precision** of data. The greater the degree of scatter, and therefore the effect of random error, the lower the precision of the results.

Random error

Random errors in AAS can cause fluctuations between the predicted absorbance and the measured absorbance for a given concentration. Random errors can occur to both increase or decrease the value obtained. In AAS, random errors occur in the preparation of standard solutions. This includes washing, filling and delivery procedures, and variance in ambient light when readings are taken.

Systematic error

It is expected that the line of best fit for AAS should pass through the **origin** (0,0) (Figure 1.5.15). This would indicate that a concentration of zero produces an absorbance of the same reading. This may not occur in the following situations:

The single data point generated for the blank may be contaminated with the element under analysis (although with good technique unlikely). As only one data point is altered, this would represent a random error.

The readings including the blank solution have not been calibrated. Calibration needs to account for the light reaching the detector from the burner head and any ambient light that enters the apparatus. In this case, all readings would be altered by a consistent amount, in the same way, generating a source of **systematic error**. The line of best fit would sit consistently higher or consistently lower than expected and not pass through the origin.

As considered in Page 53, systematic errors arise from a consistent shift in measured values due to an inherent error in the procedure or apparatus. Systematic errors impact on the **accuracy** of data.

Summary test 1: Monitoring the environment

1

1. Large quantities of carbon dioxide are emitted during the production of cement. Carbon dioxide is released during the generation of heat and electricity for the plant, and as a product of the calcination phase.
- (a) During calcination, calcium carbonate is heated, decomposing to produce calcium oxide and carbon dioxide.
- (i) **Write** an equation for the decomposition of calcium carbonate.

(2 marks) **KA4**

- (ii) **State** one other human activity that is responsible for increased carbon dioxide levels in the troposphere.

(1 mark) **KA1**

- (iii) **Explain** how increased levels of atmospheric carbon dioxide have led to an increased average temperature in the Earth's troposphere.

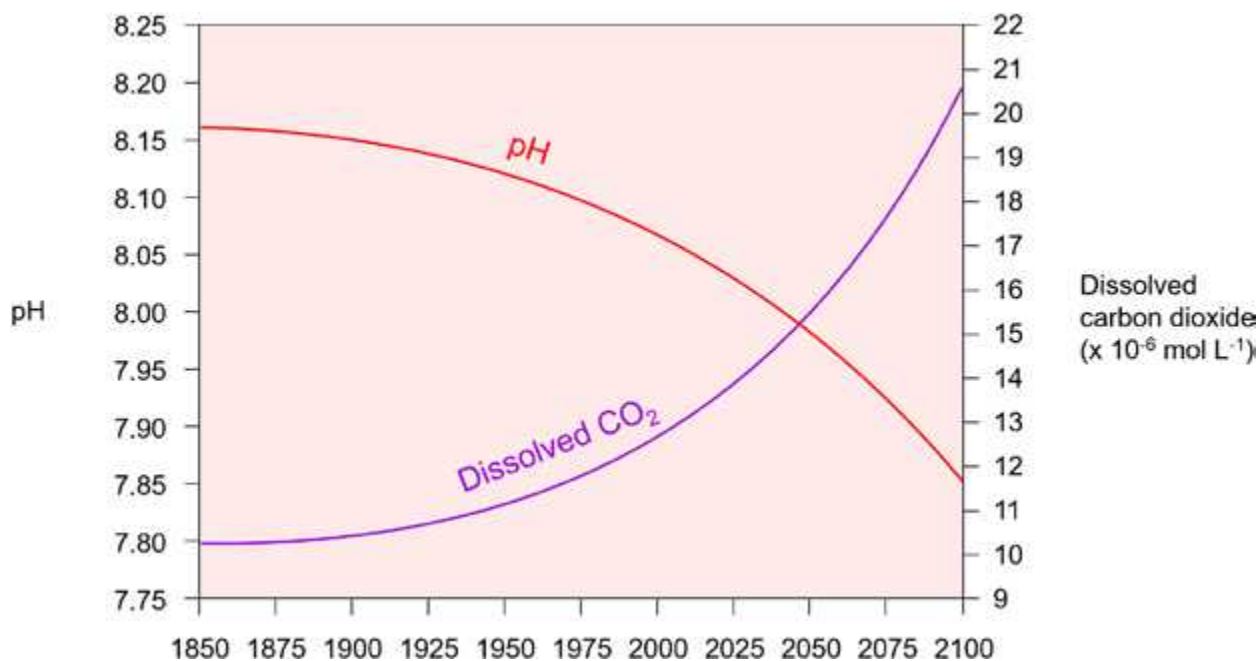
(3 marks) **KA1**

- (b) 0.927 kg of carbon dioxide is released for every 1 kg of cement produced. 4.18 giga tonnes (Gt) of cement are produced annually around the world.

Calculate the total annual emissions of carbon dioxide from cement production.

(2 marks) **KA4**

- (c) A large proportion of the carbon dioxide released from human activities, such as cement production, is dissolved in the oceans.



- (i) With the aid of an equation, **explain** the trends shown in the graph above.

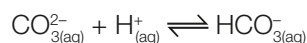
(3 marks) **IAE3**

- (ii) The pH of the ocean has been measured at a value of 8.15 and is predicted to reach 7.85.

Calculate the concentration of hydrogen ions (H^+) at each pH and state which pH represents the higher concentration.

(3 marks) **KA4**

- (iii) Carbonate ions are required for the formation of shells and skeletons of some marine species. Carbon dioxide dissolved in the oceans may be present in the form of carbonate ions or hydrogen carbonate ions according to the equation below.



State and explain the effect of increased ocean acidity on the availability of carbonate ions for marine species.

(3 marks) **KA2**

- (d) Cement requires limestone, silica, and minerals containing aluminium and iron, obtained from mining. Part of the human contribution to atmospheric carbon dioxide comes from emissions generated from mining practices.

Mining practices have contributed to rising concentrations of atmospheric carbon dioxide. Seeking raw materials and fossil fuels as feedstock, directly releases carbon dioxide into the atmosphere. The combustion of fuels by mining machinery, as well as consumption of fuels associated with electricity production during processing, and further transportation of refined products all contribute emissions.

In an attempt to reduce demands on finite resources and offset emissions of carbon dioxide in the atmosphere, we have sought renewable alternatives. However, mining for the raw materials for future renewable energy infrastructure contributes to overall emissions, as well as severely impacting native species and ecosystems.

Solar panels, wind farms, and battery technologies all require materials processed from mining. Australia is recognised for the plentiful reserves of many renewable energy materials that are in high demand, such as lithium, graphite, and rare earth elements required for high powered magnets. These important resource exports contribute significantly to Australia's current and future economy.

Researchers have begun to map the geographical locations of renewable resources in Australia in comparison to known areas of native biodiversity. This comparison has indicated implications for extracting raw materials in these resource rich locations, with the threat to species and biodiversity. In some cases, the threat to plant and animal life due to mining has been predicted to have a greater impact than the challenges species face from climate change.

The research has put into perspective the need to balance our need for renewable energy materials, emissions from mining, and impact on native ecology. Recommendations from this research allow government to support growth in renewable infrastructure, while planning for conservation and sustainability and limiting impact upon natural biodiversity valued by indigenous people and communities across Australia.

With reference to the key concept of influence, **explain** how considerations around obtaining raw materials for renewable energies exemplifies science as a human endeavour.

(4 marks) **KA3**

2. Nitrogen dioxide emissions in heavily populated cities are primarily due to the use of motor vehicles.

- (a) Nitrogen dioxide is present in the exhaust emissions from internal combustion engines.

- (i) **State** one requirement for the formation of nitrogen dioxide that is provided during the combustion of fuel in an engine.

(1 mark) **KA1**

- (ii) **Write an equation** for the formation of nitrogen dioxide from nitric oxide.

(2 marks) **KA2**

- (b) When exposed to sunlight, nitrogen dioxide emissions in cities may result in the formation of ground-level tropospheric ozone.

(i) **State** why ultraviolet light is required for the formation of ozone.

(1 mark) **KA1**

(ii) **Write equations** for the formation of ozone from nitrogen dioxide.

(4 marks) **KA4**

(iii) **State** one undesirable consequence of pedestrians being exposed to elevated concentrations of ozone in the troposphere.

(1 mark) **KA1**

Credit will be given for the correct use of significant figures in answers to part (c).

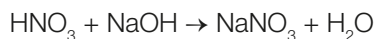
(1 mark)

- (c) The concentration of nitrogen dioxide at low levels in air can be determined by bubbling a sample of air through a solution of hydrogen peroxide, oxidising the nitrogen dioxide to nitric acid.



A 5.00 L sample of air was introduced to a solution of hydrogen peroxide.

The nitric acid formed was titrated with 0.100 mol L⁻¹ sodium hydroxide.



A titre value of 9.16 mL was obtained.

- (i) Methyl red was used as the indicator. Methyl red is red at a pH below 4.4 and yellow at a pH over 6.2.

State the colour obtained at the endpoint of the titration.

(1 mark) **KA2**

(ii) **Calculate** the number of moles of sodium hydroxide that reacted with the nitric acid formed.

(2 marks) **KA4**

(iii) Hence, **calculate** the moles of nitric acid formed.

(1 mark) **KA4**

- (iv) **Calculate** the moles of nitrogen dioxide present in the original sample of air.

(1 mark) **KA4**

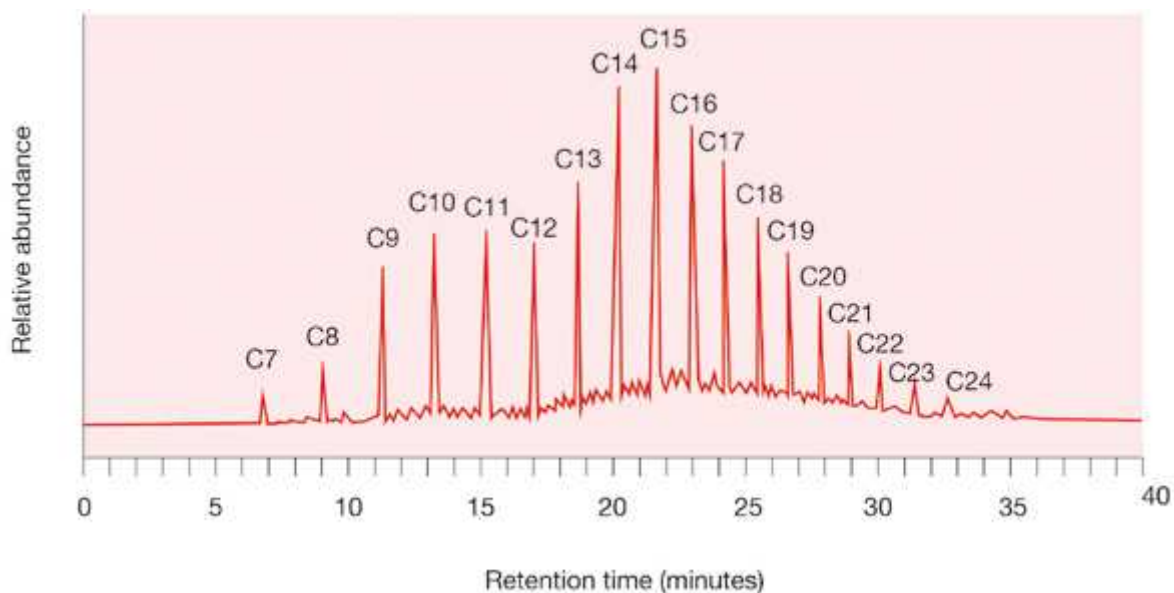
- (v) **Calculate** the concentration of nitrogen dioxide, in ppm, in the original sample of air.

(4 marks) **KA4**

3. Remediation of industrial sites for urban redevelopment requires the analysis of soil and groundwater for the presence of potentially harmful wastes.

- (a) Oils and fuels present in the soil from small localised spills can be detected using gas chromatography (GC).

The chromatogram below indicates the presence of diesel fuel, due to the range of hydrocarbon peaks present for the alkane series.



- (i) **State** the systematic name of the straight chain alkane containing eight carbon atoms.
- (ii) **Determine** the retention time (in minutes) of the alkane containing 15 carbon atoms. State the answer to three significant figures.
- (iii) **Describe** the relationship between carbon chain length and retention time.

(1 mark) **KA1**

(2 marks) **KA4**

(1 mark) **IAE3**

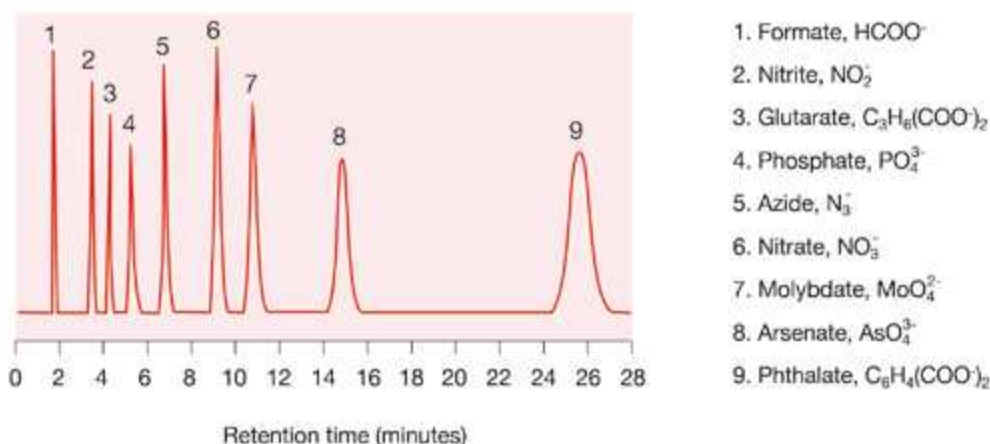
- (iv) **State** and **explain** whether the stationary phase chosen for the separation is more likely to be polar or non-polar.

(2 marks) **IAE3**

- (v) **Suggest** one reason why the presence of diesel fuel contamination is more difficult to determine for spills that are not recent.

(1 mark) **KA2**

- (b) Groundwater was analysed from a site that was suspected of being used for market gardening. The groundwater was analysed for the presence of nitrate ions (NO_3^-) and phosphate ions (PO_4^{3-}), which would indicate the possible use of fertilisers.



Ion-chromatography (IC) was used to analyse the water sample for the presence of nitrate and phosphate ions. An anion exchange column was used.

- (i) **State** the charge on the resin surface in the column.

(1 mark) **KA1**

- (ii) **State** and **explain** which anion would exhibit the largest retention time.

(3 marks) **IAE3**

4. Copper chromium arsenate (CCA) has been used for many years to treat pine fencing posts often used in the viticulture industry to support vines. Concern has been raised over the leaching of copper, chromium and arsenic metals from the posts into the surrounding soil.

- (a) Chromium trioxide (CrO_3) is one compound used in CCA formulations.

- (i) **State** the block of the periodic table to which chromium belongs.

(1 mark) **KA1**

- (ii) **Write** the electronic configuration of chromium.

(2 marks) **KA4**

- (iii) **Calculate** the oxidation state of chromium in CrO_3 .

(2 marks) **KA1**

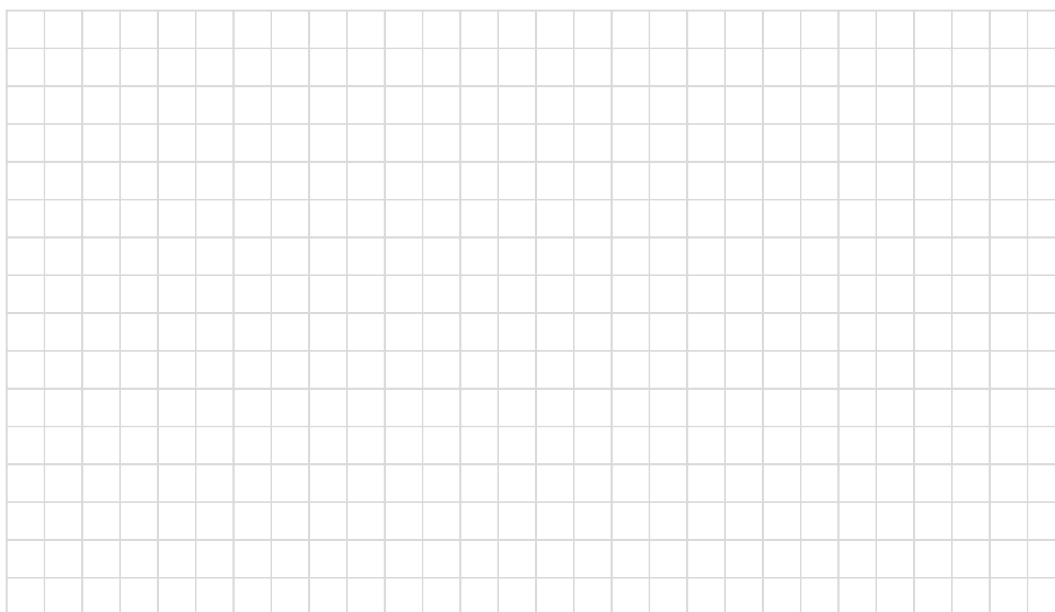
- (b) Standard solutions were prepared and analysed for copper producing the following results.

Concentration (ppm)	Absorbance
0	0.00300
5	0.148
10	0.290
15	0.431
20	0.566

- (i) **Identify** which column represents the dependent variable.

(1 mark) **IAE1**

- (ii) Using the grid below, **construct** a calibration graph for the known copper solutions.



(6 marks) **IAE2**

- (iii) **State** the characteristic of the graph that indicates a high degree of precision.

(1 mark) **KA1**

- (iv) **Explain** why the presence of chromium and arsenic do not interfere with the analysis for copper.

(2 marks) **KA2**

- (c) In regions where acid rain has been recorded, there is even greater concern about the use of CCA posts.

Suggest one disadvantage of the use of CCA posts under these conditions.

(1 mark) **KA2**

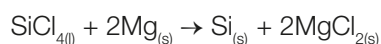
- (d) About 89 million timber posts are installed in vineyards across Australia, of which 78% are treated with CCA. CCA protects the timber from fungal and insect attack, and it is very effective, providing a working life of up to 40 years. However, it is estimated that between 1.3 – 3.3 million CCA posts (12,000 – 30,000 tonnes) need to be replaced annually due to breakage. These used posts are typically stockpiled on the vineyard as waste, with some sent to landfill.

The viticulture industry has been looking to create alternatives for CCA posts. Steel posts have lower breakage rates and are more sustainable than wooden posts, yet they are more than double the price and require custom parts.

With reference to one or more SHE concepts, **discuss** how the search for alternatives to CCA posts represents science as a human endeavour.

(4 marks) **KA3**

5. Pure silicon, required for computer chips, is made by the reaction:



- (a) **Write** the electron configuration of silicon.

(2 marks) **KA4**

- (b) If you begin with 225g each of SiCl_4 and Mg:

- (i) **Calculate** the moles of each reactant

(2 marks) **KA4**

- (ii) **Determine** which reactant is limiting and which is in excess.

(2 marks) **KA4**

- (iii) **Calculate** the mass, in grams, of Si that can be produced.

(3 marks) **KA4**

- (c) Read the following information and answer the questions that follow.

“The world is one step closer to 6G communications and ultra-fast data transfers following a breakthrough in silicon chip technology led by researchers at the University of Adelaide.”

In August 2024, scientists at the University of Adelaide, collaborating with Osaka University, developed a ground-breaking device called a **polarisation multiplexer**, which could enable 6G wireless communications. The multiplexer is implemented on a silicon chip, and the device operates at a much higher frequency than the current 5G technology. Professor Fujita anticipates that, “within the next one to two years, researchers will begin to explore new applications and refine the technology.” Over the following three-to-five years, the team expects to see significant advancements in high-speed communications, leading to commercial prototypes and early-stage products. This chip can be manufactured using existing semiconductor processes, making it suitable for mass production and market integration within a few years.

- (i) **Explain** how silicon-based technologies used in computing have influenced other areas of science, technology, engineering, and mathematics.

(2 marks) **KA3**

- (ii) **Explain** how society’s growing demand for data-intensive applications has influenced the development of this new technology.

(2 marks) **KA3**

- (iii) **Discuss** how international collaboration, like that between the University of Adelaide and Osaka University, impacts the development and implementation of new technologies like 6G.

(2 marks) **KA3**

- (iv) **Discuss** some potential ethical concerns surrounding the implementation of 6G networks, especially regarding data privacy and security.

(2 marks) **KA3**

- (v) **Discuss** how faster and more efficient communication networks change the way people may work, learn, or interact in the future.

(2 marks) **KA3**

- (vi) **Discuss** some environmental factors in developing and implementing high-frequency networks like 6G.

(2 marks) **KA3**

Topic 2: Managing chemical processes

2.1 Rates of reaction

Science understanding

The rates of a reaction at different times can be compared by considering the slope of a graph of quantity or concentration of reactant or product against time.

Draw and interpret graphs representing changes in quantities or concentration of reactants or products against time.

© SACE 2025

Chemical changes occur when reacting particles form new products. The evidence of chemical change occurring could be observed as follows:

- Gas forming, seen in the reaction vessel and as bubbles if in a liquid
- Colour change in the reaction vessel
- Precipitate formed; insoluble compound formed from two previously soluble compounds
- Light produced
- Heat produced

Law of Conservation of Energy

The Law of Conservation of Energy states that energy cannot be created or destroyed and therefore, the net energy of a system is conserved. The rearrangement of chemical bonds is an energy intensive process hence energy can be converted to heat and light.

Law of Conservation of Mass

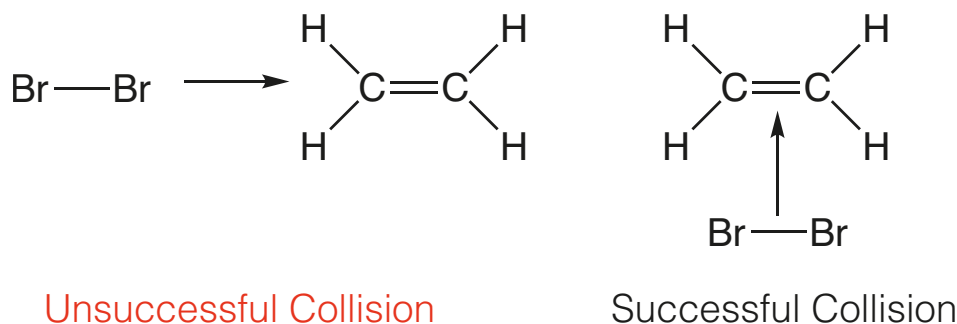
The Law of Conservation of Mass is based on the conservation of energy and states that the total mass of a system is conserved during a reaction and as such, when chemical bonds are rearranged the net mass of the system is constant.

Collision Theory

In any chemical system, particles continuously collide. According to **Collision Theory**, for a collision to result in a chemical reaction, the colliding particles must have sufficient energy to overcome the activation energy (E_a) barrier and must collide with the correct orientation. The **activation energy** is the minimum energy required for a reaction to occur. **Successful collisions** lead to the formation of products. It's important to note that many collisions are unsuccessful because they do not meet these criteria.

Worked example

In the addition reaction between bromine (Br_2) and an alkene such as ethene (C_2H_4), the correct orientation and E_a is required for the collision between these two molecules. The required orientation for the successful collision is shown in the diagram below:



Rate of Reaction

A rate is used to determine how fast or slow a quantity changes with respect to time e.g., the rate at which a beaker is filled with water could be measured in millilitres per second (mL s^{-1}). Likewise, a chemical reaction rate measures how fast or slow reactants are forming products per unit time. The rate of a chemical reaction could be measured either by the rate at that the products are formed or the rate that the reactants are consumed.

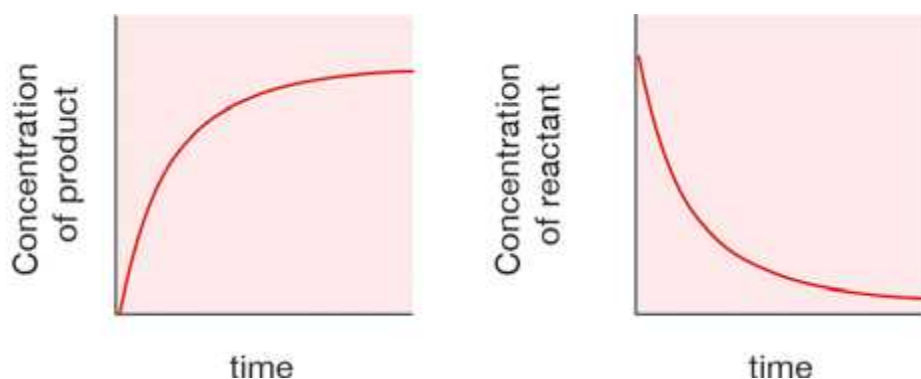


Figure 2.1.1: Changes in the quantity of a product (left) and a reactant (right) with respect to time.

The rate of products forming could be:

- Gas forming in a syringe and measured as the volume change with respect to time e.g., mL sec^{-1}
- Number of moles of products forming e.g., mol sec^{-1}

The rate of reactants being consumed could be:

- Mass of reactants reducing with respect to time e.g., g sec^{-1}
- Concentration of reactant reducing with respect to time e.g., $\text{mol L}^{-1} \text{sec}^{-1}$

Worked example

The decomposition of nitrogen dioxide ($2\text{NO}_{2(g)} \rightarrow 2\text{NO}_{(g)} + \text{O}_{2(g)}$) was studied by measuring the concentration of NO_2 at various times. The data is shown below:

Time (s)	$[\text{NO}_2]$ (mol L^{-1})
0	0.0100
50	0.0079
100	0.0065
150	0.0055
200	0.0048

Calculate the average rate of decomposition of NO_2 over the first 100 seconds of the reaction.

$$\begin{aligned}
 \text{Average rate} &= (\text{change in concentration}) / (\text{change in time}) \\
 &= \frac{(0.0065 \text{ mol L}^{-1} - 0.0100 \text{ mol L}^{-1})}{(100 \text{ s} - 0 \text{ s})} \\
 &= \frac{(-0.0035 \text{ mol L}^{-1})}{(100 \text{ s})} = -3.5 \times 10^{-5} \text{ mol L}^{-1} \text{ s}^{-1}
 \end{aligned}$$

Therefore, the average rate of decomposition of NO_2 over the first 100 seconds is $3.5 \times 10^{-5} \text{ mol L}^{-1} \text{ s}^{-1}$.



Science as a human endeavour

Process intensification is a key concept in chemical engineering that aims to drastically improve the efficiency and sustainability of chemical processes by designing novel equipment and techniques that maximise mass and heat transfer, while minimising energy consumption and waste generation. One area of focus in process intensification is the development of innovative reactor designs that can enhance reaction rates and selectivity.

An example of a novel reactor design for process intensification is the spinning disc reactor (SDR). In an SDR, reactants are fed onto a rapidly rotating disc, creating a thin film that is subjected to high centrifugal forces. This thin film provides a large surface area for mass and heat transfer, leading to intensified mixing and enhanced reaction rates. The short residence times and precise control over reaction conditions in SDRs also enable the suppression of unwanted side reactions, improving product selectivity.

Another innovative reactor design is the oscillatory baffled reactor (OBR). OBRs consist of a cylindrical tube fitted with equally spaced baffles and subjected to oscillatory motion. The oscillatory flow creates intense mixing and uniform shear rates, enhancing mass transfer and eliminating stagnant zones. This results in improved reaction rates and reduced processing times compared to conventional stirred tank reactors. OBRs have found applications in various industries, including the production of pharmaceuticals, fine chemicals, and polymers.

The development of these novel reactor designs represents a significant step towards sustainable and efficient chemical processing. By intensifying reaction rates and improving selectivity, these technologies can reduce energy consumption, minimise waste generation, and increase the overall productivity of chemical processes.

Question

1. (a) Identify two SHE descriptors that are relevant to the development of novel reactor designs for process intensification. Explain how each descriptor relates to this technology.

..

(4 marks)

- (b) With reference to the examples of spinning disc reactors and oscillatory baffled reactors, discuss how these novel reactor designs can contribute to the sustainability and efficiency of chemical processes.

..

(3 marks)

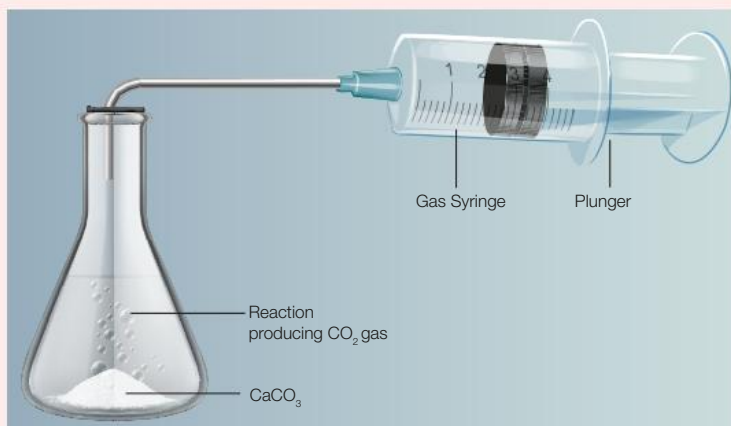
? Science inquiry skills

Skills in context

The slope of a graph can be used to determine the rate of a chemical reaction. Consider the reaction between calcium carbonate (CaCO_3) and hydrochloric acid (HCl) producing carbon dioxide gas (CO_2). The reaction equation is given below:



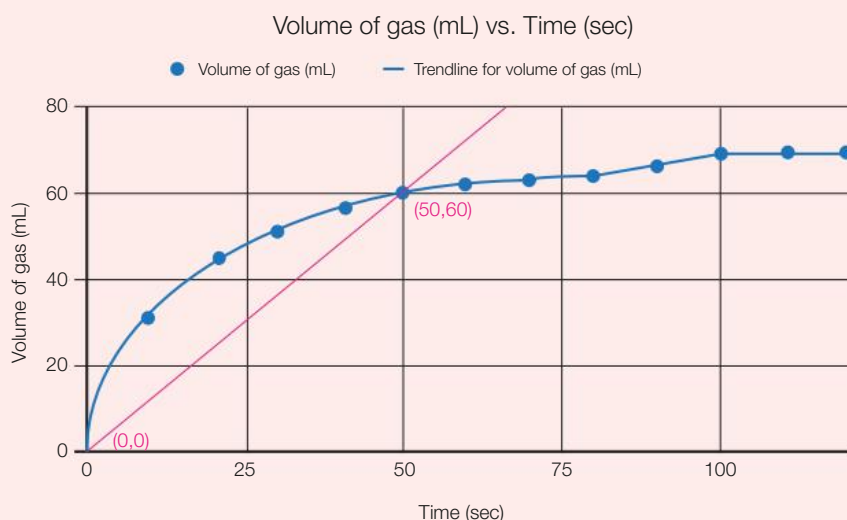
Possible variables that could be measured for this particular reaction (dependant variables) are the change in mass of CaCO_3 (g sec^{-1}) or the volume of CO_2 produced (mL sec^{-1}).



The quantity of CO_2 produced can be measured using a gas syringe, a possible setup is shown above.

The following results were produced:

Time (sec)	Volume of CO_2 gas (mL)
0	0
10	34
20	46
30	52
40	56
50	60
60	62
70	64
80	66
90	68
100	70
110	70
120	70



For the graph above the average rate of reaction for the first 50 seconds can be determined by finding the slope of a line over that period.

$$\text{slope} = \frac{\Delta y}{\Delta x}$$

$$\text{slope} = \frac{y_2 - y_1}{x_2 - x_1}$$

$$\text{Average rate of reaction} = \frac{\text{change in volume}}{\text{time elapsed}}$$

$$\therefore \text{Average rate of reaction} = \frac{60 - 0}{50 - 0}$$

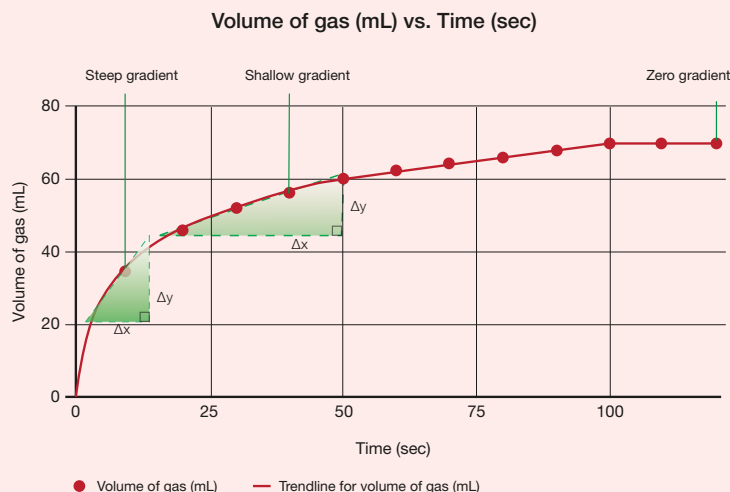
$$\therefore \text{Average rate of reaction} = \frac{60}{50}$$

$$\therefore \text{Average rate of reaction} = 1.2 \text{ mL s}^{-1}$$

Therefore, the average rate of formation of carbon dioxide gas over the first 50 seconds is 1.2 mL s^{-1} .

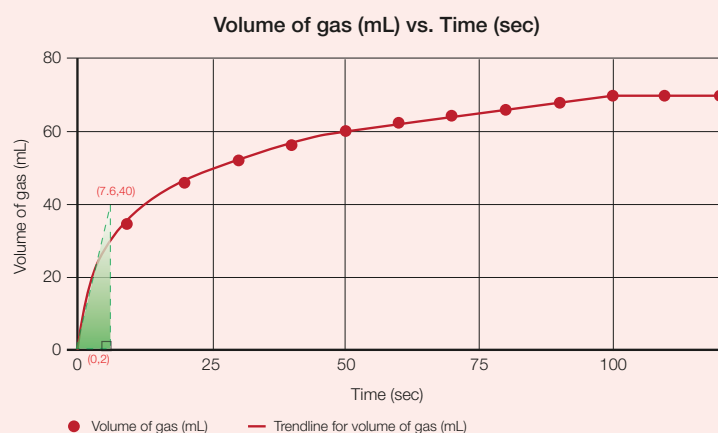
The instantaneous rate of a chemical reaction can be used to determine the rate of reaction at a given point in time. This can be useful for identifying when the rate of production is at its highest. The slope of each tangent line represents the instantaneous rate of reaction at that specific time point. A steeper slope indicates a faster rate, while a shallower slope indicates a slower rate. At $t=2$ seconds, the steep tangent line shows the reaction rate is high, while at $t=50$ seconds, the shallow tangent line indicates the reaction has slowed significantly.

? Science inquiry skills



The graph above shows the changing rate of the reaction through the tangent lines drawn. It is important to note the following:

- Steep tangent line = fast rate of reaction where the conversion of reactants to products is occurring rapidly
- Shallow tangent line = slow rate of reaction where the conversion of reactants to products is occurring slowly
- Zero gradient
 - For a **non-reversible reaction** = the reaction has stopped converting reactant into products
 - For a **reversible reaction** = the reaction has reached a state of chemical equilibrium (refer to Topic 2.2)



Referring to the tangent line drawn at approximately $t = 2$ seconds the instantaneous rate of reaction can be calculated for this point of the reaction.

$$\text{Instantaneous rate of reaction} = \frac{\Delta y}{\Delta x}$$

Therefore, at approximately $t = 2$ seconds the rate of formation of carbon dioxide gas is 5 mL per second.

$$\text{Instantaneous rate of reaction} = \frac{\text{change in volume}}{\text{time elapsed}}$$

$$\therefore \text{Instantaneous rate of reaction} = \frac{40 - 2}{7.6 - 0}$$

$$\therefore \text{Instantaneous rate of reaction} = \frac{38}{7.6}$$

$$\therefore \text{Instantaneous rate of reaction} = 5 \text{ mL s}^{-1}$$

Question

2. (a) Define activation energy (E_a).

(1 mark, KA1)

(b) Explain how the energy of a collision between molecules is related to the temperature of the substance.

(2 marks, KA1)

(c) State the two conditions necessary for a collision to successfully result in a chemical reaction.

(2 marks, KA1)

(d) Explain how the units used to measure the rate of a reaction are related to the method used.

(3 marks, KA2)

2

Science understanding

Rates of reaction can be influenced by a number of factors, including the presence of inorganic and biological catalysts (enzymes).

Predict and explain, using collision theory, the effect on rates of reaction due to changes in:

- concentration
- temperature
- pressure (for reactions involving gases)
- surface area
- the presence of a catalyst.

© SACE 2025

The rate of a chemical reaction is the rate at which the successful collisions occur per unit time. The rate of chemical reactions can be altered by:

- Increasing the frequency of collisions per unit time
- Increasing the proportion of collisions reaching or exceeding E_a

Factors which affect the rate of a chemical reaction are a change in:

- **Concentration:** Increasing the concentration of reactants generally increases the rate of reaction due to a higher frequency of collisions.
- **Pressure:** For reactions involving gases, increasing the pressure increases the rate of reaction by increasing the concentration of gaseous reactants.
- **Surface Area:** Increasing the surface area of solid reactants increases the rate of reaction by providing more area for collisions to occur.
- **Temperature:** Increasing the temperature increases the kinetic energy of particles, leading to more energetic collisions, and therefore a greater proportion of collisions are successful, thus increasing the reaction rate.
- **Catalysts:** Catalysts provide an alternative reaction pathway with a lower activation energy, increasing the rate of reaction without being consumed in the process.

Example

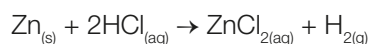
An example of speeding up the rate of a chemical reaction is when using a firelighter to light a fire, which provides more energy to the reaction between oxygen gas and the combustible material in wood. The rate of chemical reactions could also be slowed down by making fewer collisions occur which would lead to a lower chance of successful collisions occurring. In the example of keeping food in a fridge, the chemical reactions that occur to make the food 'go off' are slowed down by removing energy from the system and as a result reducing the rate of reaction.

Changes in concentration

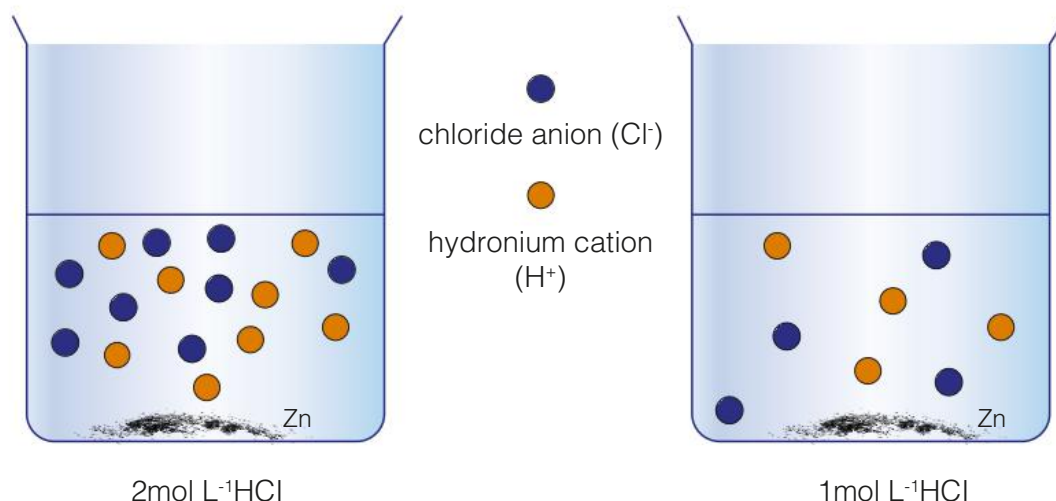
If the concentration of reacting particles is altered the rate of the chemical reaction will change. If the concentration of a species of reacting particles is increased there are more reacting particles in the system. The frequency of collisions is increased. More collisions occur between reacting particles and as a result, a larger number of successful collisions occur. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction.

Worked example

Consider the reaction between zinc metal (Zn) and hydrochloric acid (HCl) represented by the reaction equation below.



If the concentration of hydrochloric acid is increased from 1 mol/L to 2 mol/L, the number of HCl molecules available for reaction increases, leading to a higher frequency of collisions between HCl and zinc particles. This increase in collision frequency results in a higher rate of successful collisions per unit time, thereby increasing the rate of formation of zinc chloride (ZnCl_2) and hydrogen gas (H_2).



In this example, the frequency of collisions between H^+ ions and zinc metal is increased. More collisions occur and as a result a larger number of successful collisions occur between H^+ ions and zinc metal. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of formation of ZnCl_2 and H_2 gas.

? Science inquiry skills

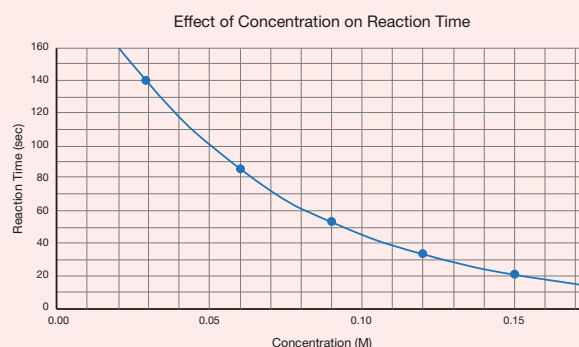
Skills in context

The rate of formation of a precipitate could be used to measure the rate of a chemical reaction. Consider the example of hydrochloric acid reacting with different concentrations of sodium thiosulfate, resulting in an opaque solution from the insoluble sulfur (S) precipitate.

The variable that could be measured in this example is the time taken for the reaction to produce an opaque solution, this is the **dependant variable**. The concentration of sodium thiosulfate is being altered by the scientist and is the **independent variable**.

This experiment is carried out producing the following results:

Conc. $\text{Na}_2\text{S}_2\text{O}_3$ (M)	Reaction Time (sec)
0.15	24.31
0.12	29.96
0.09	51.23
0.06	81.4
0.03	141.63



From the graph above, it can be deduced that as the concentration of sodium thiosulfate increases, the time taken for the solution to become opaque decreases. This indicates that the rate of formation of sulfur is increasing. As the concentration of sodium thiosulfate increases there are more reacting particles in the solution. The frequency of collisions between reacting particles is increased. More collisions occur and as a result a larger number of successful collisions occur between sodium thiosulfate and hydrochloric acid. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of formation of the precipitate sulfur.

Changes in pressure

The pressure of a system is determined by the movement of particles within a given volume. To increase the pressure of a system, the volume of that system is decreased or more particles are introduced into a given volume. The overall effect of these changes is an increase in concentration, represented in the diagram below.

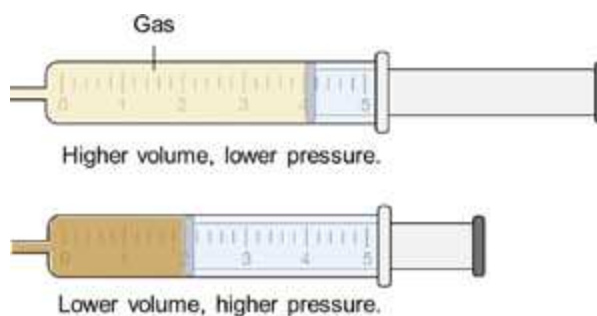


Figure 2.1.2: Relationship between the volume and pressure of a gas.

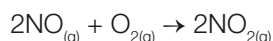
Change in pressure is effectively a change in concentration applied to a gaseous system.

If the pressure of a system involving gaseous reactants is increased (i.e., by decreasing the volume of the reaction vessel), the concentration of gaseous particles increases. This leads to a higher frequency of collisions between reactant molecules. As a result, the rate of reaction increases due to the increased number of successful collisions per unit time. Conversely, decreasing the pressure (by increasing the volume) reduces the collision frequency and, consequently, the reaction rate. The frequency of collisions between gaseous particles is increased. More collisions occur between reacting gaseous particles and as a result a larger number of successful collisions occur. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction.

If the pressure of a system is increased by reducing the volume of the gaseous system, more collisions occur between gaseous particles. The frequency of collisions between gaseous particles is increased and as a result a larger number of successful collisions occur. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction.

Worked example

Consider the reaction between nitric oxide (NO) and oxygen gas (O₂) producing nitrogen dioxide (NO₂).



If the pressure of the reaction vessel is increased by altering the volume of the vessel from 2L to 1L. More collisions occur between nitric oxide and oxygen molecules within the smaller volume. The frequency of collisions between gaseous particles is increased and as a result a larger number of successful collisions between nitric oxide and oxygen molecules occur. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of formation of nitrogen dioxide.

Changes in surface area

The surface area of particles can be increased by division into smaller particles as can be seen by the diagram below.

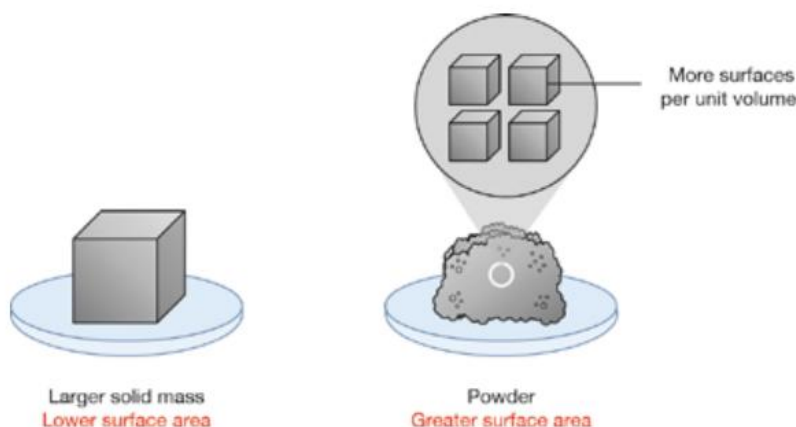
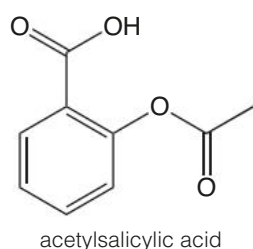


Figure 2.1.3: Samples of solid zinc (metal) with different surface area.

If the surface area of reacting particles within a system is altered, the rate of the chemical reaction will change. In chemical reactions that involve solids, the interactions resulting in successful collisions occur on the surface of the solid. If the surface area of a species of reacting particles is increased, exposing more particles and altering the surface area to volume ratio. The frequency of collisions increases as more particles are exposed. More collisions occur between reacting particles and as a result a larger number of successful collisions occur. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction.

Worked example

Medication such as aspirin (acetylsalicylic acid) can exist as both tablets and powder.



The rate of the chemical reaction within the human body is faster for the powder form of the medication. The surface area to volume ratio of a particle increases as the particle size decreases. This means that for a given mass of aspirin, a finely powdered sample will have a much greater surface area exposed to the solvent compared to a single large crystal.

The dissolution rate of a substance is proportional to its surface area. In the case of aspirin, the powdered form will dissolve more rapidly in the stomach than a whole tablet because the greater surface area allows for a greater frequency of successful collisions per unit time between the aspirin particles and the stomach fluid.

This increased leads to a faster rate of solvation and dissociation of the aspirin molecules, allowing them to be absorbed into the bloodstream more quickly.

In contrast, a whole aspirin tablet has a lower surface area to volume ratio, so it will take longer for the entire tablet to dissolve and release the active ingredient as the number of successful collisions per unit time is lower. This is why aspirin tablets are often designed to be chewable or fast-dissolving, as breaking the tablet into smaller pieces increases the surface area and speeds up the dissolution process.

Question

3. A solid block of calcium carbonate (CaCO_3) will react with hydrochloric acid (HCl) producing calcium chloride, water, and carbon dioxide.

(a) **Explain** the change in the rate of the chemical reaction if the surface area of CaCO_3 is increased by crushing the block.

(3 marks) KA1

(b) **Explain** the change in the rate of the chemical reaction if the concentration of hydrochloric acid is reduced.

(3 marks) KA1

(c) **Explain** why the instantaneous rate of reaction is higher at $t = 5$ seconds compared to at $t = 50$ seconds.

(4 marks) IAE3

(d) **Describe** a practical process that could be used to measure the rate of this chemical reaction.

(3 marks) KA1

Changes in temperature

If the temperature of a system is altered, the rate of the chemical reaction will change. If the temperature of a system is increased this results in the average kinetic energy of the reacting particles increasing and exhibiting more thermal energy. Therefore, a larger proportion of collisions reach or exceed the Activation Energy.

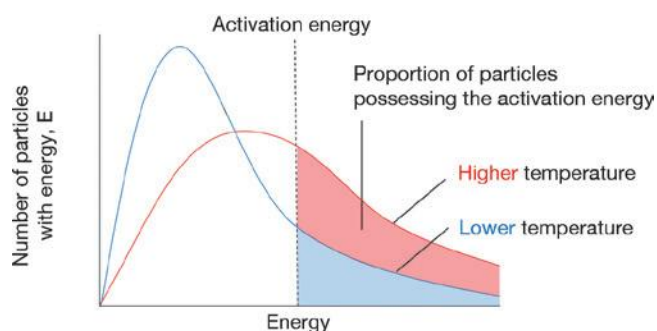


Figure 2.1.4: Effect of temperature on the number of particles possessing the activation energy.

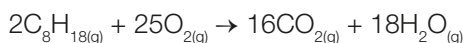
Increasing the temperature of a reaction mixture shifts the distribution of molecular kinetic energies to the right. This increases the proportion of molecules with enough energy to overcome the activation energy barrier when they collide, leading to a higher reaction rate.

The shaded areas under each curve represent the fraction of molecules with kinetic energies greater than the activation energy (E_a) at the respective temperatures.

There is an increased frequency of successful collisions occurring. Therefore, a greater number of successful collisions occur per unit time resulting in an increase in the rate of reaction.

Worked example

Fuels such as octane (C_8H_{18}) react with oxygen gas (O_2) through a combustion reaction represented below.



If the temperature of the reaction mixture is increased from 20°C to 1000°C , this results in the average kinetic energy of the reacting particles increasing and exhibiting more thermal energy. Therefore, there is a larger proportion of collisions between octane and oxygen molecules reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring between the molecules. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of formation of carbon dioxide and water.

Presence of a catalyst

Catalysts are substances that are used to increase or decrease (inhibitor) a rate of reaction; these include enzymes which are biological catalysts.

Positive catalysts provide an alternate reaction pathway with a lower E_a , increasing the rate of chemical reactions.

Negative catalysts, or inhibitors, decrease the rate of chemical reactions, by increasing E_a , or stopping chemical reactions occurring.

If a catalyst is introduced to a system, the rate of the chemical reaction will alter. If a positive catalyst is introduced this would provide an alternative reaction pathway for the reacting particles with a lower Activation Energy. This results in a larger proportion of collisions between reacting particles reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction.



Science as a human endeavour

Researchers at the University of Adelaide have developed a new class of catalysts that can significantly improve the efficiency of hydrogen production through the water-splitting reaction. These catalysts, based on metal-organic frameworks (MOFs) containing earth-abundant elements such as nickel and cobalt, have shown remarkable activity and stability in electrochemical water splitting.

The water-splitting reaction, represented by the equation $2\text{H}_2\text{O}_{(l)} \rightarrow 2\text{H}_{2(g)} + \text{O}_{2(g)}$, is a promising method for generating clean hydrogen fuel from renewable energy sources. However, the reaction typically requires high overpotentials and suffers from slow kinetics, limiting its practical application. The new MOF-based catalysts address these challenges by providing abundant active sites and facilitating rapid charge transfer, enabling water splitting at lower overpotentials and higher current densities.

Furthermore, the modular nature of MOFs allows for fine-tuning of their properties through careful selection of metal centers and organic linkers. This flexibility in design opens up opportunities for optimising the catalysts for specific operating conditions and enhancing their long-term stability.

The development of these efficient water-splitting catalysts represents a significant step towards sustainable hydrogen production and the transition to a hydrogen-based energy economy. By enabling cost-effective and scalable hydrogen generation from renewable sources, this technology can contribute to the reduction of greenhouse gas emissions and help mitigate the impacts of climate change.

Question

4. (a) Identify the key SHE descriptor that best aligns with the research into novel MOF-based catalysts for efficient hydrogen production. Explain your choice with reference to the information provided.

..

.....

..

.....

..

..... (3 marks)

- (b) Discuss the potential impact of these new catalysts on the future of sustainable energy production and the challenges that need to be addressed for their widespread implementation.

..

.....

..

.....

..

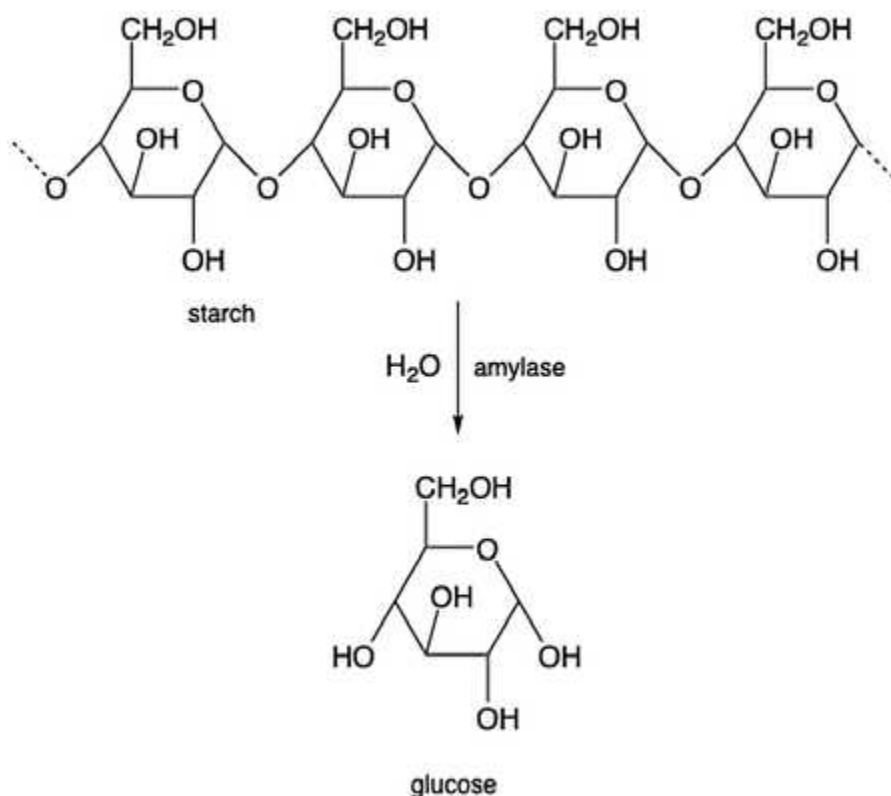
.....

..

..... (4 marks)

Worked example

Amylase is an enzyme in human saliva that catalyses the hydrolysis of starch in the mouth, breaking it down to simple sugars, according to the below reaction.

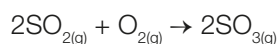


2

Hydrolysis of starch

Amylase provides an alternative pathway with a lower E_a for the starch to hydrolyse into simpler sugars. This results in a larger proportion of collisions between reacting particles reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring. Therefore, a larger number of successful collisions occur per unit time increasing the rate of hydrolysis of starch molecules.

Vanadium oxide (V_2O_5) catalysts are used in the contact process for producing sulfuric acid. In this process, sulfur dioxide (SO_2) is oxidised to sulfur trioxide (SO_3) by reacting with oxygen gas. The key step is:



This reaction is typically carried out at temperatures around 450°C and pressures of 1-2 atm, in the presence of a V_2O_5 catalyst. The vanadium oxide catalyst works by adsorbing the SO_2 and O_2 molecules onto its surface, orienting them favorably for reaction. This adsorption weakens the bonds within the SO_2 and O_2 molecules, effectively lowering the activation energy barrier for the reaction.

As a result, a greater proportion of collisions between the adsorbed SO_2 and O_2 molecules have sufficient energy to overcome this lowered activation energy barrier. This leads to a substantially increased rate of SO_3 formation compared to the uncatalysed reaction. The SO_3 product then desorbs from the catalyst surface, regenerating the catalyst for the next reaction cycle.

By enabling the reaction to proceed quickly at more moderate temperatures and pressures, the V_2O_5 catalyst makes the sulfuric acid production process much more economically viable. Without this catalytic rate enhancement, the harsh conditions required would make the process prohibitively expensive. Vanadium oxide's ability to accelerate this reaction while remaining stable at high temperatures makes it uniquely suited for its role in this important industrial synthesis.

Question

5. Lactose intolerance is a condition that affects millions of people worldwide. It occurs when the body does not produce enough of the enzyme lactase, which is necessary for breaking down lactose, the sugar found in milk and dairy products. Lactase is produced by the cells lining the small intestine and helps to digest lactose by catalysing its hydrolysis into glucose and galactose, which can then be absorbed into the bloodstream.

The reaction catalysed by lactase can be represented as follows:



People with lactose intolerance may experience symptoms such as bloating, diarrhea, and abdominal pain after consuming milk or dairy products. The severity of symptoms can vary depending on the amount of lactose consumed and the individual's level of lactase deficiency.

- (a) **Explain** how lactase increases the rate of digestion of lactose in the human gut.

(3 marks) **KA1**

When milk is heated, it leads to secondary reactions occurring, which can form harder to digest compounds.

- (b) **Explain** how the increased temperature of the milk leads to more by-products being formed.

(3 marks) **KA2**

Science understanding

Energy profile diagrams can be used to represent the relative enthalpies of reactants and products, the activation energy, and the enthalpy change for a chemical reaction.

Draw and interpret energy profile diagrams.

© SACE 2025

Enthalpy is the energy content of a system at constant temperature and pressure, represented by the letter H. The overall change of energy content in a system for the reaction pathway is represented by a delta H (ΔH), representing the change in enthalpy.

A chemical reaction pathway can be explained by looking at the enthalpy change of a system. This reaction pathway can be represented graphically and is termed an **energy profile diagram**. Energy profile diagrams illustrate the energy changes during a chemical reaction, showing the relative enthalpies of reactants and products, the activation energy (E_a), and the overall change in enthalpy (ΔH). For an exothermic reaction, the products have lower enthalpy than the reactants, resulting in a negative ΔH . Conversely, in an endothermic reaction, the products have higher enthalpy than the reactants, leading to a positive ΔH . These diagrams help visualise the energy barriers and the effect of catalysts in lowering the activation energy.

If the overall enthalpy of the products is greater than the enthalpy of the reactants, the system has gained energy (ΔH is positive) and the reaction is **endothermic**. The energy profile diagram below shows the increase of energy in the system. The horizontal axis (x-axis) represents the reaction pathway, and the vertical axis (y-axis) represents the total thermal energy of the system (H). The Activation Energy of the system is represented in the diagram as E_a .

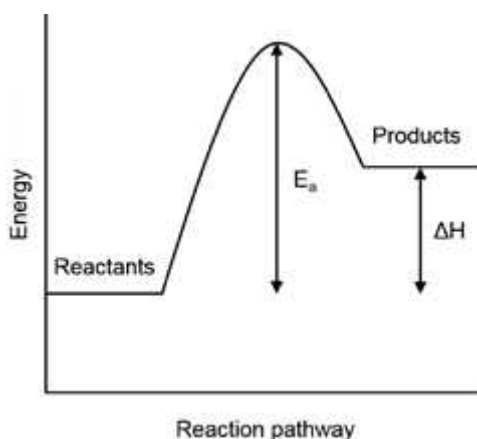


Figure 2.1.5: Energy profile diagrams for an endothermic chemical reaction.

If the overall enthalpy of the products is less than the enthalpy of the reactants, the system has lost energy (ΔH is negative) and the reaction is **Exothermic**. The energy profile diagram below shows the decrease of energy in the system.

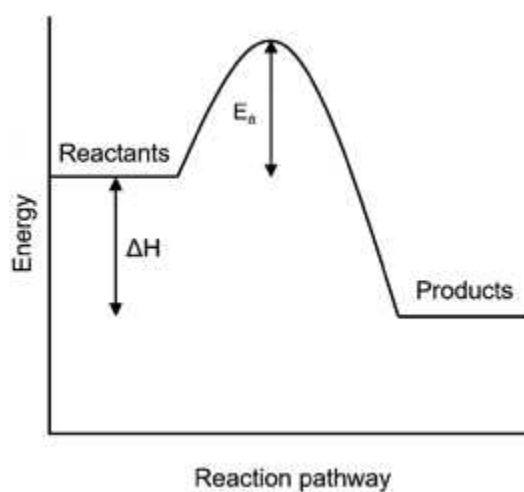


Figure 2.1.6: Energy profile diagrams for an exothermic chemical reaction.

The energy profile diagram for an exothermic reaction with and without a catalyst can be seen below.

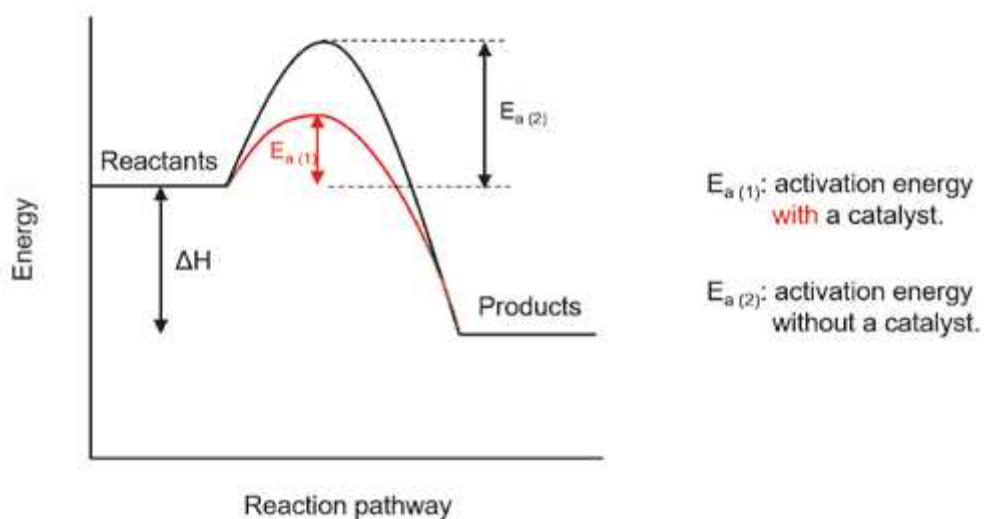


Figure 2.1.7: Energy profile diagram for an exothermic reaction showing the activation energy barriers for the catalysed and uncatalysed reaction pathways.

Note that the reaction with the catalyst provides an alternate pathway with a lower activation energy.

Question

6. In fireworks, magnesium is commonly used in the form of a fine powder or ribbons. When ignited, magnesium burns with a bright white light, making it an essential component in many pyrotechnic displays. The intense white light is due to the high energy released during the exothermic reaction between magnesium and oxygen in the air.

This reaction produces solid magnesium oxide (MgO) and releases a significant amount of energy in the form of heat and light. The brightness of the magnesium flame is attributed to the high temperature of the reaction, which can reach up to 3,100°C.

- (a) **Write** the balanced chemical equation for magnesium reacting with oxygen gas.

(1 mark) **KA1**

- (b) **Explain** how the rate of reaction is increased when powdered magnesium is used instead of magnesium strips.

(3 marks) **KA1**

To ignite the magnesium in fireworks, a fuse is first lit.

- (c) **Explain** the purpose of the fuse.

(3 marks) **KA2**

- (d) **Explain** why the fuse is no longer needed for the reaction once it is lit.

(2 marks) **KA2**

- (e) **Draw** an energy profile diagram to represent the effect of a catalyst being used in the reaction between magnesium and oxygen.

(3 marks) **KA1**

2.2 Equilibrium and yield

Science understanding

Chemical systems may be open or closed.

Over time, reversible chemical reactions carried out in a closed system at fixed temperature eventually reach a state of chemical equilibrium.

The changes in concentrations of reactants and products, as a system reaches equilibrium, can be represented graphically.

Draw and interpret graphs representing changes in quantities or concentration of reactants or products against time.

© SACE 2025

A chemical system can either be an open system or a closed system. An **open chemical system** is one where both chemical matter and energy can be transferred into and out of the system. A **closed chemical system** has no net loss or gain of matter and only energy can be transferred into and out of the system e.g., thermal energy, light energy.

An open chemical system is one in which both matter and energy can be exchanged with the surroundings. In an open system, reactants can be added, and products can be removed continuously. Examples of open systems include a beaker of water exposed to the atmosphere, where water molecules can evaporate and condense, or a chemical reaction taking place in a test tube without a stopper, allowing gases to escape.

On the other hand, a closed chemical system is one in which matter cannot be exchanged with the surroundings, but energy can be transferred in the form of heat or light. In a closed system, the total mass of the reactants and products remains constant. An example of a closed system is a sealed container with a chemical reaction occurring inside, such as a pressure tube used for organic synthesis or a sealed battery cell. The key difference between open and closed systems lies in the transfer of matter. In open systems, matter can be exchanged with the surroundings, while in closed systems, matter is conserved within the system. This distinction is important because it affects the behavior of chemical reactions. In a closed system, a reversible reaction can reach a state of chemical equilibrium where the forward and reverse reactions occur at equal rates, and the concentrations of reactants and products remain constant over time. In an open system, equilibrium cannot be established because the concentrations of reactants and products can change due to the exchange of matter with the surroundings.

Chemical reactions can be either **non-reversible reactions** or **reversible reactions**. A non-reversible reaction is one where the chemical reaction proceeds to completion.

Worked example

An example of a non-reversible reaction occurs when baking a cake. One of those reactions is between baking powder and water. The baking powder dissolves in water, releasing the acid and sodium bicarbonate present from their ionic structures and allowing them to react together. This reaction produces carbon dioxide gas which can be seen as the bubbles in your cake and what makes it rise. As the carbon dioxide leaves the chemical system this reaction has lost a product and so cannot proceed in the backward direction.

A reversible reaction is characterised by the fact that reactants can form products, and products can revert to reactants. In a closed system at a constant temperature, such reactions will reach a state of dynamic equilibrium. At equilibrium, the rates of the forward and reverse reactions are equal, resulting in constant concentrations of reactants and products.

Although the concentrations remain unchanged at equilibrium, the molecular processes of the forward and reverse reactions continue to occur.

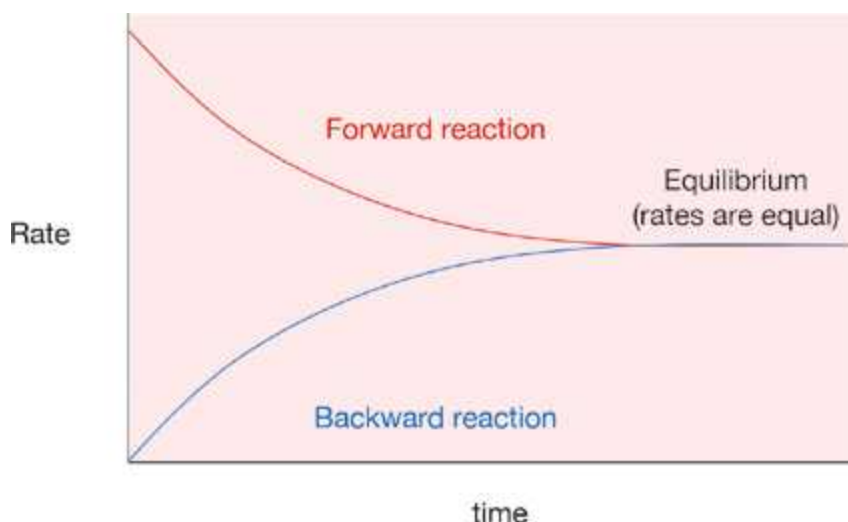
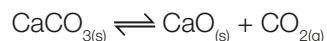


Figure 2.2.1: Rate of formation (forward reaction) and decomposition (backward reaction).

On the macroscopic level there is no observable change to the chemical system when it is in a state of equilibrium. However, on the atomic level there are reactants colliding producing products and products colliding producing reactants at the same rate.

Worked example

Lime or calcium oxide (CaO) is an important compound, and the industrial production of lime occurs according to the following chemical equation. Note the reversible arrow ($\rightleftharpoons$) used for an equilibrium reaction.



This reaction will eventually reach a state of equilibrium. At equilibrium, calcium carbonate is forming calcium oxide and carbon dioxide. At the same time calcium oxide and carbon dioxide are reacting, producing calcium carbonate.

As a chemical reaction reaches equilibrium the concentrations of reactants and products can be represented graphically, showing the point at which equilibrium is reached. It is important to note that at this point the rate of the forward and backward reactions are equivalent. Hence there is no net change in concentration of reactants or products, indicated by parallel lines and a slope of 0. It is important to note that the reaction has not stopped.

The following graphical representation shows the previous equilibrium reaction for the formation of calcium oxide.

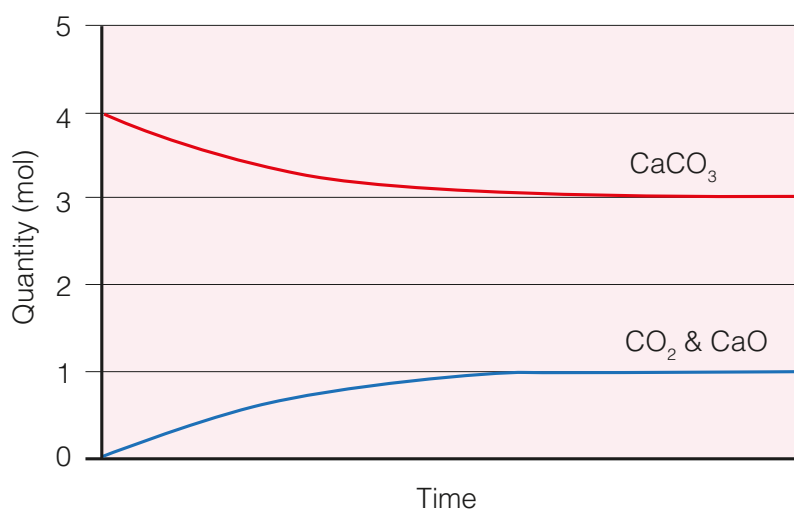


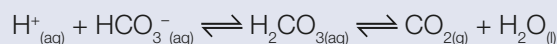
Figure 2.2.2: Changes in the molar quantities of calcium carbonate, carbon dioxide and calcium oxide in a reversible reaction at constant pressure and temperature.



Science as a human endeavour

The regulation of blood pH is a critical aspect of human physiology, as even slight deviations from the normal range (7.35-7.45) can have severe consequences for health. The body maintains blood pH within this narrow range through a complex interplay of chemical equilibrium reactions, involving various buffer systems, respiratory regulation, and renal compensation.

One of the primary buffer systems in the blood is the bicarbonate-carbonic acid buffer pair, which operates based on the following equilibrium reaction:



When blood pH drops below the normal range (acidosis), the concentration of H^+ ions is increased and this causes the equilibrium to shift to the right, consuming excess hydrogen ions (H^+) and raising the pH. Conversely, when blood pH rises above the normal range (alkalosis), the concentration of H^+ ions is decreased and this causes the equilibrium to shift to the left, releasing hydrogen ions and lowering the pH.

The respiratory system also plays a crucial role in regulating blood pH by controlling the concentration of dissolved CO_2 in the blood. When blood pH drops, the respiratory center in the brain is stimulated, leading to an increase in the rate and depth of breathing. This hyperventilation helps to expel more CO_2 from the body, which causes the equilibrium to shift to the right and raises the blood pH. On the other hand, when blood pH rises, the respiratory rate decreases, allowing more CO_2 to accumulate in the blood, which causes the equilibrium to shift to the left, thereby lowering the pH.

The kidneys provide long-term regulation of blood pH by adjusting the excretion of hydrogen ions and bicarbonate ions. In response to acidosis, the kidneys increase the excretion of hydrogen ions into the urine while reabsorbing more bicarbonate ions into the bloodstream. This process helps to raise blood pH by removing excess acid and retaining base. During alkalosis, the kidneys increase the excretion of bicarbonate ions and reduce the excretion of hydrogen ions, effectively lowering blood pH.

The intricate balance of chemical equilibrium reactions in the blood, along with the coordinated actions of the respiratory and renal systems, ensures that blood pH remains within the optimal range for proper physiological function. Understanding these equilibrium processes is crucial for medical professionals in diagnosing and treating acid-base disorders, which can arise from various underlying health conditions.

Question

7. (a) Identify the key SHE descriptor that is most applicable to the regulation of blood pH through chemical equilibrium. Justify your choice by referring to the information provided.

..
..
..

.....
.....
.....

(3 marks)

- (b) With reference to the bicarbonate-carbonic acid buffer system, explain how an understanding of chemical equilibrium principles can be applied in the diagnosis and treatment of acid-base disorders.

..
..
..
..

.....
.....
.....
.....

(4 marks)

Science understanding

The position of equilibrium in a chemical system at a given temperature can be indicated by a constant, K_c , related to the concentrations of reactants and products.

Write K_c expressions that correspond to given reaction equations for homogeneous equilibrium systems.

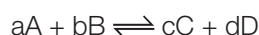
Undertake calculations involving K_c and initial and/or equilibrium quantities of reactants and products for homogeneous equilibrium systems.

© SACE 2025

The equilibrium constant, K_c , is used to indicate the position of equilibrium at a given temperature. The expression for K_c is given below.

$$K_c = \frac{[\text{products}]}{[\text{reactants}]}$$

Given a reaction between A and B, forming C and D.



An equilibrium equation can be written to represent the equilibrium constant for the above reaction.

$$K_c = \frac{[C]^c \cdot [D]^d}{[A]^a \cdot [B]^b}$$

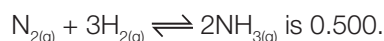
The position of chemical equilibrium can be determined by the K_c value. Understanding the position of equilibrium is useful for identifying whether the products or reactants have the greater concentration.

A K_c much greater than 1 indicates that the concentration of the products is greater than reactants, so the forward reaction is being favoured and the position of equilibrium lies to the right.

A K_c much less than 1 indicates that the concentration of the reactants is greater than products, so the backward reaction is being favoured and the position of equilibrium lies to the left.

Worked example

At 430°C, the equilibrium constant K_c for the reaction



If a mixture at equilibrium contains 0.200 mol L⁻¹ of H₂ and 0.300 mol L⁻¹ of NH₃, calculate the concentration of N₂ in the mixture.

Step 1: Write the equilibrium constant expression for the reaction.

$$K_c = \frac{[NH_3]^2}{[N_2][H_2]^3}$$

Step 2: Substitute the known values into the equilibrium constant expression and solve for [N₂].

$$0.500 = \frac{(0.300)^2}{[N_2](0.200)^3}$$

$$0.500 = \frac{0.090}{[N_2] 0.008}$$

$$0.500 \times 0.008 [N_2] = 0.090$$

$$0.004[N_2] = 0.090$$

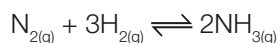
$$\frac{[N_2] = 0.090}{0.004}$$

$$[N_2] = 22.5 \text{ mol L}^{-1}$$

Therefore, the concentration of N₂ at equilibrium is 22.5 mol L⁻¹.

Worked example

Consider a reaction between nitrogen and hydrogen forming ammonia.



The expression for this reaction is shown below:

$$K_c = \frac{[\text{NH}_3]^2}{[\text{N}_2]^1 \cdot [\text{H}_2]^3}$$

The concentrations of the species in this reaction are recorded below, showing the change in concentration once equilibrium is reached.

	N_2	3H_2	2NH_3
Initial concentration (mol L^{-1})	0.600	0.400	1.00
Change in concentration (mol L^{-1})	- 0.016	- 0.048	+ 0.032
Concentration at equilibrium (mol L^{-1})	0.584	0.352	1.032

K_c for these quantities can be calculated by substituting the concentration values into the expression shown above.

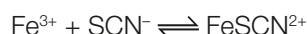
$$\begin{aligned} \therefore K_c &= \frac{[1.032]^2}{[0.584]^1 \cdot [0.352]^3} \\ \therefore K_c &= \frac{1.065024}{0.584 \times 0.04361421} \\ \therefore K_c &= 41.8 \text{ (3sf)} \end{aligned}$$

Note that the value for K_c has no units as it is a constant.

This K_c value indicates that the position of equilibrium lies to the right of the arrow, favouring the products.

Worked example

Consider the reaction between iron (III) ions (Fe^{3+}) and thiocyanate ions (SCN^-) producing iron thiocyanate ions (FeSCN^{2+}).



A 100 mL sealed reaction vessel is used and to it is added 5.04×10^{-4} mol of Fe^{3+} and 2.14×10^{-3} mol of SCN^- . At equilibrium it is determined that the reaction vessel contained 4.00×10^{-4} mol of FeSCN^{2+} .

These values are placed into the table below to calculate the equilibrium moles of Fe^{3+} and SCN^- .

	Fe^{3+}	SCN^-	FeSCN^{2+}
Initial moles	5.04×10^{-4}	2.14×10^{-3}	0.00
Change in moles			
Equilibrium moles			4.00×10^{-4}

The number of moles of FeSCN^{2+} has increased by 4.0×10^{-4} mol.

	Fe^{3+}	SCN^-	FeSCN^{2+}
Initial moles	5.04×10^{-4}	2.14×10^{-3}	0.00
Change in moles			+ 4.00×10^{-4}
Equilibrium moles			4.00×10^{-4}

To calculate the number of moles at equilibrium for the reactants, the stoichiometric ratio is used.

The ratio of FeSCN^{2+} to both reactants is 1:1, therefore if there is an increase of 4.0×10^{-4} mol to the products, there will be a decrease of 4.0×10^{-4} mol for both reactants.

	Fe^{3+}	SCN^-	FeSCN^{2+}
Initial moles	5.04×10^{-4}	2.14×10^{-3}	0.00
Change in moles	$- 4.00 \times 10^{-4}$	$- 4.00 \times 10^{-4}$	$+ 4.00 \times 10^{-4}$ mol
Equilibrium moles			4.00×10^{-4} mol

The number of moles at equilibrium for both reactants can now be determined by subtracting 4.00×10^{-4} moles from both initial mole values.

	Fe^{3+}	SCN^-	FeSCN^{2+}
Initial moles	5.04×10^{-4}	2.14×10^{-3}	0.00
Change in moles	$- 4.00 \times 10^{-4}$	$- 4.00 \times 10^{-4}$	$+ 4.00 \times 10^{-4}$
Equilibrium moles	1.04×10^{-4}	1.74×10^{-3}	4.00×10^{-4}

The reaction vessel is 100 mL in capacity and this is used to calculate the concentrations of all species. The number of moles at equilibrium for all species are divided by 0.100 L to calculate the concentrations in mol L^{-1} .

	Fe^{3+}	SCN^-	FeSCN^{2+}
Equilibrium moles	1.04×10^{-4}	1.74×10^{-3}	4.00×10^{-4}
Concentration at equilibrium (mol L^{-1})	$\frac{1.04 \times 10^{-4}}{0.100}$ $= 1.04 \times 10^{-3}$	$\frac{1.74 \times 10^{-3}}{0.100}$ $= 1.74 \times 10^{-2}$	$\frac{4.00 \times 10^{-4}}{0.100}$ $= 4.00 \times 10^{-3}$

Now that the concentrations at equilibrium are known, the value can be determined.

$$\therefore K_c = \frac{[\text{FeSCN}^{2+}]^1}{[\text{Fe}^{3+}]^1 \cdot [\text{SCN}^-]^1}$$

$$\therefore K_c = \frac{4.0 \times 10^{-3}}{1.04 \times 10^{-3} \times 1.74 \times 10^{-2}}$$

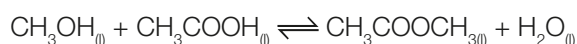
$$\therefore K_c = 221 \text{ (3sf)}$$

The K_c value of 221 is much greater than 1 which indicates that the concentration of FeSCN^{2+} ions is greater than the net concentration of Fe^{3+} ions and SCN^- ions. Therefore, the formation of "products" being favoured and the position of equilibrium lies to the right.

Question

8. One common example of an esterification reaction is the formation of ethyl ethanoate (also known as ethyl acetate) from ethanol and ethanoic acid (also known as acetic acid).

Ethyl ethanoate is a widely used solvent in various applications, such as in the production of nail polish removers, glues, and printing inks. It is also used as a flavouring agent in the food industry, particularly in the production of confectionery and baked goods. 1.2 mol of ethanol (CH_3OH) and 1.2 mol of ethanoic acid (CH_3COOH) are placed into an empty 200 mL vessel and react to form the ester ethyl ethanoate ($\text{CH}_3\text{COOCH}_3$) and water (H_2O) according to the following equation.



- (a) **Write** the equilibrium expression for the reaction.

(1 mark) **KA4**

At equilibrium, the mixture is found to contain 0.5 mol of $\text{CH}_3\text{COOCH}_3$.

(b) **Calculate** the concentration of ethanol at equilibrium.

(3 marks) **KA4**

(c) **Calculate** the value of the equilibrium constant, K_c .

(2 marks) **KA4**

2

Science understanding

The final equilibrium concentrations, and hence position of equilibrium, for a given reaction depend on various factors. Predict and explain, using Le Châtelier's principle, the effect on the equilibrium position of a system of a change in the:

- concentration of a reactant or product
- overall pressure of a gaseous mixture
- temperature of an equilibrium mixture for which the ΔH value for the forward or back reaction is specified.

Predict the change that occurred in a system, or whether a reaction is exothermic or endothermic, given the effect of the change on the equilibrium position of the system.

© SACE 2025

In a closed system, equilibrium reactions are in a state of dynamic equilibrium and there is no change in the concentrations of species. If an external change is introduced to the equilibrium system, the system will attempt to counteract the change. According to Le Châtelier's principle the system will shift the position of equilibrium in order to counteract the change that is placed upon it, allowing the system to re-establish equilibrium.

The position of equilibrium can be affected by the following factors:

- **Concentration**
- **Pressure**
- **Temperature**

It is important to note that the addition of a catalyst will not alter the position of a system in equilibrium. A catalyst alters the rate of the chemical reaction and thus the rate of both the forward and backward reaction would change equally, it would therefore have no net effect on equilibrium and reach a state of equilibrium faster.

In the presence of a catalyst, the rates of both the forward and reverse reactions increase equally. This is because the catalyst affects the activation energy of both the forward and reverse reactions to the same extent. As a result, the catalyst does not alter the equilibrium position or the equilibrium constant (K_c) of a reversible reaction. The equilibrium constant is determined by the ratio of the rate constants of the forward and reverse reactions, which are not affected by the presence of a catalyst. The effect of a catalyst on the reaction rate can be visualised using energy profile diagrams. In the presence of a catalyst, the activation energy is lowered, resulting in a smaller energy barrier for both the forward and reverse reactions. This leads to an increase in the rates of both reactions. Although a catalyst does not change the equilibrium position, it allows the system to reach equilibrium faster.

By increasing the rates of both the forward and reverse reactions, a catalyst enables the system to quickly attain the dynamic balance between reactants and products, characteristic of the equilibrium state.

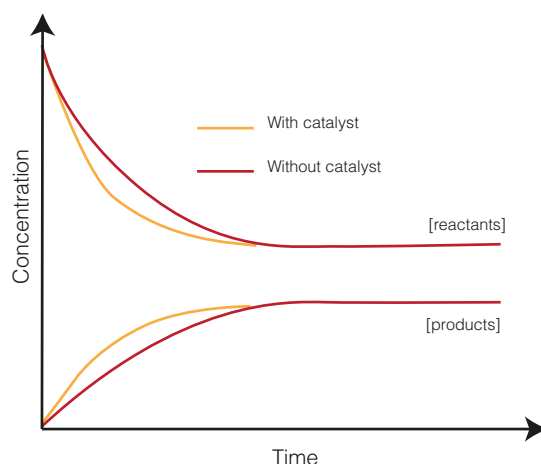


Figure 2.2.3: Effect of the presence of a catalyst on the system reaching a state of equilibrium.

Changes in concentration

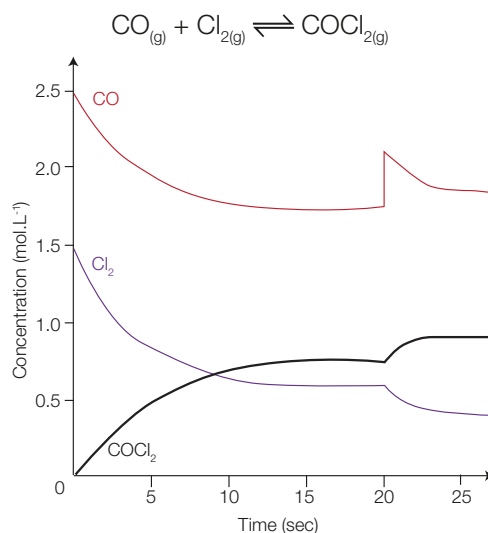
The position of equilibrium is affected if the concentration of one of the reactants is altered when a system is in a state of equilibrium.

If the concentration of a reactant is increased by adding more of the substance to the equilibrium mixture, the system will counteract the introduced change placed on the equilibrium mixture by attempting to reduce the concentration of that reactant. This will result in the forward reaction being favoured in order to convert reactants into products, shifting the position of equilibrium to the right until equilibrium is re-established.

If the concentration of a reactant is decreased by removing some of the substance from the equilibrium mixture, the system will counteract the introduced change placed on the equilibrium mixture by attempting to increase the concentration of that reactant. This will result in the backward reaction being favoured to create more of the lost reactant by converting products into reactants, shifting the position of equilibrium to the left until equilibrium is re-established.

Worked example

The effect of an increase in concentration can be seen in the reaction pathway diagram below representing the reaction between carbon monoxide (CO) and chlorine gas (Cl_2), forming COCl_2 .



At $t = 20$ seconds the concentration of CO is increased which introduces a change to the system at equilibrium. According to Le Châtelier's principle the system will attempt to counteract the change in concentration by reducing the concentration of CO. This will result in the forward reaction being favoured in order to convert reactants into products, shifting the position of equilibrium to the right until equilibrium is re-established. Therefore, resulting in the concentration of Cl_2 decreasing and COCl_2 increasing as can be seen in the diagram.

Summary of concentration changes to equilibrium mixtures

Introduced change at equilibrium	Effect on K_c	Effect on the position of equilibrium
Increase in concentration of reactant	No change	Shifts the position of equilibrium in the direction that reduces the reactant concentration (right)
Decrease in concentration of reactant	No change	Shifts the position of equilibrium in the direction that increases the reactant concentration (left)
Increase in concentration of product	No change	Shifts the position of equilibrium in the direction that reduces the product concentration (left)
Decrease in concentration of product	No change	Shifts the position of equilibrium in the direction that increases the product concentration (right)

Summary of concentration changes on a reaction pathway diagram

Change observed	Change to system
Sharp increase in concentration of one substance	Increase in concentration of one substance
Sharp decrease in concentration of one substance	Decrease in concentration of one substance

Changes in pressure

The position of equilibrium is affected if the pressure of the closed system is altered when a system is in a state of equilibrium.

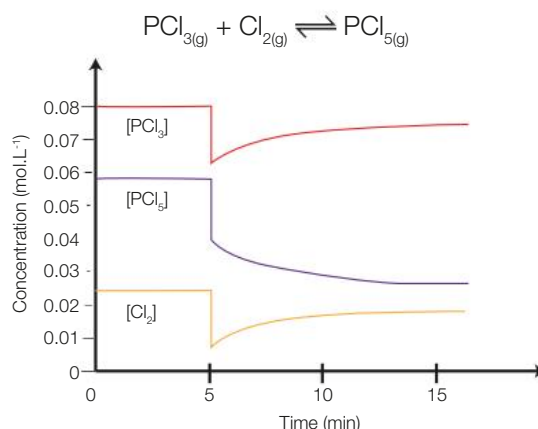
If the pressure of a system is increased by reducing the volume of the reaction vessel, the system will counteract the introduced change placed on the equilibrium mixture by attempting to reduce the pressure of the system. Le Châtelier's principle states that the reduction in pressure is achieved by shifting to the side of the equation which results in the formation of the least moles of gaseous particles until equilibrium is re-established.

If the pressure of a system is decreased by increasing the volume of the reaction vessel, the system will counteract the introduced change placed on the equilibrium mixture by attempting to increase the pressure of the system. Le Châtelier's principle states that the increase in pressure is achieved by shifting to the side of the equation which results in the formation of the most moles of gaseous particles until equilibrium is re-established.

If the number of moles of gaseous particles is equivalent on both sides of the reaction, there is no change to the position of equilibrium.

Worked example

The effect of a decrease in pressure can be seen in the reaction pathway diagram below representing the reaction between phosphorous trichloride (PCl_3) and chlorine gas (Cl_2), forming phosphorous pentachloride (PCl_5).



From the diagram above it can be concluded that at $t = 5$ mins the concentration of all species has decreased due to an increase in volume and therefore a decrease in pressure. According to Le Châtelier's principle the system will counteract the introduced change placed on the equilibrium mixture by attempting to increase the pressure. The increase in pressure is achieved by shifting to the side of the equation which results in the formation of the

most moles of gaseous particles until equilibrium is re-established. In the reaction the left hand side has 2 moles of gas whilst the right hand side has 1 mole of gas. Therefore, the position of equilibrium would shift to the left in the backward direction as this creates the most moles of gas. Therefore, increasing the concentrations of PCl_3 and Cl_2 and decreasing the concentration of PCl_5 .

Summary of pressure changes to equilibrium mixtures

Introduced change at equilibrium	Effect on K_c	Effect on the position of equilibrium
Increase in pressure of system	No change	Shifts the position of equilibrium in the direction of the production of fewer moles of gas
Decrease in pressure of system	No change	Shifts the position of equilibrium in the direction of the production of greater moles of gas

Summary of pressure changes on a reaction pathway diagram

Change observed	Change to system
Sharp increase in concentration of all gaseous species	Decrease in volume of reaction vessel Increase in pressure within reaction vessel
Sharp decrease in concentration of all gaseous species	Increase in volume of reaction vessel Decrease in pressure within reaction vessel

Changes in temperature

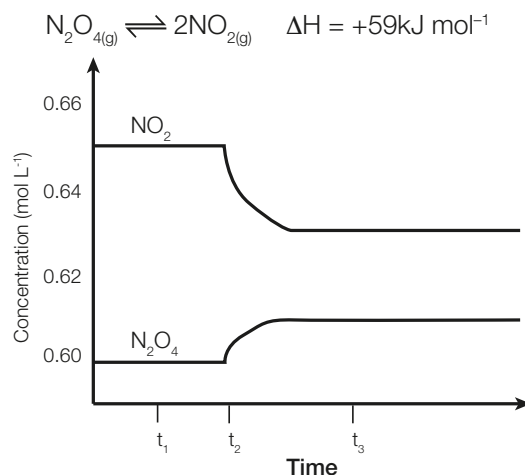
The position of equilibrium is affected if the temperature (thermal energy) of the closed system is altered when a system is in a state of equilibrium. According to Le Châtelier's principle the system will attempt to counteract the change in temperature with respect to the change that is applied. The direction in which the position of equilibrium responds is dependent on the ΔH value for the reaction. Note that the ΔH value is always in reference to the forward reaction.

If the temperature of a system is increased, the system will counteract the introduced change placed on the equilibrium mixture by absorbing the additional thermal energy. Le Châtelier's principle states that the increase in temperature leads to the position of equilibrium shifting in the endothermic (ΔH is positive) direction, absorbing the thermal energy.

If the temperature of a system is decreased, the system will counteract the introduced change placed on the equilibrium mixture by releasing thermal energy. Le Châtelier's principle states that the decrease in temperature leads to the position of equilibrium shifting in the exothermic (ΔH is negative) direction, releasing thermal energy.

Worked example

The effect of a decrease in temperature can be seen in the reaction pathway diagram below representing the dynamic equilibrium between N_2O_4 and NO_2 .



From the diagram above it can be concluded that the change that occurred resulted in the production of N_2O_4 being favoured which is the backward reaction. The enthalpy given for this reaction is positive, indicating that the

forward reaction is endothermic and hence the backward is exothermic. According to Le Châtelier's principle, the exothermic reaction is favoured when the temperature of the reaction mixture is decreased. This will result in the backward reaction being favoured in order to release energy, shifting the position of equilibrium in the backward direction until equilibrium is re-established.

Effect of introduced changes to system at equilibrium on K_c value

It is important to note that the value of K_c for a given temperature is unchanged. If an introduced change to a system at equilibrium was on the concentration of species the K_c value would remain unchanged. Likewise, if the introduced change to the system at equilibrium was on the pressure of the system the K_c would also remain unchanged.

The value is only altered due to temperature changes in the system. The table below shows that as the temperature changes, the value also changes for the chemical reaction below.

Temperature (°C)	K_c
25	4.64×10^{-3}
127	1.53

As the temperature decreases from 127°C to 25°C, the K_c value also decreases, indicating that the reactants N_2O_4 have the greater concentration.

Summary of temperature changes to equilibrium mixtures

Introduced change at equilibrium	Effect on K_c	Effect on the position of equilibrium
Increase in system temperature	Changes	Shifts the position of equilibrium in the Endothermic direction
Decrease in system temperature	Changes	Shifts the position of equilibrium in the Exothermic direction

Summary of temperature changes on a reaction pathway diagram

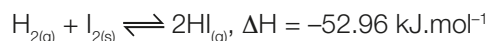
Change observed	Change to system
Gradual changes	Increase or decrease in temperature of the system

Question

9. In the atmosphere, hydrogen iodide can be formed through the reaction of hydrogen gas with iodine gas, especially in areas with volcanic activity or in marine environments where iodine is naturally present.

This reaction contributes to the cycling of iodine compounds in the environment.

Hydrogen gas (H_2) reacts with iodine (I_2), forming hydrogen iodide (HI) according to the following reaction equation.



0.3 mol of I_2 is reacted with 0.5 mol of H_2 in a 100 mL vessel and at equilibrium the number of moles of HI is found to be 0.2 mol.

- (a) **Calculate** the equilibrium concentration of I_2 .

(3 marks) **KA4**

- (b) **Calculate** the K_c value for the above reaction at equilibrium.

(3 marks) **KA4**

- (c) **Explain** the effect on the position of equilibrium if the vessel is decreased to 50 mL.

(3 marks) **KA1**

- (d) **Explain** the effect on the position of equilibrium if the temperature of the system is increased.

(3 marks) **KA1**

- (e) **State** the effect on the K_c value if the concentration of hydrogen gas is increased.

(1 mark) **KA1**

2.3 Optimising Production

Science understanding

Designing chemical-synthesis processes involves constructing reaction pathways that may include more than one chemical reaction.

The steps in industrial chemical processes can be conveniently displayed in flow charts.

Interpret flow charts and use them for such purposes as identifying raw materials, chemicals present at different steps in the process, waste products, and by-products.

© SACE 2025

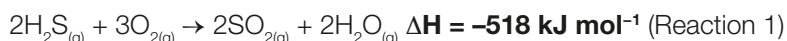
Industrial chemists and engineers around the world use chemical principles to identify and design the ideal reaction conditions and pathways for chemical reactions. These reaction pathways may involve multiple chemical reactions occurring. The steps involved in reaction pathways can be represented in a flow chart for a common process to show the key reactions necessary in industrial processes.

The key components of industrial chemical process flow charts are as follows:

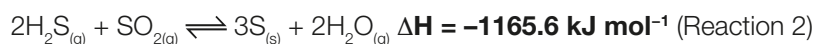
- **Raw Materials** are added into the reaction pathway
- **By-products** are substances produced which are either reused in the reaction pathway or collected and used for another purpose.
- **Waste Products** are those which are disposed of or released into the environment.

Worked example

The Claus process is used in the petroleum industry to recover elemental sulfur from hydrogen sulfide (H_2S) gas produced during the refining of crude oil. The process involves a series of reactions, the first of which is the combustion of H_2S to form sulfur dioxide (SO_2) and water:



The SO_2 then reacts with the remaining H_2S to produce elemental sulfur and water:



Reaction 2 is an equilibrium reaction, and the yield of sulfur is limited by the equilibrium constant at the given temperature. To maximise sulfur recovery, the Claus process is typically carried out in multiple stages, with each stage operating at a different temperature to shift the equilibrium position and drive the reaction towards the production of sulfur.

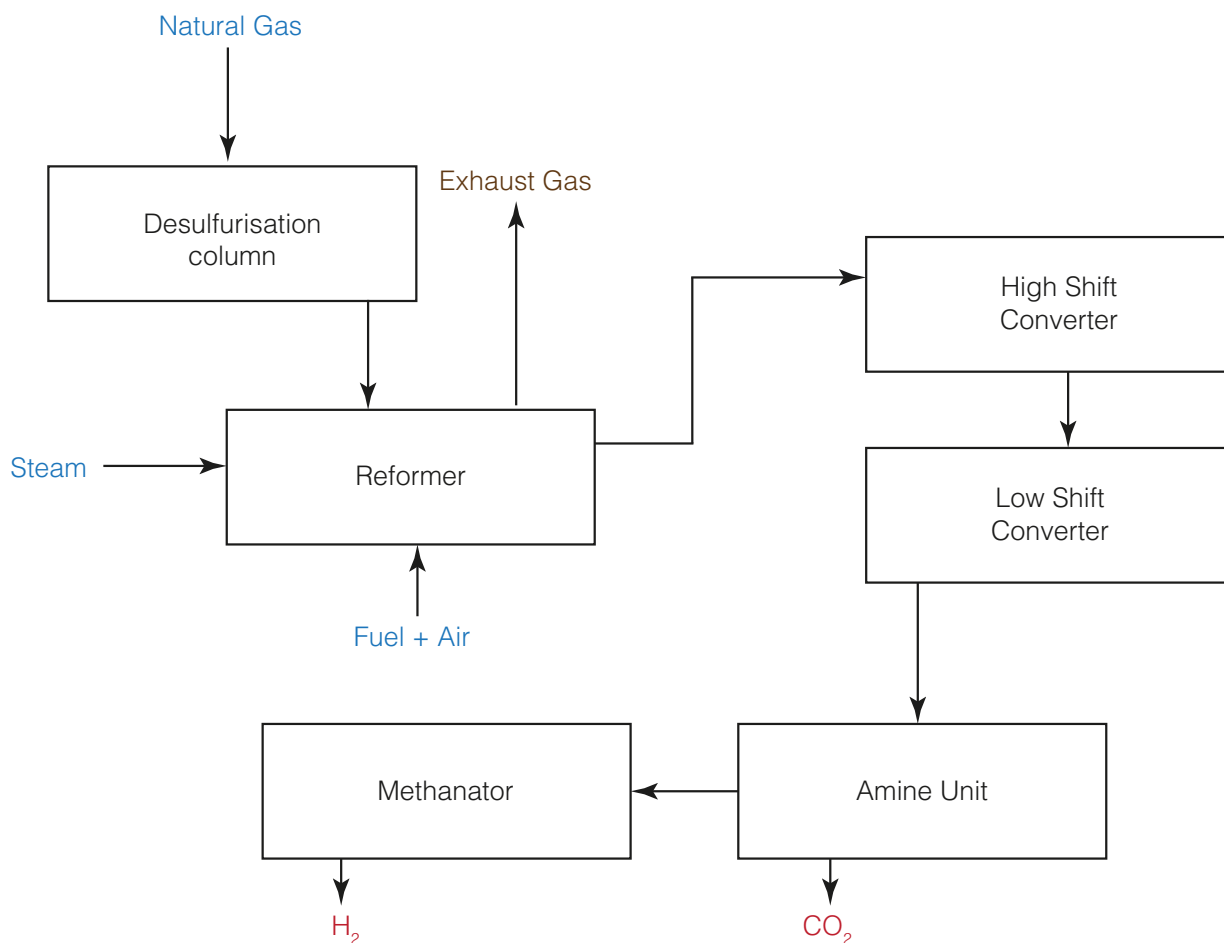
In the first stage, Reaction 2 is carried out at a high temperature ($1000\text{--}1400^\circ\text{C}$) to produce a molten sulfur product. However, the high temperature favours the backward reaction. The molten sulfur is cooled and collected, and the remaining gases are sent to the next stage.

In the subsequent stages, the temperature is lowered to around $200\text{--}350^\circ\text{C}$, which shifts the equilibrium position towards the formation of S and H_2O . By using a series of reactors at progressively lower temperatures, the Claus process can achieve an overall sulfur recovery of up to 97%.

This optimises the industrial process. By carefully controlling the temperature at each stage of the process, engineers can maximise the yield of the desired product (sulfur) while minimising the release of harmful byproducts (H_2S and SO_2) into the environment. This not only improves the efficiency and profitability of the process but also helps to reduce its environmental impact.

Blue hydrogen gas production involves using methane gas (CH_4) as the main chemical feedstock whilst green hydrogen gas production receives its energy from 100 percent renewable sources e.g. solar energy, wind energy, hydroelectric energy.

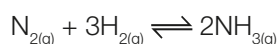
The following flow chart represents the industrial production of blue hydrogen gas.



In this reaction pathway Natural Gas (CH₄) is a raw material along with steam, fuel and air. CO₂ Rich and Exhaust Gas are classified as waste products.

Worked example

The Haber process for producing ammonia is a prime example of how industrial reaction conditions can have significant environmental impacts.



This process typically operates at temperatures between 400-450°C and pressures of 150-200 atm to achieve a commercially viable yield of ammonia.

However, these high temperature and pressure conditions come with substantial energy costs. The Haber process consumes about 1-2% of the world's total energy production, largely due to the need to compress the reactant gases to such high pressures. This energy is often derived from burning fossil fuels, which releases CO₂ into the atmosphere and contributes to global warming.

Additionally, the hydrogen gas used in the process is usually obtained from steam reforming of methane (natural gas), which also produces CO₂ as a byproduct. The CO₂ emissions from ammonia production via the Haber-Bosch process account for about 1% of global CO₂ emissions.

While the Haber process has revolutionised agriculture and allowed for the production of food for billions of people, it is clear that the high temperature and pressure conditions used have a significant environmental footprint.

Researchers are actively seeking ways to modify the process to reduce its energy consumption and associated CO₂ emissions, such as by developing more efficient catalysts that can operate at lower temperatures and pressures.

This example highlights the importance of considering the environmental impacts when designing and optimising industrial chemical processes. While it may be tempting to focus solely on maximising yield and profitability, the long-term sustainability and global consequences of the chosen reaction conditions must also be taken into account.



Science as a human endeavour

Scientists at the Tokyo Institute of Technology have developed a new catalyst that can facilitate the production of ammonia from nitrogen and water at ambient temperatures and pressures. This catalyst, composed of titanium dioxide and ruthenium nanoparticles, has the potential to revolutionise the ammonia production industry by providing a more environmentally friendly and energy-efficient alternative to the traditional Haber-Bosch process.

The Haber process, which has been the primary method of ammonia production for over a century, requires high temperatures (400-450°C) and pressures (150-300 atm) to achieve a commercially viable yield. These harsh conditions necessitate a significant energy input, often derived from fossil fuels, leading to substantial CO₂ emissions. In contrast, the new catalyst enables ammonia synthesis at room temperature and pressure, significantly reducing the energy requirements and carbon footprint of the process.

Furthermore, the new catalyst allows for the use of water as a hydrogen source instead of relying on fossil fuel-derived hydrogen. This innovation opens up the possibility of using renewable energy sources, such as solar or wind power, to generate the electricity needed for water electrolysis, making the entire process more sustainable.

The development of this catalyst is a prime example of how scientific research can lead to technological advancements that address global challenges, such as the need for sustainable food production and the reduction of greenhouse gas emissions. As the world's population continues to grow, the demand for ammonia-based fertilisers is expected to increase. This new catalyst offers a promising solution to meet this demand while minimising the environmental impact of ammonia production.

2

Question

10. (a) Identify the SHE descriptor(s) that best relate to the development of the new catalyst for sustainable ammonia production. Explain your answer with reference to the information provided.

..

(3 marks)

- (b) Explain the significance of this new catalyst in addressing the increasing global demand for ammonia-based fertilisers while minimising the environmental impact of ammonia production.

..

(4 marks)

Science understanding

Industrial processes are designed to maximise profit and to minimise impact on the environment.

Explain how certain reaction conditions represent a compromise that will give maximum yield in a short time.

Explain the impact of increases in temperature and pressure on manufacturing conditions and costs, and on the environment.

Explain how use of a catalyst may benefit both the manufacturer and the environment.

© SACE 2025

In industry compromises in reaction conditions are made to balance various aspects of chemical processes. This is done to maximise profits whilst minimising the impact on the environment. If the reaction rate is high, this will ensure that the products the industry are seeking are produced in the minimum time. An example of how this could increase profits is that it would result in the product being available for the consumer sooner and less money being spent on wages for their workers.

Yield

The quantity of product formed during a process is referred to as **yield**. The yield of a chemical reaction refers to the efficiency of the reaction.

Theoretical Yield refers to the quantity of product that is expected to be obtained using stoichiometric quantities.

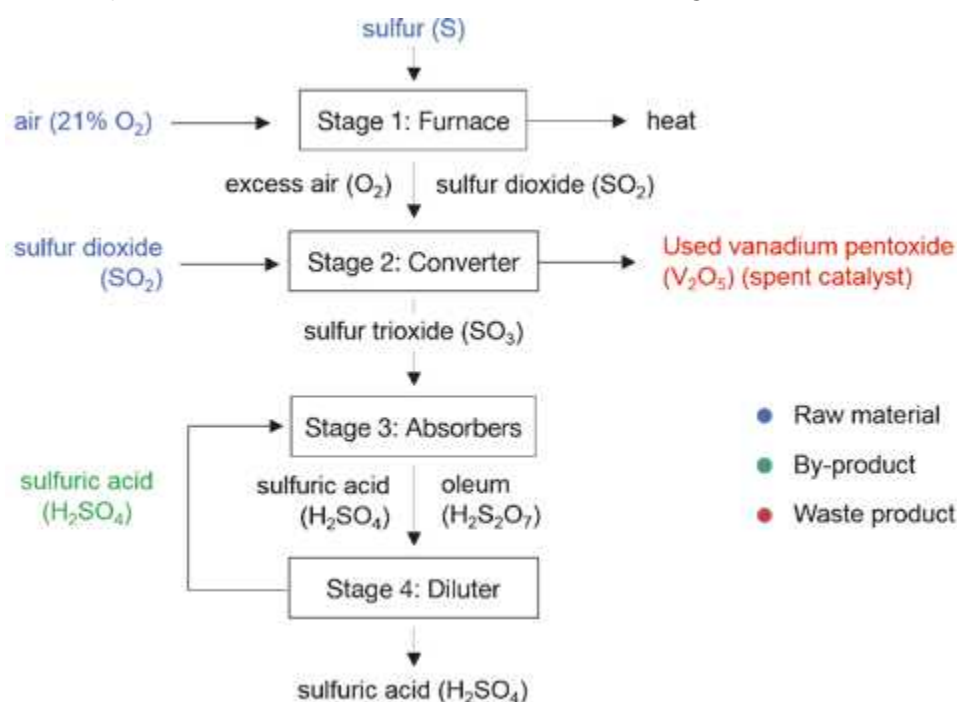
Actual Yield refers to the quantity of product that was obtained through the chemical process.

Percentage Yield is the percent ratio of actual yield to theoretical yield is calculate using the expression below.

If the actual yield of the product is high by altering the position of equilibrium for the chemical process, this would result in an increase in profits. Unfortunately, achieving the maximum reaction rate and maximum yield is not always possible and the industry has to balance both factors to achieve the maximum profit.

Worked example

Consider the industrial production of sulfuric acid as shown in the flow diagram below.



The reaction equation most influenced by rate and equilibrium changes for the above process is the reaction between sulfur dioxide (SO₂) and oxygen (O₂) to produce sulfur trioxide (SO₃).

If the temperature of the reaction mixture is increased, this results in the average kinetic energy of the sulfur dioxide and oxygen molecules increasing and exhibiting more thermal energy. Therefore, there is a larger proportion of collisions between sulfur dioxide and oxygen molecules reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of formation of sulfur trioxide.

This reaction is an exothermic reaction as represented by the negative enthalpy value. If the temperature of the reaction mixture is increased, this would place an introduced change on the equilibrium system. According to Le Châtelier's Principle the system would attempt to counteract the introduced change by absorbing the excess energy. This is an endothermic process and so the position of equilibrium would shift in the endothermic direction, which is to the left, favouring the formation of reactants and reducing the yield of sulfur trioxide.

If the pressure of this system is increased, the system will counteract the introduced change placed on the equilibrium mixture by attempting to reduce the pressure of the system. Le Châtelier's principle states that the reduction in pressure is achieved by shifting to the side of the equation which results in the formation of the least moles of gaseous particles. Therefore, the position of equilibrium shifts to the right favouring the formation of sulfur trioxide molecules.

If a positive catalyst is introduced this would provide an alternative reaction pathway for the reacting particles with a lower Activation Energy. This results in a larger proportion of collisions between sulfur dioxide and oxygen molecules reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of formation of sulfur trioxide molecules.

Theoretical conditions	Actual Conditions	Explanation
Increase temperature leading to an increased rate of formation of SO_3	Moderate temperature (450°C)	An increased temperature will lead to the favouring of the backward reaction, reducing yield of SO_3 A moderate temperature is used as a compromise between rate and equilibrium
Increase pressure leading to the formation of less moles of gaseous particles and the reaction occurring at a faster rate, favours the formation of SO_3	Atmospheric pressure (1 atm)	Reaction vessels required for high pressures are costly to the manufacturer Achieving high pressure is an energy intensive process therefore energy costs are high
Alternative reaction pathway with a lower E_a leading to an increased rate of formation of SO_3	vanadium oxide (V_2O_5) catalyst	Vanadium oxide catalyst used to reduce production costs as the SO_3 is produced in a shorter amount of time

From this example it is evident that by increasing the rate of reaction through an increase in temperature, this would result in a reduction of yield of sulfur trioxide due to equilibrium principles. Therefore, industry finds a compromise between rate and equilibrium in order to maximise yield and subsequently maximise the profits. This reaction occurs industrially at atmospheric pressure (1 atm), at a moderate temperature of 450°C in the presence of a vanadium oxide (V_2O_5) catalyst, achieving a yield of 95%.



Science as a human endeavour

Flow chemistry is an emerging technology that is revolutionising the way chemicals and pharmaceuticals are synthesised. Unlike traditional batch processes, where reactants are mixed in a single vessel and allowed to react for a set time, flow chemistry involves the continuous flow of reactants through a series of interconnected reactors. This approach offers several advantages, including improved reaction control, enhanced safety, and increased efficiency.

In the pharmaceutical industry, flow chemistry is being used to streamline the production of active pharmaceutical ingredients (APIs) and to enable the synthesis of novel drug compounds. By precisely controlling reaction conditions, such as temperature, pressure, and residence time, flow chemistry allows for the optimisation of reaction rates and the minimisation of unwanted side products. This level of control is particularly important in the synthesis of complex pharmaceutical compounds, where even slight variations in reaction conditions can have a significant impact on product quality and yield.

The adoption of flow chemistry in the pharmaceutical industry has the potential to accelerate drug discovery and development, reduce manufacturing costs, and improve the flexibility and agility of the production process. As the technology continues to evolve, it is expected to play an increasingly important role in the future of pharmaceutical manufacturing.

Question

11. (a) Identify the key SHE descriptor that best aligns with the use of flow chemistry in the pharmaceutical industry. Explain your choice with reference to the information provided.

..

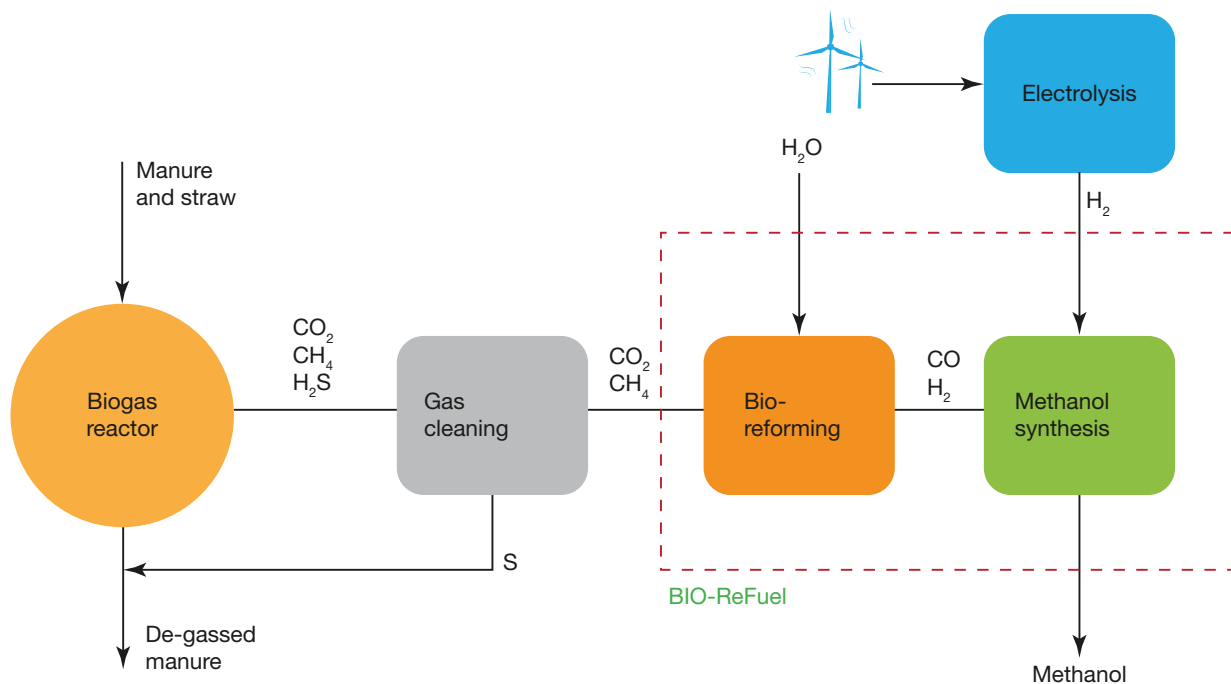
(3 marks)

- (b) Discuss the potential benefits of adopting flow chemistry in the pharmaceutical industry and the challenges that need to be addressed for its widespread implementation.

..

(4 marks)

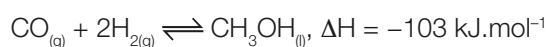
12. Methanol (CH_3OH) has many uses as a chemical or fuel and there are currently studies underway to obtain it through greener processes. The flow diagram for one of these processes is shown below.



- (a) **Identify** a raw material in this process.

(1 mark) **IAE3**

In order to form methanol, carbon monoxide (CO) and hydrogen (H_2) are reacted together at 350°C according to the following reaction equation.



- (b) **Write** the equilibrium expression for the reaction.

(1 mark) **KA4**

- (c) **Discuss**, using equilibrium principles, the optimum reaction conditions a manufacturer would use to favour the production of methanol.

(3 marks) **KA2**

(d) **Explain** why the use of a higher temperature is a compromise for the production of methanol.

(3 marks) **KA3**

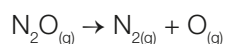
(e) **Explain** the effect on the yield of methanol if a catalyst is used.

(3 marks) **KA1**

2

Summary test 2: Managing chemical processes

1. Nitrous oxide (N_2O), also known as laughing gas, is a chemical compound used in various applications, including as an anaesthetic in medical procedures and as a fuel additive in motor racing. The decomposition of nitrous oxide into nitrogen and oxygen gases is a crucial process in understanding its behaviour and potential environmental impact.



In a laboratory experiment, the decomposition of nitrous oxide was studied by measuring the concentrations of N_2O , N_2 , and O over time. The data obtained from this experiment is presented in the table below:

Time (sec)	N_2O (mol L ⁻¹)	N_2 (mol L ⁻¹)	O (mol L ⁻¹)
0	1.00	0.00	0.00
20	0.82	0.18	0.18
40	0.67	0.33	0.33
60	0.55	0.45	0.45
80	0.45	0.55	0.55
100	0.37	0.63	0.63
120	0.30	0.70	0.70
140	0.25	0.75	0.75
160	0.21	0.79	0.79

- (a) (i) Identify the dependent variable for the decomposition reaction of N_2O .

(1 mark) **IAE1**

- (ii) Calculate the instantaneous rate of N_2O decomposition at 80 seconds using the data provided.

(3 marks) **KA4**

- (iii) Explain, using collision theory, why the decomposition of N_2O proceeds faster at the start of the experiment.

(3 marks) **KA2**

- (b) The decomposition of phosphorus pentachloride (PCl_5) into phosphorus trichloride (PCl_3) and chlorine gas (Cl_2) is an important reaction in the production of various organophosphorus compounds. The reaction can be represented as:



- (i) Write the equilibrium expression for the reaction.

(1 mark) **KA4**

- (ii) The equilibrium constant (K_c) values for the decomposition of PCl_5 at different temperatures are given below:

Temperature (°C)	K_c
250	1.8×10^{-3}
350	1.5×10^{-2}

- 1) Explain, referring to the K_c data, whether the decomposition of PCl_5 is an exothermic or endothermic process.

(3 marks) **KA4**

- 2) In a separate experiment at 250°C , the equilibrium concentrations of the reactants and products were measured:

PCl_5 (mol L^{-1})	PCl_3 (mol L^{-1})	Cl_2 (mol L^{-1})
0.0120	0.0336	0.0336

- (iii) Determine if the reaction is at equilibrium under these conditions.

(3 marks) **KA4**

- 1) In another experiment, 0.250 mol of PCl_5 was placed in a 2.00 L flask and allowed to reach equilibrium at 350°C . At equilibrium, the concentration of Cl_2 was found to be $0.0650 \text{ mol L}^{-1}$. Calculate the equilibrium concentration of PCl_5 . Give your answer to the correct number of significant figures.

(4 marks) **KA4**

- 2) Calculate K_c for this reaction at 350°C .

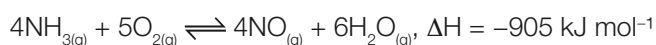
(2 marks) **KA4**

- 3) State the effect on the K_c value if the pressure of the system is increased.

(1 mark) **KA1**

2. The Ostwald process is an important industrial method for producing nitric acid (HNO_3), which is used in the manufacture of fertilisers, explosives, and other chemicals. The process involves the oxidation of ammonia (NH_3) to nitric oxide (NO), followed by the oxidation of NO to nitrogen dioxide (NO_2), and finally the absorption of NO_2 in water to form nitric acid.

The key reaction in the Ostwald process is the oxidation of ammonia:



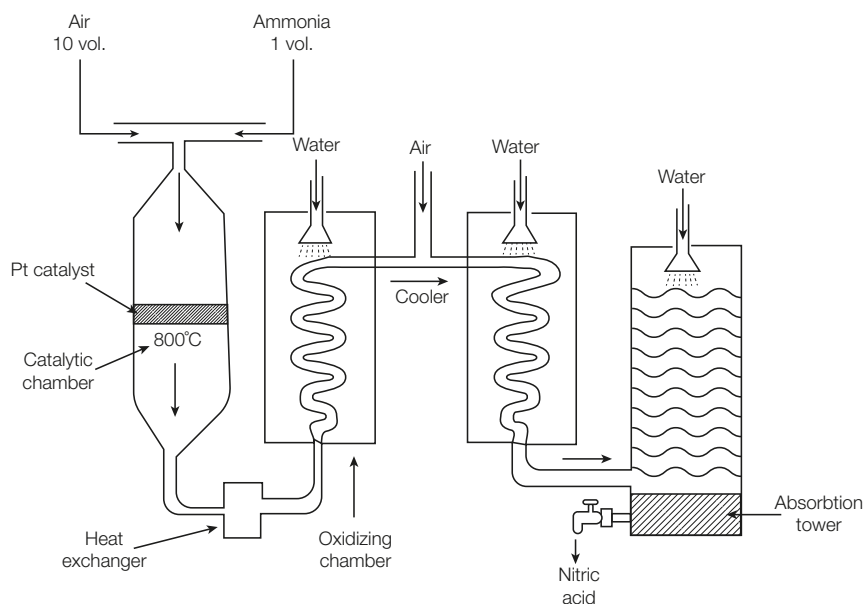
- (a) Explain why the oxidation of ammonia requires high temperatures (around 900°C) to proceed at an appreciable rate.

(3 marks) **KA1**

- (b) Discuss, using equilibrium principles, the optimum reaction conditions for maximising the yield of nitric oxide in the Ostwald process.

(4 marks) **KA2**

(c) A simplified flow chart of the Ostwald process is shown below:



(i) Identify a raw material used in this process other than ammonia.

(1 mark) **IAE3**

(ii) The oxidation of ammonia in the Ostwald process is carried out at temperatures around 900°C and pressures of 1-10 atm in the presence of a platinum-rhodium catalyst. Explain why these reaction conditions are considered a compromise for manufacturers.

(3 marks) **KA2**

(d) (i) Explain how the platinum-rhodium catalyst increases the reaction rate for the oxidation of ammonia.

(3 marks) **KA1**

(ii) Draw an energy profile diagram for the oxidation of ammonia, both in the presence and absence of the platinum-rhodium catalyst. Label E_a and ΔH using correct chemical conventions.

(4 marks) **KA4**

Researchers are investigating the use of perovskite-type oxides as alternative catalysts for the oxidation of ammonia in the Ostwald process. These catalysts have shown promise in reducing the reaction temperature while maintaining high selectivity for nitric oxide formation.

(iii) Using the concept of sustainability, explain how the development of more efficient catalysts for the Ostwald process could contribute to reducing the environmental impact of nitric acid production.

(4 marks) **KA3**

- (iv) In addition to reducing energy costs, explain why lowering the reaction temperature in the Ostwald process would be advantageous for nitric acid manufacturers in terms of the equilibrium yield of nitric oxide.

(3 marks) **KA2**

3. The Contact process is the primary industrial method for producing sulfuric acid (H_2SO_4), which is a crucial raw material in various industries, including fertiliser production, oil refining, and chemical synthesis. The key reaction in the Contact process is the oxidation of sulfur dioxide (SO_2) to sulfur trioxide (SO_3) using oxygen gas:



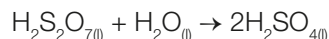
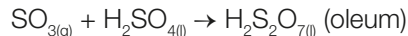
- (a) Explain, using Le Chatelier's principle, how an increase in pressure affects the equilibrium position of the reaction and the yield of sulfur trioxide.

(3 marks) **KA2**

- (b) In the Contact process, the oxidation of sulfur dioxide is carried out at temperatures around 400-450°C in the presence of a vanadium(V) oxide (V_2O_5) catalyst. Explain why a catalyst is essential for this process.

(2 marks) **KA2**

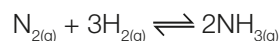
- (c) The recovery of sulfur trioxide and its subsequent conversion to sulfuric acid is a critical step in the Contact process. The incorporation of sulfur trioxide in concentrated sulfuric acid produces oleum, which is then diluted with water to form sulfuric acid:



Explain the purpose of concentrating the sulfuric acid through the above reaction.

(2 marks) **KA4**

4. The Haber-Bosch process, used for the industrial production of ammonia, relies on the recycling of unreacted nitrogen and hydrogen gases to maximise the overall yield of ammonia. In a typical Haber-Bosch plant, the conversion of nitrogen and hydrogen to ammonia per pass is only about 15%.



- (a) Explain why the recycling of unreacted gases is essential for the economic viability of the Haber-Bosch process.

(2 marks) **KA2**

- (b) In the Haber-Bosch process, the reaction mixture is cooled after exiting the reactor to condense the ammonia product. The remaining gases are then separated from the liquid ammonia and recycled back into the reactor. Explain how the introduction of recycled, unreacted N_2 and H_2 affects the equilibrium position of the reaction and the yield of ammonia.

(3 marks) **KA2**

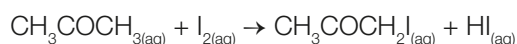
- (c) The purge gas is a small fraction of the recycled gas stream that is removed to prevent the build-up of inert gases, such as argon and methane, which can enter the system as impurities in the nitrogen and hydrogen feedstocks. The purge gas is usually used as a fuel in the reforming process to generate hydrogen.
- (i) Explain why the build-up of inert gases in the reaction mixture would be detrimental to the efficiency of the Haber-Bosch process.

(2 marks) **KA2**

- (ii) The purge gas contains valuable unreacted nitrogen and hydrogen. Propose a method for recovering these gases from the purge gas stream to improve the overall efficiency of the process.

(2 marks) **KA3**

5. The iodination of acetone is a second-order reaction that involves the formation of iodoacetone and hydroiodic acid. The reaction is often used in laboratory experiments to study reaction kinetics due to its moderate rate and easy monitoring by observing the disappearance of the brown colour of iodine.



In a laboratory experiment, a student investigated the effect of initial reactant concentrations on the rate of the iodination of acetone. The student prepared several reaction mixtures containing different initial concentrations of acetone and iodine, and measured the time taken for the brown colour of iodine to disappear. The results are shown in the table below:

Experiment	Initial $[\text{CH}_3\text{COCH}_3]$ (mol L ⁻¹)	Initial $[\text{I}_2]$ (mol L ⁻¹)	Time for I_2 colour to disappear (s)
1	0.100	0.0100	160
2	0.200	0.0100	80
3	0.100	0.0200	80
4	0.200	0.0200	40

- (a) Explain the effect of doubling the initial concentration of acetone on the rate of the reaction, keeping the initial concentration of iodine constant.

(2 marks) **KA2**

- (b) Explain the effect of doubling the initial concentration of iodine on the rate of the reaction, keeping the initial concentration of acetone constant.

(2 marks) **KA2**

- (c) The student repeated the experiment at a higher temperature and found that the time taken for the brown colour of iodine to disappear in Experiment 1 was reduced to 80 seconds. Explain, using the concept of activation energy, why the rate of the reaction increased with temperature.

(3 marks) **KA2**

6. Aspirin (acetylsalicylic acid) is a widely used pain reliever and anti-inflammatory drug that has been in use for over a century.

Aspirin was synthesised in 1897 by Felix Hoffmann, a chemist working for the German pharmaceutical company Bayer. Hoffmann was searching for a safer alternative to salicylic acid, which was known to have pain-relieving and anti-inflammatory properties but caused stomach irritation. By acetylating salicylic acid, Hoffmann created acetylsalicylic acid, which was found to have similar therapeutic effects but with reduced side effects.

Bayer began marketing aspirin as a prescription drug in 1899, and it quickly gained widespread use as a pain reliever and anti-inflammatory agent. During World War I, aspirin was used extensively to treat pain and fever among soldiers, further increasing its popularity. In the following decades, research continued to uncover new potential applications for aspirin, such as reducing the risk of heart attacks and certain types of cancer.

Today, aspirin is one of the most widely used medications in the world, with an estimated 50 to 120 billion tablets consumed annually. Although its use as a painkiller has declined somewhat since the development of paracetamol and ibuprofen in the 1950s and 60s. Its development and widespread use have revolutionised the treatment of pain, inflammation, and cardiovascular diseases, and have had a significant impact on public health.

- (a) Explain how the societal needs and scientific knowledge at the time of aspirin's discovery influenced its development as a pharmaceutical drug.

(3 marks) **KA1**

- (b) Discuss how the widespread use of aspirin during World War I contributed to its acceptance and popularity as a medication.

(3 marks) **KA2**

- (c) The discovery of aspirin's potential to reduce the risk of heart attacks and certain types of cancer was a result of ongoing scientific research. Explain how these findings have influenced the use and perception of aspirin as a preventive medication.

(3 marks) **KA3**

- (d) Aspirin's development as a medication was driven by the need to find a safer alternative to salicylic acid. Discuss the role of scientific research in identifying and addressing the limitations of existing drugs and developing new, improved medications.

(3 marks) **KA3**

Topic 3: Organic and biological chemistry

3.1 Introduction

Science understanding

Organic compounds can be represented by molecular and structural formulae.

Organic compounds are named systematically to provide unambiguous identification.

© SACE 2025

Organic chemistry is the study of covalently-bonded compounds which contain carbon, called 'organic compounds'. Carbon can form single bonds with four separate atoms, which allows for complex branching chains and rings. Consequently, there are many millions of known compounds that contain carbon and scientists are discovering and creating new ones each year.

Organic compounds are everywhere: in foods, fragrances, pharmaceuticals, cosmetics, plastics, and, of course, in our bodies.

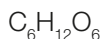


DNA

An organic polymer found in a cell's nucleus



Glucose



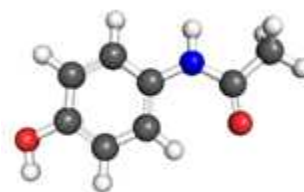
A simple sugar



Propane



A gas used as fuel



Paracetamol



A pain-relieving medicinal compound

Figure 3.01: Common organic compounds

The term "organic chemistry" once referred only to the chemistry of living things. However, in 1828, German chemist Friedrich Wöhler created urea—an organic compound found in the urine of mammals—by heating an inorganic substance. This expanded the definition of "organic chemistry" and proved that the fundamental chemistry of inanimate matter and living things was the same. Since then, scientists have developed many new carbon-containing compounds in the field of synthetic organic chemistry.



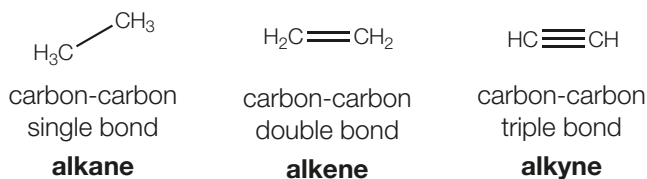
Science as a human endeavour

The discovery and understanding of ethene (ethylene) as a plant hormone represents a fascinating journey in scientific understanding that bridges organic chemistry with agricultural practices. In the 1900s, scientists observed that gas lighting caused premature defoliation in plants, leading to the eventual discovery of ethene as the active compound. This understanding has revolutionised the fresh produce industry.

Controlled ripening facilities use precise concentrations of ethene to ripen fruits like bananas, mangoes, and avocados. The development of ethene scrubbers helps extend produce shelf life during transportation. Modified atmosphere packaging technology helps control ethene levels in food storage.

This scientific knowledge has practical applications in everyday life, such as the common practice of ripening avocados by placing them near bananas. The commercial production of ethene has become a crucial industry, with global production exceeding 180 million tonnes annually, demonstrating how fundamental organic chemistry research leads to widespread industrial applications.

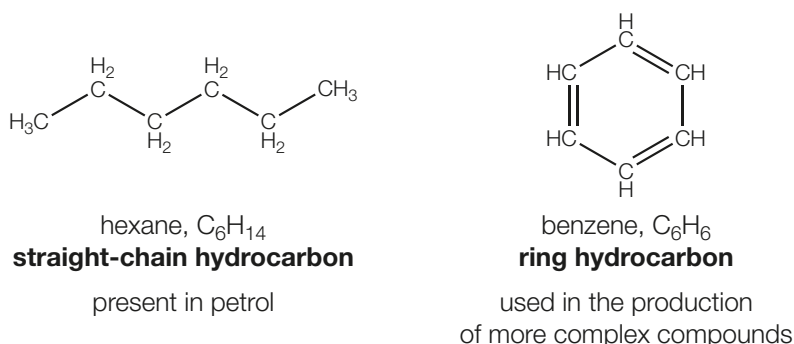
Because carbon has four valence electrons, it forms four bonds in almost all its compounds. These bonds can be single, double, or triple bonds.



The simplest class of organic compounds is composed of only carbon and hydrogen – these are the **hydrocarbons**. Hydrocarbons are classified into three general types: alkanes, alkenes, and alkynes.

Alkanes are hydrocarbons that contain only single bonds between carbon atoms. They are called **saturated** hydrocarbons because they contain the largest number of hydrogen atoms per carbon atom. **Alkenes** are hydrocarbons that contain double bonds between carbon atoms, and **alkynes** contain triple bonds between carbon atoms. Alkenes and alkynes are **unsaturated** hydrocarbons.

Carbon atoms can be arranged in straight chains or rings. Straight-chain hydrocarbons are classified as **aliphatic** while some rings are classified as **aromatic**.



As there are so many compounds of carbon, they have been organised into families based on their similarities and named systematically.

Naming Hydrocarbons

The systematic naming of organic compounds was established by the International Union of Pure and Applied Chemistry (IUPAC). The basic name of an organic compound has two parts:

- The prefix: the first half of the name indicates how many carbons are in the longest continuous carbon chain
- The suffix: the second half of the name indicates to which family, or *homologous series*, this compound belongs.

The prefix **alk-** refers to any non-specific hydrocarbon. When naming a specific compound, the prefix in the base name is based on the longest continuous carbon chain. Table 3.01 below shows the prefixes associated with continuous carbon chains up to a length of 10.

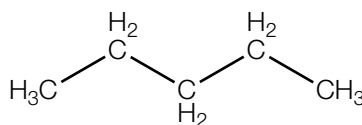
Number of carbons	Prefix
1	meth-
2	eth-
3	prop-
4	but-
5	pent-
6	hex-
7	hept-
8	oct-
9	non-
10	dec-

Table 3.01: Organic chemistry prefixes

Hydrocarbons with only single bonds take the suffix **-ane** (hence the name 'alk-ane' for this class of compounds).

Example

An alkane molecule has the structure:

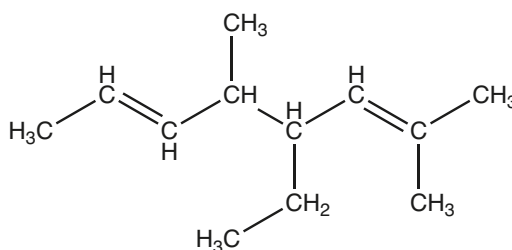


- The longest continuous chain is made up of 5 carbon atoms, so its name begins with the prefix *pent-*.
- The compound is a hydrocarbon with only single bonds, so its name ends with the suffix *-ane*.
- Therefore, the name of this compound is **pentane**.

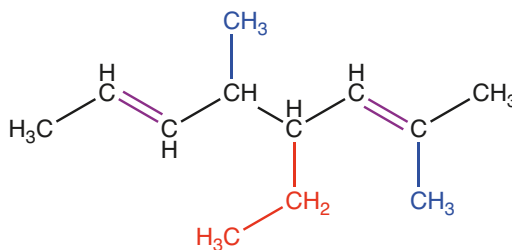
Hydrocarbons with carbon-carbon double-bonds take the suffix **-ene**, and hydrocarbons with carbon-carbon triple bonds take the suffix **-yne**.

Alkenes and alkynes containing four carbons or more require a number to be added before the base name to indicate the position of the multiple bond. When there is more than one double- or triple-bond in a compound, the prefixes **di-**, **tri-**, **tetra-** and so on are added to indicate this. *The naming of hydrocarbons is covered in detail in Topic 3 of the Stage 1 course.*

Example



- The longest continuous carbon chain is made up of 8 carbon atoms, so the base prefix is *oct-*.
- There is at least one double-bond in the molecule, so the base suffix is *-ene*.
- There are two double-bonds in the molecule, at positions 2 and 6, so the base name becomes *2,6-octadiene*.
- There are methyl substituents on carbons 2 and 5, so the prefix *2,5-dimethyl* is added.
- There is an ethyl substituent on carbon 4, so the prefix *4-ethyl* is added.
- Substituents are listed in alphabetical order (ignoring di-, tri-, and so on); ethyl comes before methyl.
- The compound is named **4-ethyl-2,5-dimethyl-2,6-octadiene**.



4-ethyl-2,5-dimethyl-2,6-octadiene

(can also be written as **4-ethyl-2,5-dimethylocta-2,6-diene**)

Formulae

Organic compounds can be represented by different types of formulae.

- The **molecular formula** gives the exact number and type of atoms present.
- The **empirical formula** gives the simplest ratio of atoms present.
- The **complete structural formula** shows all the atoms and how they are connected by bonds.
- The **condensed structural formula** can show the carbon-carbon bonds, but hydrogens and other atoms are simplified.
- The **skeletal structural formula** does not show the carbons and hydrogens in the carbon chain. This leaves a carbon “skeleton” with functional groups shown. Carbon atoms which appear to have fewer than four bonds in a skeletal structural formula have **implied hydrogens**.

Example

Consider straight-chain decane

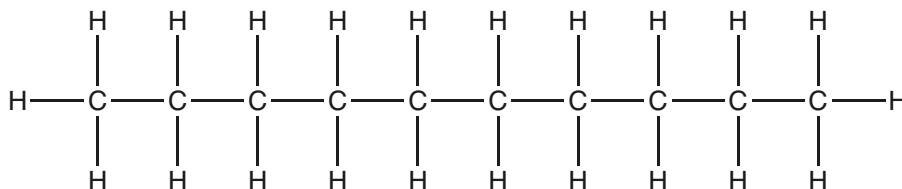
Molecular formula



Empirical formula

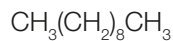
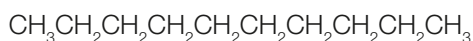
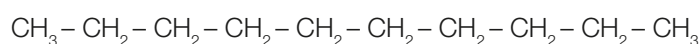
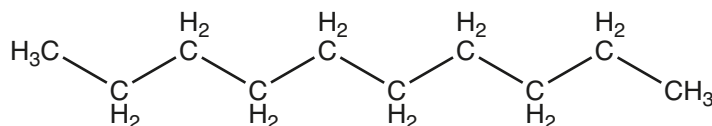
The simplest ratio of atoms for $\text{C}_{10}\text{H}_{22}$ is C_5H_{11} .

Complete structural formula

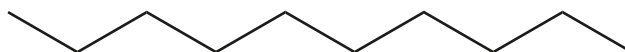


Condensed structural formula

There are several ways this can be represented:

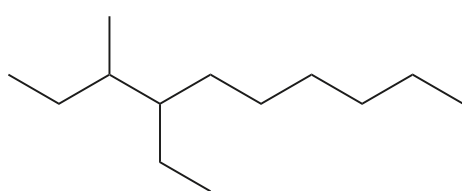


Skeletal structural formula

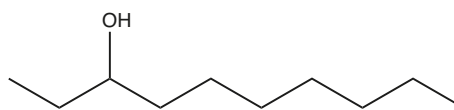


Each point on the “skeleton” represents a carbon atom. Skeletal structural formulas *must* show a ‘corner’ for each carbon. Atoms other than the hydrocarbon “skeleton” are still shown.

Example



4-ethyl-3-methyldecane

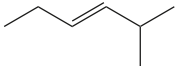
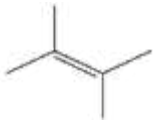


decan-3-ol

Questions

1. Hydrocarbons are the principal constituents of petroleum and natural gas. They serve as **fuels** and **lubricants** as well as raw materials to produce plastics, fibres, rubbers, solvents, explosives, and industrial chemicals. They are named and drawn systematically.

(a) Complete the table below

Name	Molecular formula	Empirical formula	Complete structural formula	Condensed structural formula	Skeletal structure
				$\text{CH}_3\text{-CH}_2\text{-CH}_2\text{-CH}_3$	
2-methylpentane					
					
3-ethyl-3-methylhexane					
					

25 marks **KA4**

(b) Name the following compounds:

$ \begin{array}{ccccccc} \text{H} & \text{H} & & \text{H} & \text{H} \\ & & & & \\ \text{H}-\text{C}-\text{C}-\text{C}\equiv\text{C}-\text{C}-\text{C}-\text{H} \\ & & & & \\ \text{H} & \text{CH}_3 & & \text{H} & \text{H} \end{array} $	$ \begin{array}{c} \text{CH}_3 \\ \\ \text{CH}_2=\text{C}-\text{CH}_3 \end{array} $	$ \begin{array}{ccccccc} \text{H} & \text{H} & & \text{H} & \text{H} \\ & & & & \\ \text{C}=\text{C}-\text{C}=\text{C}-\text{C}-\text{H} \\ & & & \\ \text{H} & & \text{H} & \text{H} \end{array} $

(6 marks) **KA4**

(c) Draw the structural formula for the following:

2,3-dimethylbut-2-ene	3-ethylhept-1-yne

(4 marks) **KA4**

- (d) The following compounds have been named incorrectly. Draw their structural formulas from the incorrect name, and provide the correct name.

Compound	Correct name	Structural formula
3-ethylbutane		
1-methyl-4-propylhexane		
3-methyl-3-butene		

(12 marks) (KA4)



Science as a human endeavour

Fiery ice

Large amounts of methane gas are stored around the world trapped as solid methane hydrate. Although methane hydrate looks like regular ice, it has one significant difference: it burns as shown in Figure 3.03.

This fiery ice results from the trapped methane being released from the lattice as the ice begins to melt. Arctic regions hold large reserves of methane hydrate both on the surface and deep in oceans where low temperatures and high pressures trap methane. Anaerobic decomposition of organic material by bacteria is responsible for the production of methane which is subsequently trapped within the ice. Methane hydrate and its molecular structure are shown in Figure 3.04.

There are concerns that rising ocean temperatures may cause the deposits of methane hydrate throughout the oceans to melt, releasing large amounts of methane into the atmosphere. Methane is a potent greenhouse gas, and its presence in the atmosphere accelerates global warming.



Figure 3.03: Methane hydrate combusting

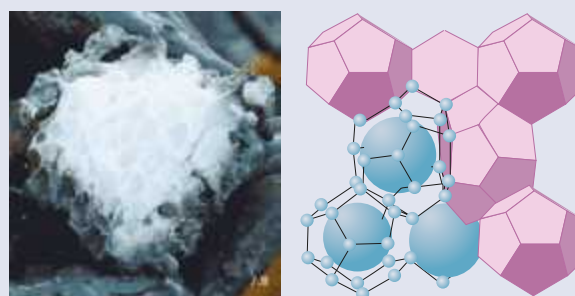


Figure 3.04: Structure of methane hydrate

3

Science understanding

The physical properties of organic compounds are influenced by the molar masses of the molecules, and the number and polarity of functional groups.

© SACE 2025

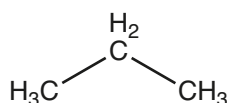
Physical properties of compounds include melting point, boiling point, miscibility, volatility, and solubility. Trends in these properties can be explained by:

- Intermolecular forces occurring between molecules
- Molecular mass

Melting point and Boiling Point

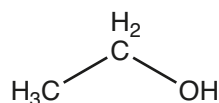
Intermolecular forces

Propane is used for water heaters and cooking. It has a molar mass of 44 g mol^{-1} and is a gas at room temperature. Ethanol has a similar molar mass of 46 g mol^{-1} but is a liquid at room temperature. The differences in the physical properties of these molecules can be explained through intermolecular forces.



propane

44.11 g/mol
boiling point: -42°C

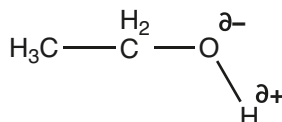


ethanol

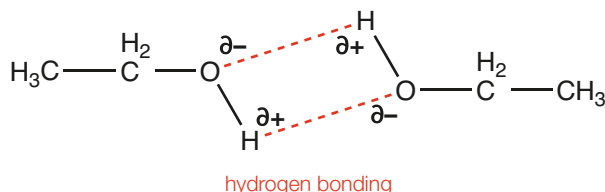
46.08 g/mol
boiling point: 78°C

Propane is a non-polar molecule that experiences only dispersion forces between it and other propane molecules. Dispersion forces are the weakest intermolecular force and do not require a lot of energy to overcome; hence, propane has a low boiling point.

Ethanol has a hydroxyl ($-\text{OH}$) functional group, which is polar. Oxygen is more electronegative than hydrogen and has a δ^- charge, while hydrogen has a δ^+ charge (δ charges are partial charges, less than a whole $1+$ or $1-$). As ethanol has a small carbon chain, the molecule is polar overall.



The intermolecular forces that occur between ethanol molecules are hydrogen bonds.

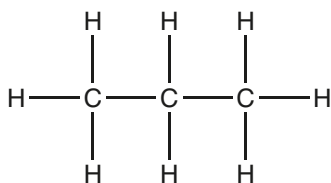


As hydrogen bonding is the strongest intermolecular force, it takes more thermal energy to separate ethanol molecules.

Molar mass

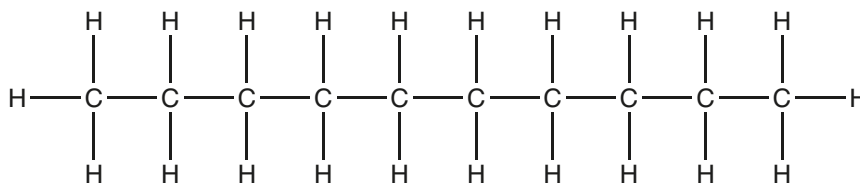
As the carbon chain length and the mass of the molecule increase, the effect of an individual hydroxyl group on the overall polarity of the molecule decreases.

Propane is non-polar and experiences only dispersion forces between molecules. It is a gas at room temperature. Decane is also non-polar and experiences only dispersion forces between molecules; however, it is a liquid at room temperature.



propane

44.11 g/mol
boiling point: -42°C



decane

142.32 g/mol
boiling point: 174°C

The difference in boiling point is due to the difference in the molar masses of the compounds. Larger molecules experience greater dispersion forces, so melting points and boiling points increase with molar mass as more thermal energy is required to overcome these forces. This trend is shown below in Table 3.02.

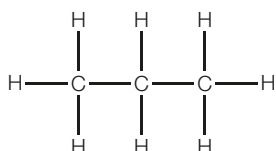
Alkane	Melting Point (°C)	Boiling Point (°C)
methane	-183	-162
ethane	-183	-89
propane	-187	-42
butane	-138	-1
pentane	-130	36
hexane	-95	69
heptane	-90	98
octane	-57	126
nonane	-54	151
decane	-30	174

Table 3.02: melting points and boiling points of alkanes

Solubility

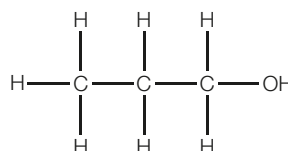
Organic compounds are more soluble in water if they experience stronger intermolecular forces with water. Therefore, the size of the molecule and the number of polar functional groups greatly affect how soluble the compound is.

Non-polar hydrocarbons will not dissolve in a polar solvent such as water; instead, they form two layers. There is hydrogen bonding between water molecules, but only dispersion forces between hydrocarbon molecules. The hydrogen bonds in water are too strong for non-polar molecules to penetrate, so hydrocarbons and water are unable to form a homogenous solution. Put another way, water molecules are much more strongly attracted to each other than to hydrocarbon molecules, and do not allow hydrocarbon molecules to mingle with them.



propane

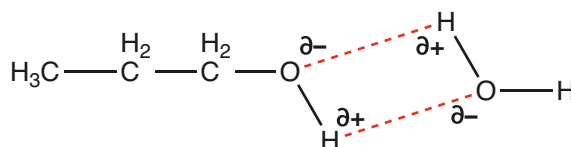
Solubility:
47 mg/L



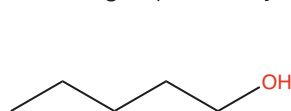
propan-1-ol

Solubility:
miscible

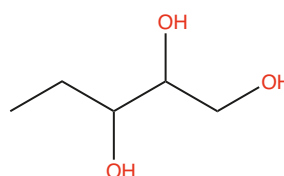
Propan-1-ol is a small, polar molecule. It can form hydrogen bonds with the polar water and is therefore miscible. (Recall that **miscible** substances can mix in any proportion; this represents maximum solubility).



As the number of polar functional groups on a hydrocarbon increases, so does solubility.



pentan-1-ol



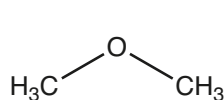
pentane-1,2,3-triol

Pentan-1-ol has a polar hydroxyl group which can form hydrogen bonds with water. However, it also has a long non-polar carbon chain which makes it harder for the water molecules to surround it and fully dissolve it. Pentane-1,2,3-triol, with its three polar hydroxyl groups, has multiple sites for hydrogen bonding to occur with water molecules; it is therefore more soluble.

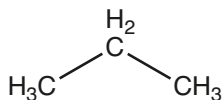
Questions

2. The boiling point of organic compounds can give important information about their physical properties and structural characteristics. Boiling point helps identify and characterise a compound.

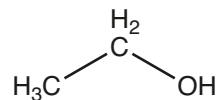
(a) Place the following compounds in order of increasing boiling points, numbering them 1 to 3.



diethyl ether
(methoxymethane)



propane



ethanol

(3 marks) **KA1**

(b) Explain your reasoning.

(3 marks) **KA1**

- (c) Butan-1-ol has a boiling point of 117.7°C whereas pentane has a boiling point of 36.1°C. Explain the differences in these boiling points.

(3 marks) **KA1**

- (d) With reference to intermolecular bonding, predict and explain which molecule from a) would have the greatest solubility in water.

(3 marks) **KA1**

- (e) Explain the following general trends:

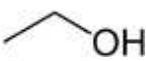
(i) Alcohols are soluble in water.

(2 marks) **KA1**

(ii) Solubility decreases as the hydrocarbon chain of an alcohol increases in length.

(2 marks) **KA1**

- (f) Place the following molecules in order of decreasing solubility in water (i.e. most soluble to least soluble). Explain your reasoning:

		
butan-1-ol	ethanol	hexan-1-ol

(3 marks) KA1



Science as a human endeavour

Food wastage

Biodegradation is nature's way of decomposing organic substances. A fallen tree in a forest will slowly decompose over the ensuing years. The number of products formed in a biodegradation reaction can be very high, depending on the type of organism being degraded. Nature uses microorganisms such as bacteria and fungi to bring about decomposition of once-living things.

Food wastage has been a major cause of concern for the environment, with Australia as a whole throwing away 7.3 million tonnes of edible food each year and 3.2 million tonnes ending up in landfill. Food waste rotting in landfill produces large amounts of greenhouse gases such as methane.

Food waste contributes approximately 3% of Australia's annual greenhouse gas emissions. As the world develops a preference for renewable energy, food waste has been identified as one such source. Large scale anaerobic bio-digesters (Figure 3.02) are being developed which allow for facilities to process mass amounts of food waste to recover energy. Through this process they are able to reduce food waste rotting in landfills. Renewable energy in the form of biogas is also produced which can potentially boost energy security.



Figure 3.02: Bio-digesters are finding success in countries such as Cambodia.

3.2 Alcohols

Science understanding

Alcohols are classified as primary, secondary, or tertiary.

© SACE 2025

Alcohols are an important part of chemical and industrial processes. An alcohol is a compound that has a **hydroxyl functional group (-OH)** attached to a carbon atom. Commonly-known alcohols include:

- Ethanol, which comes from the fermentation of simple sugars and is consumed recreationally
- Glycerol, which is used in the food industry, moisturisers, and detergents
- Cholesterol, a steroid present in the human body

All the above alcohols contain one or more hydroxyl functional groups in their molecular structure. Simple straight-chain alcohols have the **general formula** $C_nH_{2n+1}OH$.

Generic compounds can be written using 'R'. For example, alcohols can be represented with R-OH. "R" represents an **alkyl chain**: any substituent made up of only carbon and hydrogen.

Primary, Secondary, and Tertiary Alcohols

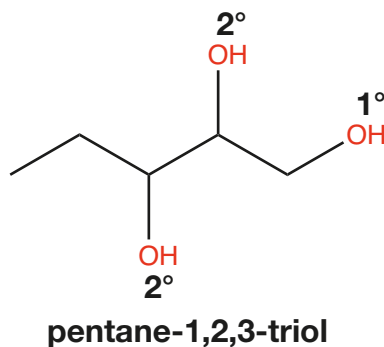
Alcohols can be classified as primary, secondary, or tertiary, depending on how many other carbons are connected to the same carbon as the hydroxyl group.

Primary (1°)		The carbon connected to the hydroxyl group is connected to one hydrocarbon chain (or none, in the case of methanol). <u>Example</u> propan-1-ol
Secondary (2°)		The carbon connected to the hydroxyl group is connected to two hydrocarbon chains. <u>Example</u> propan-2-ol
Tertiary (3°)		The carbon connected to the hydroxyl group is connected to three hydrocarbon chains. <u>Example</u> 2-methylpropan-2-ol

Sometimes, diols and triols have hydroxyl groups in primary, secondary, or tertiary positions within the same molecule.

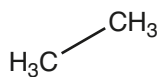
Example

Pentane-1,2,3-triol contains two secondary hydroxyl groups and one primary hydroxyl group.

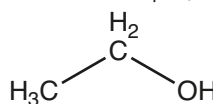


Naming alcohols

- the -e is removed from the parent alkane and replaced with -ol. For example, ethane becomes ethanol.

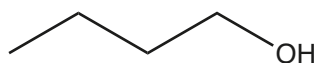


ethane

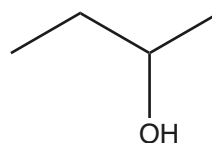


ethanol

- For all alcohols other than methanol and ethanol, it is necessary to number the position of the functional group in the name, as it can be found in different positions.

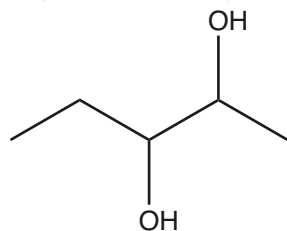


butan-1-ol

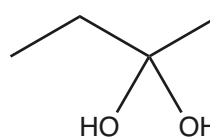


butan-2-ol

- The prefixes *di-* and *tri-* are used before -ol if there are two or three hydroxyl functional groups. Numbers are included to indicate the position of the hydroxyl groups. The -e is included at the end of the parent alkane.

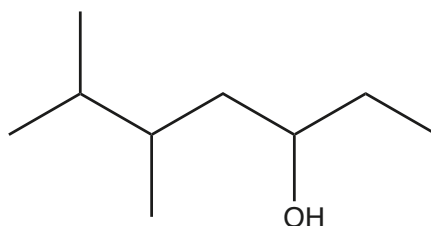


pentane-2,3-diol



butane-2,2-diol

- If there are branches, ensure the functional group (in this case, the hydroxyl) is assigned the lowest possible number.

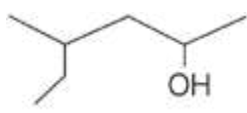


5,6-methyl-heptan-3-ol
(not 2,3-methyl-heptan-5-ol)

Questions

3. Alcohols are used as sweeteners and in making perfumes, are valuable intermediates in the synthesis of other compounds, and are among the most abundantly produced organic chemicals in industry.

(a) Systematically name each of the following alcohols.

(i) $\text{CH}_3-\text{CH}_2-\text{CH}_2-\underset{\text{OH}}{\overset{\text{CH}_3}{\text{CH}}}-\underset{\text{OH}}{\overset{\text{CH}_3}{\text{C}}}-\text{CH}_2-\text{CH}_3$	(ii) 
(iii) $\text{H}_3\text{C}-\underset{\text{OH}}{\overset{\text{OH}}{\text{C}}}-\underset{\text{CH}_3}{\overset{\text{CH}_3}{\text{C}}}-\text{CH}_2-\text{CH}_3$	(iv) $\text{HO}-\text{CH}_2-\underset{\text{OH}}{\overset{\text{CH}_3}{\text{C}}}-\text{CH}_2-\text{OH}$

(8 marks) **KA4**

- (b) Circle each of the hydroxyl groups in (a) and identify them as primary, secondary, or tertiary.

(4 marks) **KA3**

- (c) Draw the structural formula of:

(i) propan-2-ol	(ii) 3-methylbutan-1-ol
(iii) 2,3-dimethyl-pentan-3-ol	(iv) pentane-2,2-diol

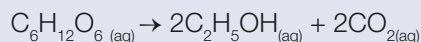
(8 marks) **KA4**



Science as a human endeavour

Champagne

The production of alcohol involves a **chemical reaction** called **fermentation** in which the glucose is broken down to **ethanol** by the action of enzymes in the yeast. Champagne and wine are made by the fermentation of glucose ($C_6H_{12}O_6$) obtained from grapes. Ethanol and carbon dioxide are formed:



When a carefully selected mixture of grapes is fermented in bottles to make champagne, the ethanol and some carbon dioxide dissolve in the aqueous solution. Due to the sparkle of the carbon dioxide that is required in the final product, the yeast must be removed from the bottles very carefully while keeping the carbon dioxide in solution.

When it is time to remove the yeast from the fermented champagne solution, the bottle is inverted and the yeast is frozen in the neck of the bottle (Figure 3.05). The stopper and yeast are then removed quickly and the stopper is replaced.



Figure 3.05: Trapped yeast in inverted champagne bottles

3

Science understanding

Primary, secondary, and tertiary alcohols behave differently with oxidising agents.

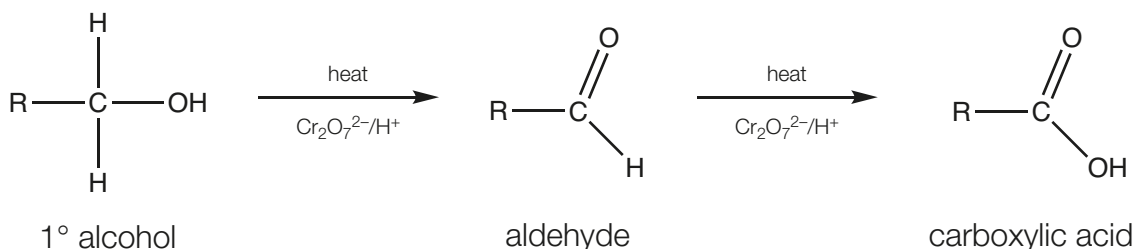
© SACE 2025

Alcohols can be converted into many compounds, including aldehydes, ketones, carboxylic acids, and esters.

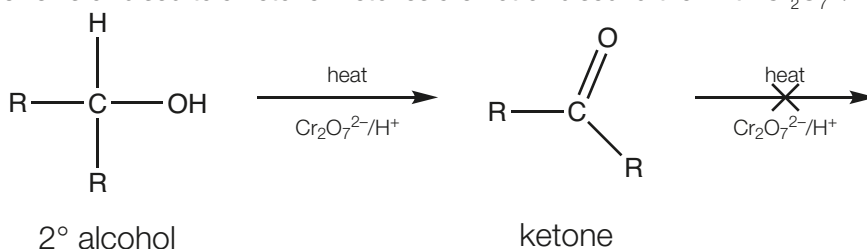
The position of the hydroxyl group can determine what type of compound the alcohol is converted to when it reacts with an oxidising agent such as acidified potassium dichromate, $Cr_2O_7^{2-}/H^+$.

Oxidation of Alcohols

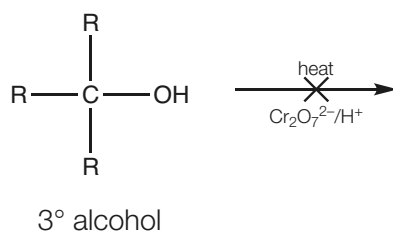
A **primary alcohol** is oxidised first to an aldehyde. If there is an excess of the oxidising agent, the aldehyde is then converted to a carboxylic acid.



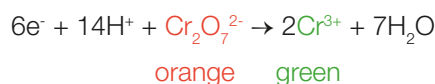
A **secondary alcohol** is oxidised to a ketone. Ketones are not oxidised further with $Cr_2O_7^{2-}/H^+$.



Tertiary alcohols cannot be oxidised without breaking a carbon-carbon bond.



The primary and secondary alcohols undergo oxidation; therefore, the dichromate solution will undergo reduction. The half-equation for the reduction of dichromate to chromium(III) ions is as follows:



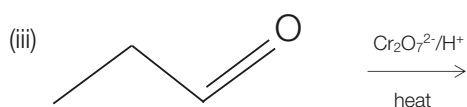
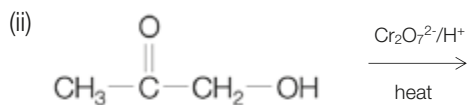
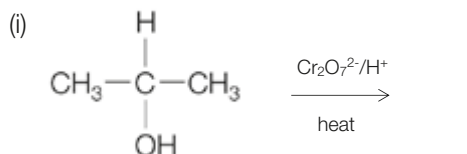
When dichromate ions are reduced to chromium(III) ions, the colour of solution changes from orange to green. Hence, primary and secondary alcohols can be distinguished from tertiary alcohols as the mixture will change colour from orange to green when acidified dichromate is added. The tertiary alcohol mixture will remain orange. *Note that it is not the alcohol itself, nor the oxidised product, that is coloured.*

The oxidation of alcohols in the presence of acidified dichromate is slow at room temperature, so the reaction is often heated to speed up the process.

Questions

4. Alcohols may be oxidised to give ketones, aldehydes, and carboxylic acids. These functional groups are useful for further reactions.

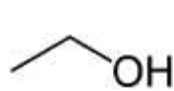
- (a) Draw the structures of the organic products when the following compounds are oxidised with acidified dichromate solution:



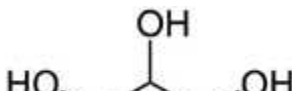
(6 marks) **KA4**

- (b) According to New Scientist (29 June 2024), the world's oldest wine was found in a 2000-year-old Roman tomb, and it was confirmed to be white wine.

White wine contains the following compounds.



Compound A



Compound B



Compound C

- (i) Name, systematically, Compound A, Compound B, and Compound C.

- (1) Compound A
- (2) Compound B
- (3) Compound C

(6 marks) **KA4**

- (ii) Write the equation for the oxidation of Compound A by excess acidified dichromate solution.

(2 marks) **KA4**

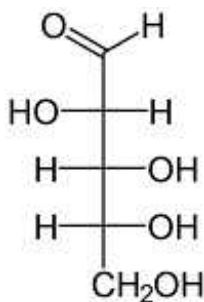
- (iii) Explain why Compound B is more soluble in water than Compound C.

(3 marks) **KA1**

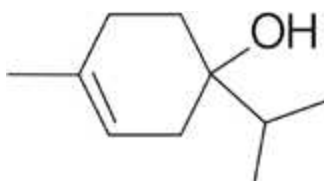
- (iv) State whether Compound C is a primary, secondary, or tertiary alcohol.

(1 mark) **KA4**

- (c) Compound D and Compound E are also found in white wine.



Compound D



Compound E

- (i) Complete the table in regards to Compound D and Compound E.

	Compound D	Compound E
Molecular formula		
Empirical formula		
Functional groups present		

(6 marks) **KA4**

- (ii) Describe and explain a chemical test you could perform in a laboratory to distinguish between Compound D and Compound E. Include any relevant observations.

(4 marks) **KA1**

3.3 Aldehydes and Ketones

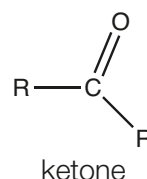
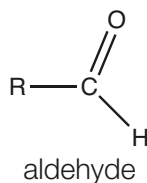
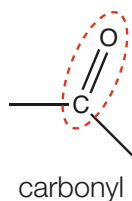
Science understanding

Aldehydes and ketones are produced by the oxidation of the corresponding primary and secondary alcohols respectively.

© SACE 2025

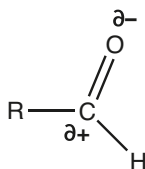
Aldehydes and ketones are found widely in fragrances and flavourings. Commonly known examples include spearmint, lemongrass, vanilla, and cinnamon.

Aldehydes and ketones each contain the **carbonyl** functional group (C=O). However, for an aldehyde, the carbonyl group is **terminal** (at the end of a chain), and for a ketone, the carbonyl group is **non-terminal** (linked to two other carbons).



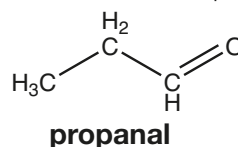
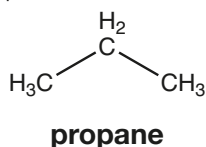
Aldehydes

Aldehydes are prepared by the oxidation of primary alcohols. They have an **aldehyde functional group**. This functional group is polar.

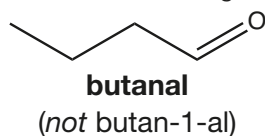


When **naming** aldehydes:

- the -e is removed from the parent alkane and replaced with -al. For example, propane becomes propanal.



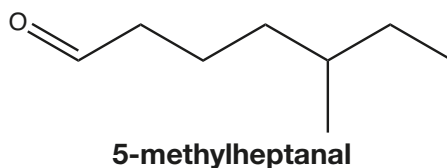
- It is not necessary to number the position of the functional group in the name, as it is always terminal.



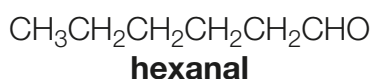
- The prefix *di-* is used before -al if there are two aldehyde functional groups. The -e is included in the name of the parent alkane.



If there are branches, always begin numbering from the functional group.



The condensed structural formula for aldehydes is written as **-CHO**.



Questions

5. Aldehydes are the key flavour components in whiskey. When oxygen diffuses into casks of whiskey, the ethanol is oxidised to an aldehyde. Draw the aldehyde product.

(2 marks) KA4

3



Science as a human endeavour

Mystery of the eye: Conversion of Vitamin A into Cis-Retinal

In 1967, Georges Wald was awarded a share of the Nobel Prize for Physiology and Medicine for his work with pigments in the retina. He discovered that vitamin A (retinal) was critical to our vision and investigated the way in which it absorbs light.

Our vision begins when molecules of retinol absorb a small packet of light called a photon. This absorption causes the *cis* form of retinal to be converted to the *trans* form (Figure 3.06), changing the shape of the retinal molecule.

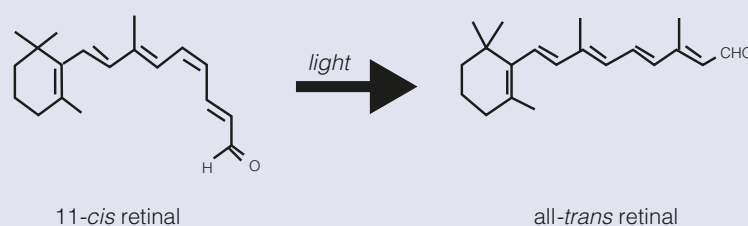


Figure 3.06: *cis* and *trans* isomers of retinal.

cis-trans isomers exhibit a type of isomerism where the atoms have different spatial arrangements in three-dimensional space.

The *cis* form of retinal is able to bond tightly to the protein opsin in our eyes. After it has absorbed light and been converted to the *trans* form, it is no longer able to sit closely within the protein, as its shape has changed. This causes the opsin protein itself to change shape, which begins a signalling pathway that sends an impulse along the optic nerve to the brain. This is how the light that enters our eyes is converted to vision in our brains.

Aldehyde preparation

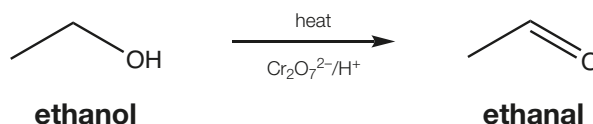
Aldehydes are prepared by the *controlled* oxidation of primary alcohols. Specific apparatus is used, as shown in Figure 3.07.

An oxidising agent (often acidified dichromate) is added, drop by drop, into the alcohol mixture once heating begins.

The primary alcohol will oxidise to form an aldehyde. The aldehyde has a lower boiling point than its parent alcohol because it exhibits dipole-dipole interactions between its molecules, compared to the stronger hydrogen bonds between the alcohol molecules. The newly formed aldehyde will immediately boil off as it forms, which prevents further oxidation to a carboxylic acid. The ice bath around the receiving flask prevents loss from evaporation.

Example

For example, ethanol can be converted into ethanal by the controlled addition of acidified dichromate:



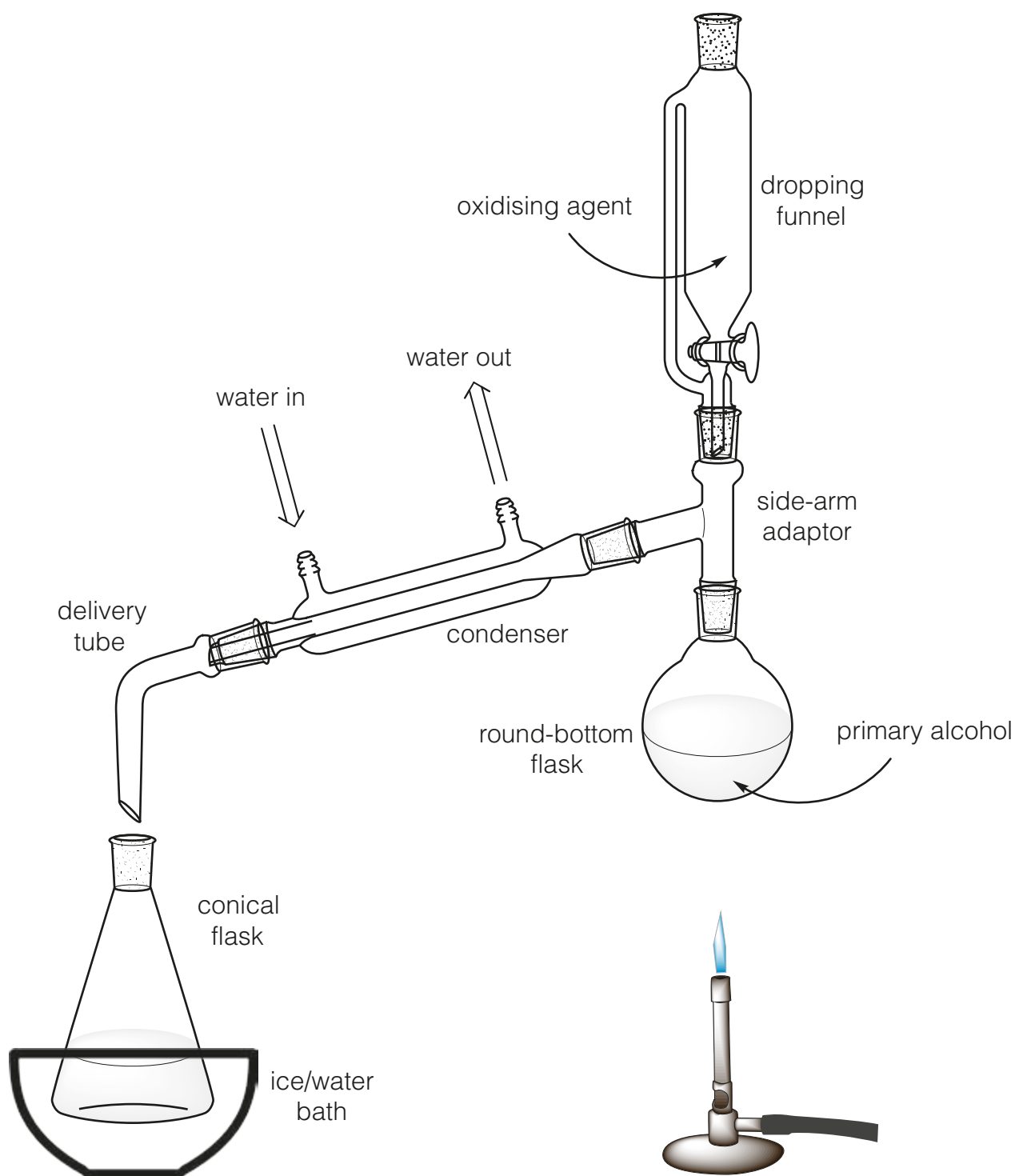
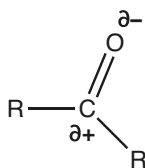


Figure 3.07: preparation of an aldehyde using distillation

Ketones

Ketones are prepared by the oxidation of secondary alcohols. They have a **ketone functional group**. This functional group is polar.

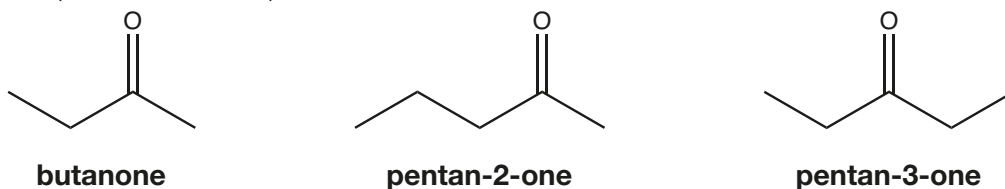


When **naming** ketones:

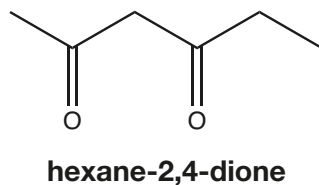
- the -e is removed from the parent alkane and replaced with *-one*. For example, propane becomes *propanone*.



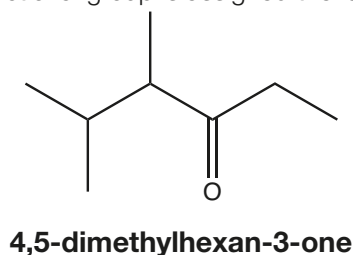
- After butanone, it is necessary to number the position of the functional group in the name, as it is non-terminal and can be placed in different positions.



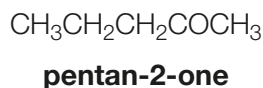
- The prefixes *di-* or *tri-* are used before *-one* if there are two or three ketone functional groups. Remember to include the numbers to indicate the position of the ketone groups. The -e is included in the name of the parent alkane.



- If there are branches, ensure the functional group is assigned the lowest number.



- The condensed structural formula for ketones is written with **-CO-** in the middle to represent the functional group.



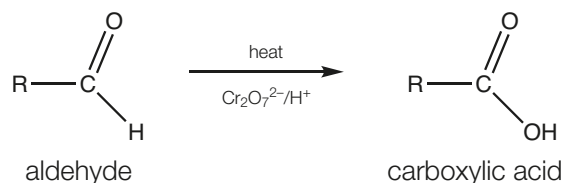
Science understanding

Aldehydes can be readily oxidised; ketones cannot.

© SACE 2025

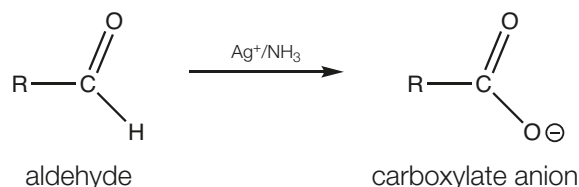
Distinguishing between an aldehyde and a ketone

Aldehydes can undergo oxidation with an oxidising agent like acidified dichromate, while ketones cannot. Earlier in the chapter we looked at how aldehydes can be oxidised to give carboxylic acids with acidified dichromate. This is oxidation under **acidic conditions**.



Aldehydes can also undergo oxidation under **alkaline conditions**. Tollens' reagent (ammoniacal silver nitrate solution, Ag^+/NH_3) oxidises the aldehyde and is itself reduced to solid silver. A silver mirror forms on the inside surface of the reaction vessel.

The alkaline conditions are due to the presence of ammonia in the solution. This means protons (H^+) are scarce in solution, rather than abundant. The **carboxylate anion** is formed instead of the carboxylic acid.



Hence, an aldehyde and a ketone can be distinguished by using either acidified dichromate or Tollens' reagent. An aldehyde will be oxidised and the reaction mixture will show a colour change from orange to green, or a silver mirror. A ketone will not be oxidised.

Acidic vs Alkaline Oxidation of Aldehydes

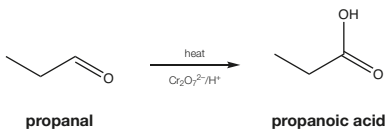
Acidified dichromate can oxidise aldehydes, primary alcohols, and secondary alcohols. However, Tollens' reagent will oxidise aldehydes only. This is useful for distinguishing alcohols from aldehydes. These reactions are summarised in Table 3.03.

Acidified dichromate will oxidise...	Tollens' reagent will oxidise...
- Aldehydes and also - Primary alcohols - Secondary alcohols	Aldehydes
<u>Observations</u> Solution turns from orange to green	<u>Observations</u> Silver mirror forms on surface
<u>Oxidation Equations</u> $ \begin{array}{ccccc} \begin{array}{c} \text{H} \\ \\ \text{R}-\text{C}-\text{OH} \\ \\ \text{H} \end{array} & \xrightarrow[\text{Cr}_2\text{O}_7^{2-}/\text{H}^+]{\text{heat}} & \begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C} \\ \\ \text{H} \end{array} & \xrightarrow[\text{Cr}_2\text{O}_7^{2-}/\text{H}^+]{\text{heat}} & \begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C} \\ \\ \text{OH} \end{array} \\ \text{1}^\circ \text{ alcohol} & & \text{aldehyde} & & \text{carboxylic acid} \\ \\ \begin{array}{c} \text{H} \\ \\ \text{R}-\text{C}-\text{OH} \\ \\ \text{R} \end{array} & \xrightarrow[\text{Cr}_2\text{O}_7^{2-}/\text{H}^+]{\text{heat}} & \begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C} \\ \\ \text{R} \end{array} & & \\ \text{2}^\circ \text{ alcohol} & & \text{ketone} & & \end{array} $	<u>Oxidation Equation</u> $ \begin{array}{ccc} \begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C} \\ \\ \text{H} \end{array} & \xrightarrow{\text{Ag}^+/\text{NH}_3} & \begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C} \\ \\ \text{O}^\ominus \end{array} \\ \text{aldehyde} & & \text{carboxylate anion} \end{array} $
<u>Reduction Equation</u> $6\text{e}^- + 14\text{H}^+ + \text{Cr}_2\text{O}_7^{2-} \rightarrow 2\text{Cr}^{3+} + 7\text{H}_2\text{O}$	<u>Reduction Equation</u> $\text{e}^- + \text{Ag}^+_{(\text{aq})} \rightarrow \text{Ag}_{(\text{s})}$

Table 3.03: The oxidation of organic compounds by acidified dichromate and Tollens' reagent.

Example

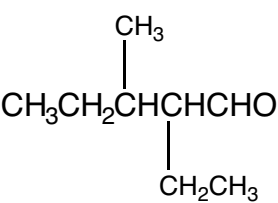
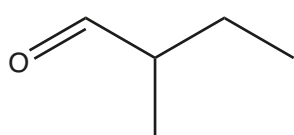
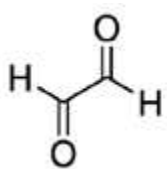
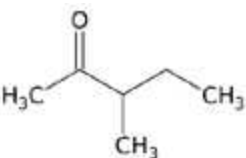
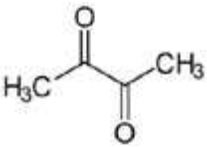
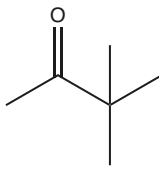
Describe and explain the chemical tests that could be performed to distinguish between propanal and propanone.

Propanal	Propanone
Adding $\text{Cr}_2\text{O}_7^{2-}/\text{H}^+$ Propanal is oxidised to propanoic acid.  propanal propanoic acid Mixture changes colour from orange to green due to reduction of dichromate to chromium(III).	Adding $\text{Cr}_2\text{O}_7^{2-}/\text{H}^+$ Propanone will not oxidise. Mixture remains orange.
Adding Tollens' reagent Propanal is oxidised to propanoate ion.  propanal propanoate ion Silver mirror forms in reaction vessel.	Adding Tollens' reagent Propanone will not oxidise. Mixture remains colourless.

Questions

6. **Aldehydes** are versatile compounds that can help make resins, dyes, and organic acids, as well as perfumes for cologne, detergents, and soaps. Ketones are most widely used as solvents, especially in industries manufacturing explosives, lacquers, paints, and textiles. Ketones are also used in tanning, as preservatives, and in hydraulic fluids.

(a) Name the following aldehydes and ketones.

(i)		(ii)		(iii)	
(iv)		(v)		(vi)	

(12 marks) KA4

(b) Draw the structure of the following aldehydes and ketones.

(i)	propanone	(ii)	4-methylheptane-2,6-dione	(iii)	methanal
(iv)	2-methylbutanal	(v)	4,5-dimethylhexanal	(vi)	4,5-dimethylheptan-2-one

(12 marks) **KA4**

(c) Describe and explain the chemical test that could be used to distinguish between compound (ii) and (iii) in part b). Include in the description the *procedures used* and the *expected observations*.

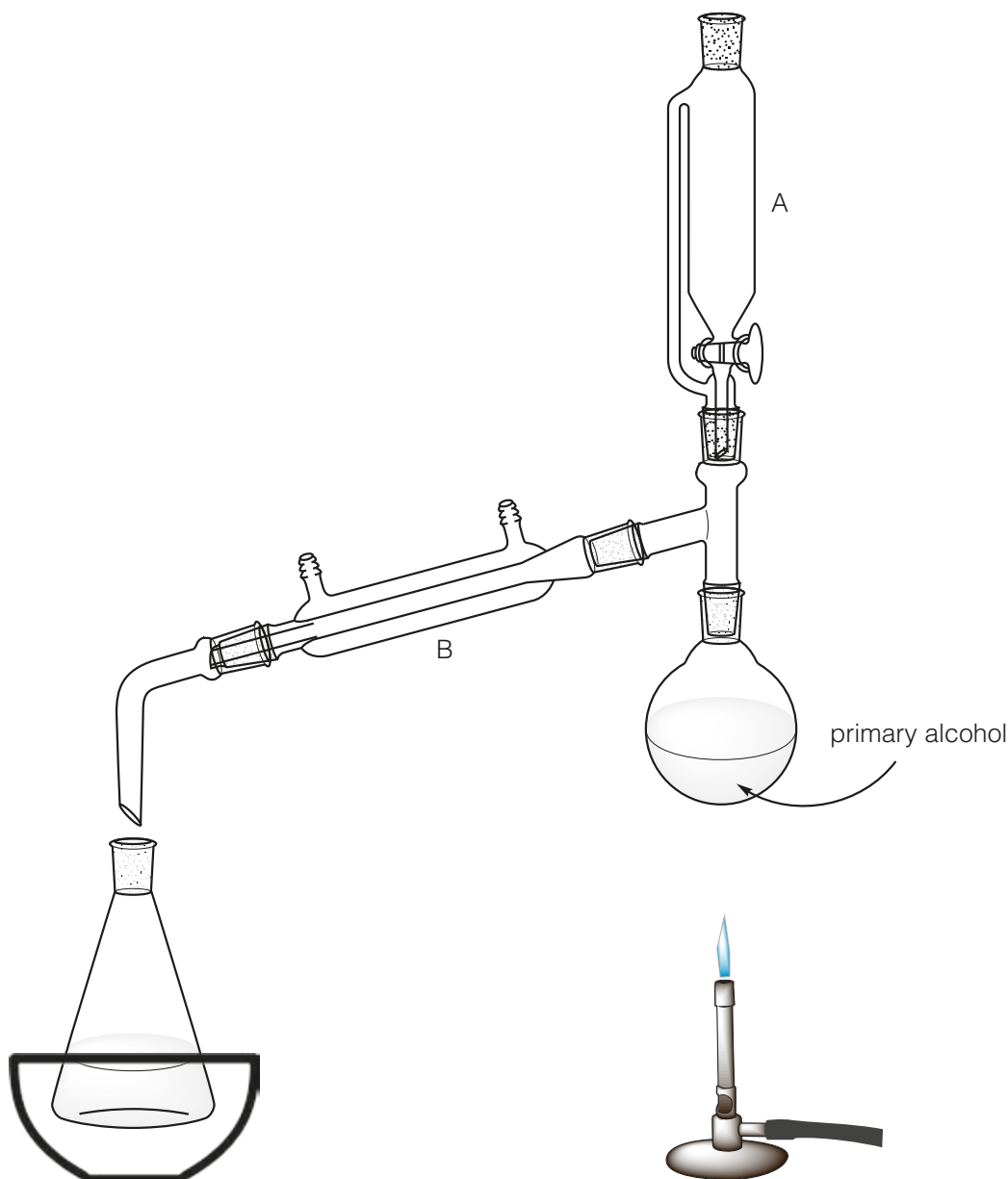
(4 marks) **KA1**

(d) Draw the structural formulae for the alcohols that could be oxidised to produce the aldehydes or ketones in part a).

(i)		(ii)		(iii)	
(iv)		(v)		(vi)	

(12 marks) **KA4**

- (e) An aldehyde can be prepared from an alcohol using the apparatus shown below:



- (i) Name the pieces of glassware labelled **A** and **B**.

(2 marks) **KA1**

- (ii) On the diagram above, show the direction of the water flow on the glassware labelled **B**.

(1 mark) **KA1**

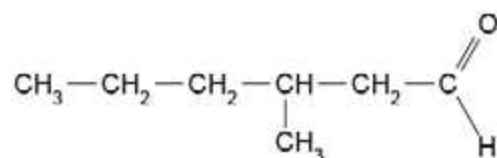
- (iii) The glassware labelled **A** contained acidified dichromate ($\text{Cr}_2\text{O}_7^{2-}/\text{H}^+$). When it reacted with the alcohol, the $\text{Cr}_2\text{O}_7^{2-}$ ions converted to Cr^{3+} ions. Write the half-equation for this conversion.

(2 marks) **KA1**

- (iv) Name the functional group that would be formed if the alcohol, acidified dichromate ($\text{Cr}_2\text{O}_7^{2-}/\text{H}^+$) and H_2SO_4 were refluxed together rather than reacted in the apparatus shown.

(1 mark) **KA1**

- (f) The structural formula of one aldehyde is shown below:



- (i) Give the systematic name of the aldehyde shown above.

(1 mark) **KA4**

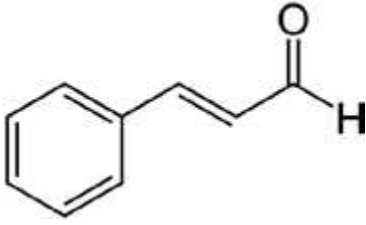
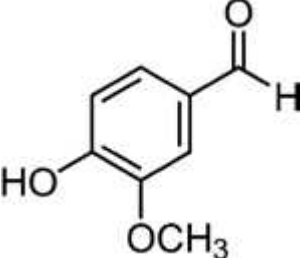
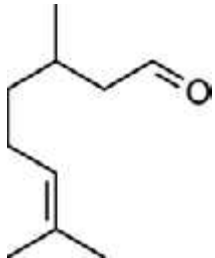
- (ii) Draw the structural formula of a ketone that is an isomer of the aldehyde shown above

(2 marks) **KA4**

- (iii) When oxidised using Tollens' reagent, the ketone drawn in (ii) produces a carboxylate anion. Describe the solubility of the produced anion in comparison to that of its parent ketone.

(3 marks) **KA1**

- (g) Many aldehydes have pleasant odours and are used in perfumes. The structures of three aldehydes are shown below.

		
Cinnamaldehyde (Cinnamon) A	Vanillin (Vanilla essence) B	Citronellal (Lemon) C

- (i) Draw the structure of the alcohol from which A could be formed.

(2 marks) **KA4**

- (ii) Identify a functional group in C but not in B

(1 mark) **KA4**

- (iii) Draw the structure of the organic product formed when B is treated with Tollens' reagent.

(2 marks) **KA4**

3.4 Carbohydrates

Science understanding

Carbohydrates are naturally occurring sugars and their polymers. They are defined as either polyhydroxy aldehydes or polyhydroxy ketones, or substances that form these compounds on hydrolysis.

Disaccharides and polysaccharides are produced by the condensation of monosaccharide units linked in chains by covalent bonds.

In aqueous solution there is an equilibrium between a ring form and a chain form of glucose.

© SACE 2025

Carbohydrates are one of the most abundant types of naturally occurring organic compounds. They perform many functions, including storing chemical energy and building the physical structure of plants.

All carbohydrates contain carbon, hydrogen, and oxygen, and have the general formula $C_x(H_2O)_y$. They are formally defined as **polyhydroxyaldehydes** (an aldehyde with multiple hydroxyl group substituents, also called an **aldose**), **polyhydroxyketones** (a ketone with multiple hydroxyl group substituents, also called a **ketose**), or compounds that yield either of these when hydrolysed.

The members of the carbohydrate family with the lowest molar masses are called “saccharides” or, more commonly, sugars. (‘Saccharin’ comes from the Greek word *sakkharon*, meaning sugar.) Saccharides can be classified as monosaccharides, disaccharides, or polysaccharides, depending on how many simple sugar units make up the molecule.

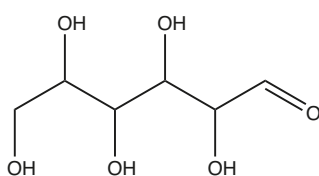
Monosaccharides

Molecular formula: $C_6H_{12}O_6$

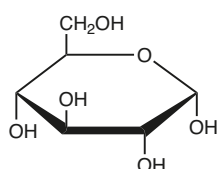
Empirical formula: CH_2O

Monosaccharides are the monomers that make up more complex carbohydrates, such as disaccharides and polysaccharides. Common monosaccharides include glucose and fructose.

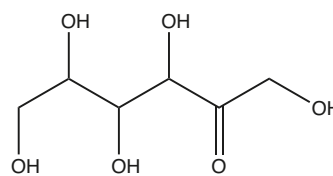
In an aqueous solution, monosaccharides exist in an equilibrium between a chain form and a cyclic (ring) form. The equilibrium lies very much in favour of the cyclic (ring) form; only 0.02% of molecules are in chain form at any one time. Notice that the ring forms do not contain aldehyde or ketone functional groups; these are the “compounds that yield polyhydroxyaldehydes or polyhydroxyketones when hydrolysed” in the definition of carbohydrates.



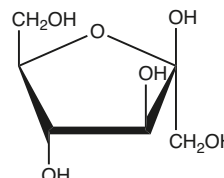
glucose
(chain form)



glucose
(ring form)



fructose
(chain form)



fructose
(ring form)

Glucose and fructose are **functional group isomers**: they have the same molecular formula ($C_6H_{12}O_6$), but different functional groups in their structures.

Physical properties

Monosaccharides are colourless crystalline solids. They have many polar hydroxyl groups per carbon atom (ratio is almost 1:1) which can form extensive hydrogen bonds with water. Hence, they are very soluble in water.

Monosaccharides also have high melting and boiling points due to the hydrogen bonding between the hydroxyl groups in the crystalline structure. The melting points of glucose and tridecane (a non-polar hydrocarbon with similar molar mass to glucose) are compared in Table 3.04 below.

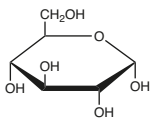
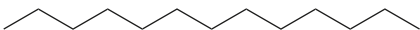
Compound	glucose	tridecane
Structure		
Molar Mass (g/mol)	180.18	184.41
Melting Point (°C)	146	-5

Table 3.04: Comparing glucose and tridecane

Disaccharides

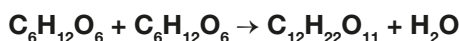
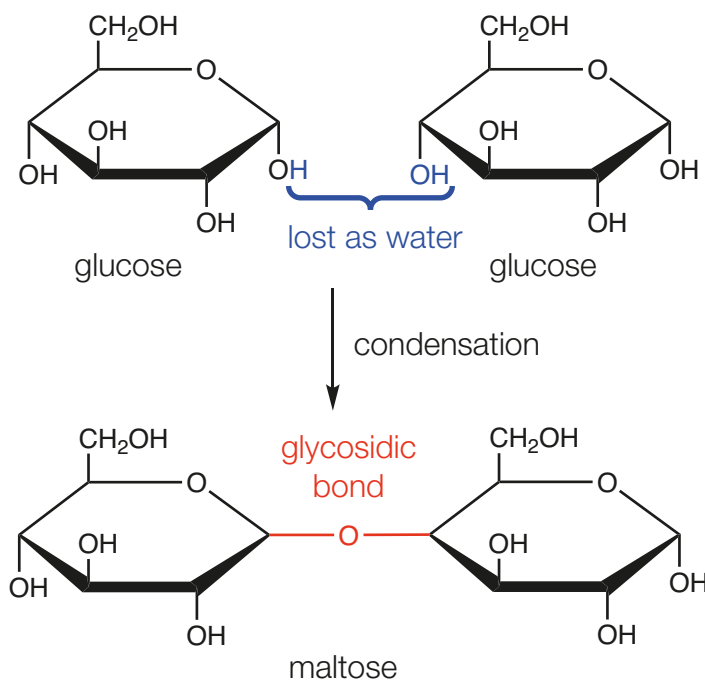
Molecular formula: $C_{12}H_{22}O_{11}$

Most carbohydrates in nature contain more than one monosaccharide unit. **Disaccharides** contain two monosaccharide monomers joined by covalent bonds. The individual atom that bridges the two monomers, and its associated bonds, are together called a **glycosidic bond**.

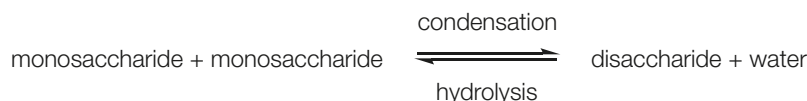
When two molecules combine to form a higher-mass product and release a molecule of water in the process, this is called a **condensation reaction**. The reverse reaction (decomposition of one molecule into two via the addition of water) is termed **hydrolysis** ('hydro' = water, 'lysis' = separation).

Example

Two units of the monosaccharide glucose can combine via a condensation reaction to form the disaccharide maltose. For each glycosidic bond that forms, one molecule of water is also produced.



The general reaction takes the form:

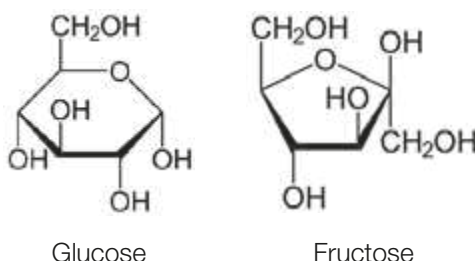


Physical properties

Like monosaccharides, disaccharides have high melting and boiling points due to the hydrogen bonding between the hydroxyl groups in the molecular structure. Many (but not all) are crystalline and soluble in water, although their solubility is in general lower than monosaccharides due to their higher molar masses.

Questions

7. Sucrose (common sugar) is a disaccharide formed from the condensation reaction between glucose and fructose.



- (a) State one piece of evidence to support that glucose is a carbohydrate.

(1 mark) **KA1**

- (b) Glucose and fructose are *functional group isomers*. Explain what is meant by this term.

(2 marks) **KA1**

- (c) Draw the structure of sucrose.

(2 marks) **KA4**

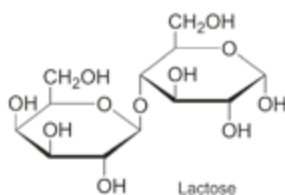
- (d) Name the type of reaction that produces sucrose.

(1 mark) **KA1**

- (e) Glucose can exist in both ring form (pictured) and as a straight chain. Describe how straight-chain glucose could be distinguished from a sample of ring-form glucose.

(3 marks) **KA1**

- (f) Another disaccharide, lactose, is the sugar found in animal-based milk products.



Individuals who are “lactose intolerant” are unable to consume many dairy products, so the food industry has been developing low-lactose or lactose-free products using hydrolysis. The enzyme lactase hydrolyses lactose into two monosaccharides.

- (i) State the molecular formula of lactose.

(1 mark) **KA1**

- (ii) Draw the monosaccharides which undergo condensation to form lactose.

(4 marks) KA4

Polysaccharides

General formula: $(C_6H_{10}O_5)_n$

Polysaccharides are polymers consisting of many monosaccharide units joined together by covalent glycosidic bonds. Commonly-known polysaccharides include starch (energy storage in plants), cellulose (found in plant cell walls), and glycogen (carbohydrate reserves in animals).

Starch

Starch is the most common carbohydrate in human diets, and is abundant in staple foods such as wheat, rice, and potatoes. It can be **malTED** to produce sugars or **fermented** to produce alcohol.

The word 'starch' refers to a mixture of two types of molecules: **amylose** and **amylopectin**. Both are long polysaccharides consisting of repeating glucose units joined by glycosidic bonds. Amylose is a straight chain made up of approximately 300–3000 glucose units, while amylopectin is a branched chain made up of 2000–200,000 glucose units.

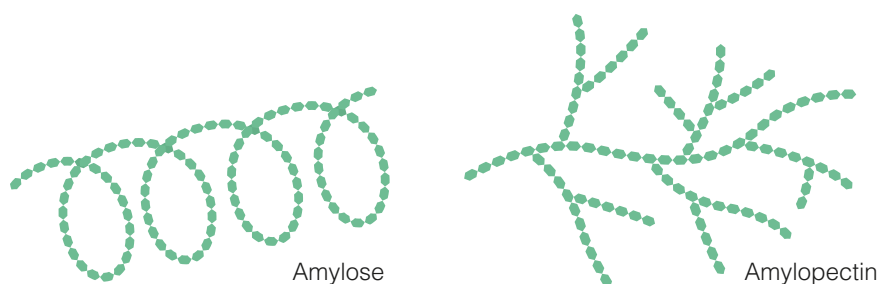
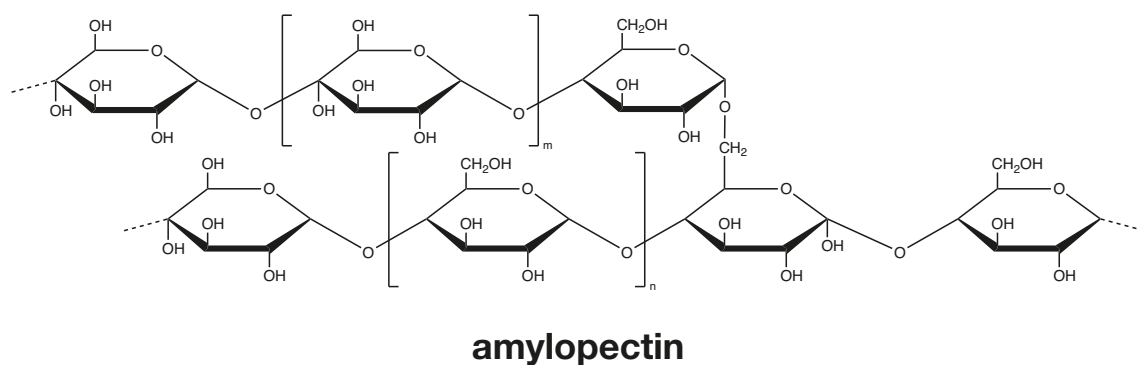
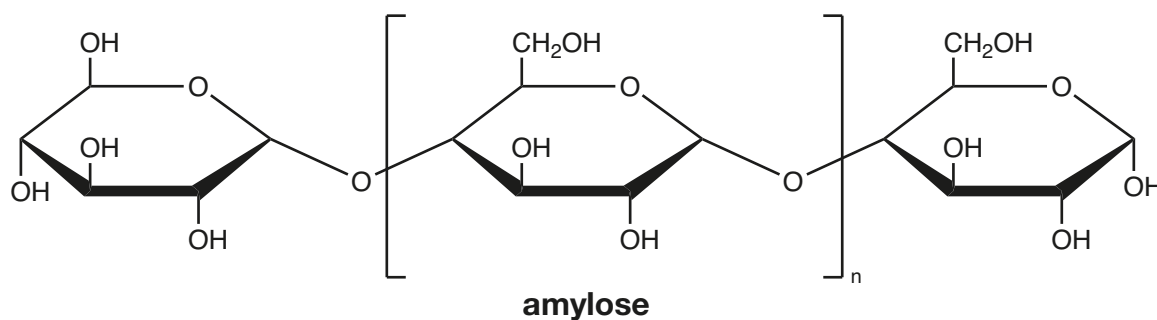


Figure 3.08 - Macromolecular structure of the components of starch

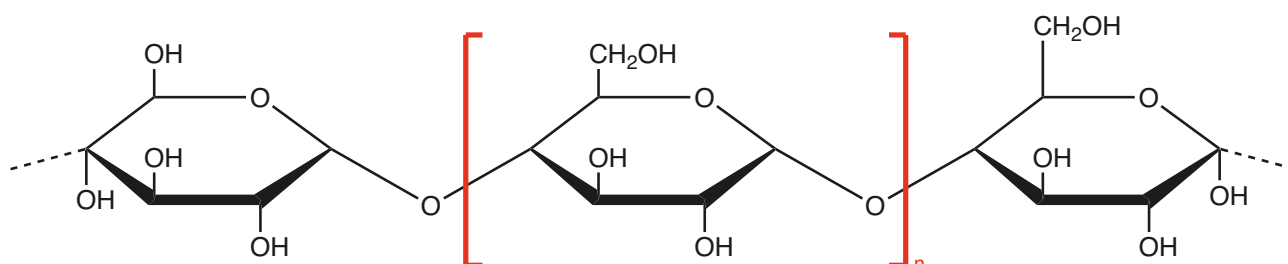
Physical properties

Due to their large molecular size, polysaccharides are insoluble in water. The polymer chains are densely tangled and form strong hydrogen bonds with each other, so water molecules cannot completely separate them. However, hydrogen bonding between polysaccharide chains and water molecules does occur; hence, polysaccharides can *absorb* significant amounts of water.

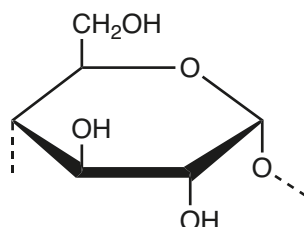
Heat can disrupt the polymer chains, so some polysaccharides can dissolve in boiling water. This is why foods that contain starch are usually only edible when cooked.

Repeating Units and Monomers

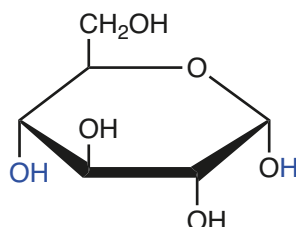
To find the repeating unit in a polysaccharide, look for the glycosidic bond that links the monomers together (the $-O-$ link). Draw square brackets around one of these, ensuring that only one glycosidic oxygen is included.



To draw the monomer from the repeating unit, transcribe the section of the repeating unit identified above.

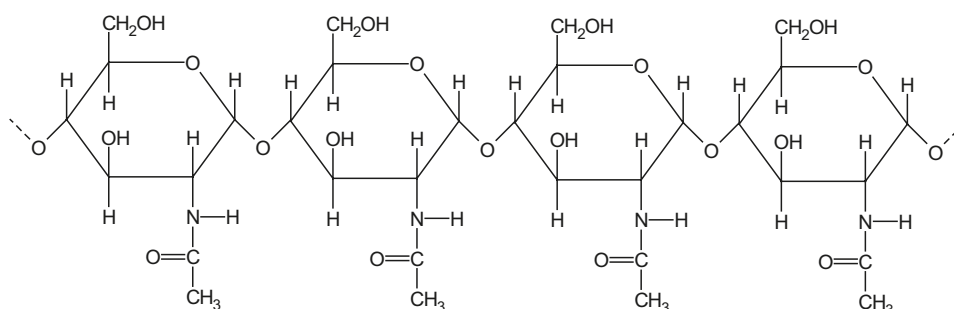


Then replace the H and OH that was lost as H_2O .



Questions

8. The following polymer represents part of the structure of chitin (pronounced /'kɪtɪn/, KY-tin). Chitin is one of the most important biopolymers in nature. It is mainly produced by fungi, arthropods, and nematodes. In insects, it functions as scaffold material.



- (a) On the structural formula above, use brackets to indicate one repeating unit.

(1 mark) KA1

(b) Draw the monomer from which chitin is formed.

(2 marks) **KA4**

(c) State whether chitin can be classified as a monosaccharide, disaccharide or polysaccharide.

(1 mark) **KA1**

3.5 Carboxylic acids

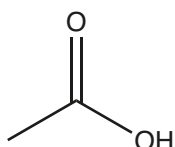
Science understanding

Carboxylic acids can be produced by the oxidation of aldehydes or primary alcohols.

© SACE 2025

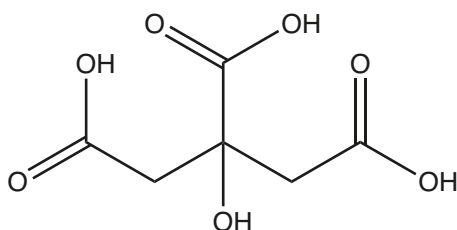
Carboxylic acids are weak organic acids found in nature. Commonly known examples include:

- Acetic acid (systematic name: ethanoic acid), the main component of vinegar
- Citric acid, found in citrus fruits
- Lactic acid, found in sour milk and also produced by our muscles during anaerobic metabolism



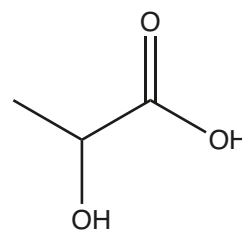
acetic acid

ethanoic acid



citric acid

2-hydroxypropane-1,2,3-tricarboxylic acid

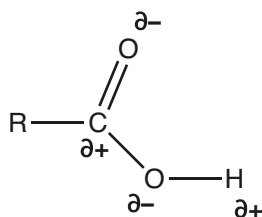


lactic acid

2-hydroxypropanoic acid

Carboxylic acids are also a very important part of the production of the polymers that make fibres and paints.

The functional group of carboxylic acids is the **carboxyl** group, named as such because it is made up of a **carbonyl** group (C=O) and a **hydroxyl** group (-OH). The carboxyl functional group is extremely polar.

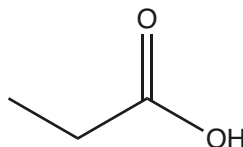


carboxylic acid

Carboxylic acids have the **general formula** $C_nH_{2n+1}COOH$. Carboxylic acids can also be written as $R-COOH$, or $R-CO_2H$, where "R" represents the alkyl chain component.

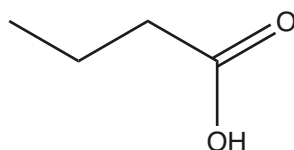
When **naming** carboxylic acids:

- the -e is removed from the parent alkane and replaced with *-oic acid*. For example, propane becomes *propanoic acid*.



propanoic acid

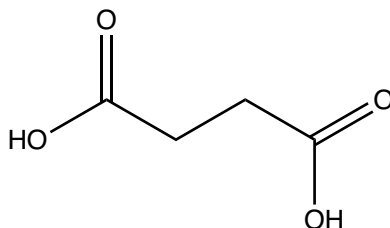
- It is not necessary to number the position of the functional group, as it is always terminal.



butanoic acid

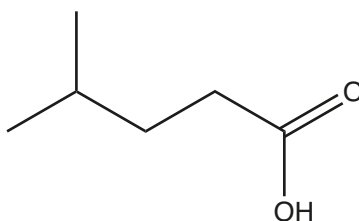
(not butan-1-oic acid)

- The prefix *di-* is used before *-oic acid* if there are two carboxyl functional groups. The *-e* is included in the name of the parent alkane.



butanedioic acid

- If there are branches, always begin numbering from the functional group.



4-methylpentanoic acid

Carboxylic acids are produced by the complete oxidation of primary alcohols and aldehydes.

Physical properties of carboxylic acids

Due to high potential of the carboxyl group to form hydrogen bonds, carboxylic acids have significantly higher melting and boiling points than other organic compounds with similar molecular masses. They are also more soluble in water than other polar organic compounds with similar molecular masses due to the many sites where hydrogen bonding can occur.

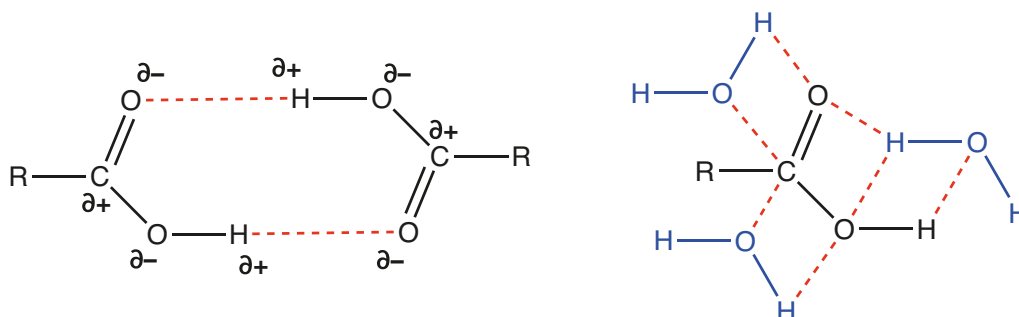


Figure 3.09: Carboxyl groups can form multiple hydrogen bonds

Compound	butanoic acid	pentan-1-ol	pentanal
Structure			
Molar Mass (g/mol)	88.1	88.1	86.1
Boiling Point (°C)	163	137	103
Solubility (g/L water)	miscible	32.7	14.8

Table 3.05: boiling points and solubility of alcohols, aldehydes, and carboxylic acids.

Carboxylic acids up to butanoic acid are very soluble in water; however, solubility decreases as the carbon chain length increases. This is because the hydrocarbon chain is non-polar and **hydrophobic**. As the carbon chain becomes longer, it becomes harder for the polar water molecules to surround and interact with the carboxylic acid to dissolve it.

Acid	Solubility (g/L water)
methanoic acid	miscible
ethanoic acid	miscible
propanoic acid	miscible
butanoic acid	miscible
pentanoic acid	50
hexanoic acid	11
heptanoic acid	2.4
octanoic acid	0.68
nonanoic acid	0.3
decanoic acid	0.15

Table 3.06: Solubility of carboxylic acids

3

Science understanding

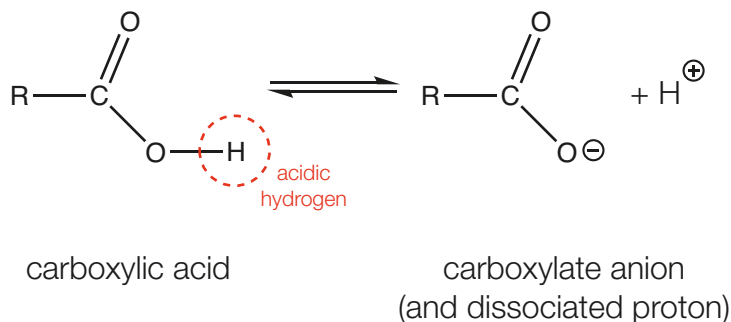
Carboxylic acids are weak acids and, to a small extent, ionise in water.

© SACE 2025

Reactions of carboxylic acids

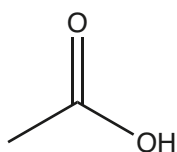
Carboxylic acids are acidic due to the acidic hydrogen in the hydroxyl group. The hydrogen can be lost as H^+ , which then bonds to water to form the hydronium ion, H_3O^+ . The anion that is formed when the carboxylic acid loses its H^+ is called the **carboxylate anion**.

Carboxylic acids are **weak acids**, meaning they do not completely dissociate in water. Typically, fewer than 5% of the molecules are dissociated at any one time.

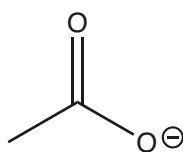


Salts of carboxylic acids are named in the same way as the salts of inorganic acids. First, the cation is named. The name of the carboxylate anion is generated by replacing *-ic acid* with *-ate*.

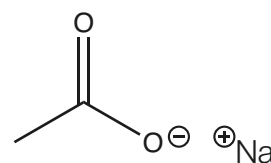
Example



ethanoic acid



ethanoate ion



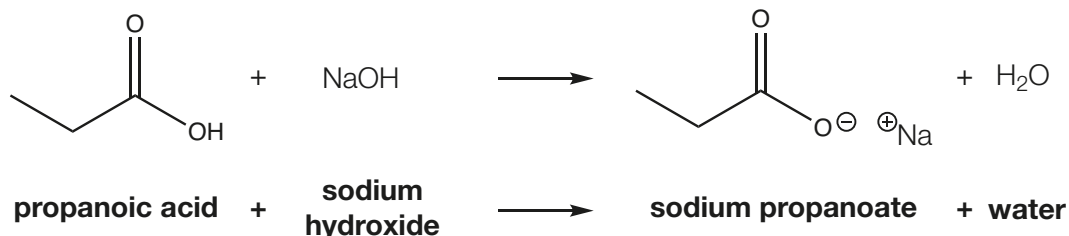
sodium ethanoate

Carboxylic acids undergo typical acid reactions, generally at a much lower rate than inorganic acids.

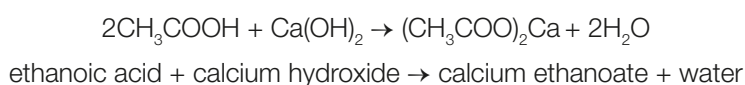
Reaction with metal hydroxides

All carboxylic acids, whether soluble or insoluble in water, react with strong bases to form water-soluble salts.

Example



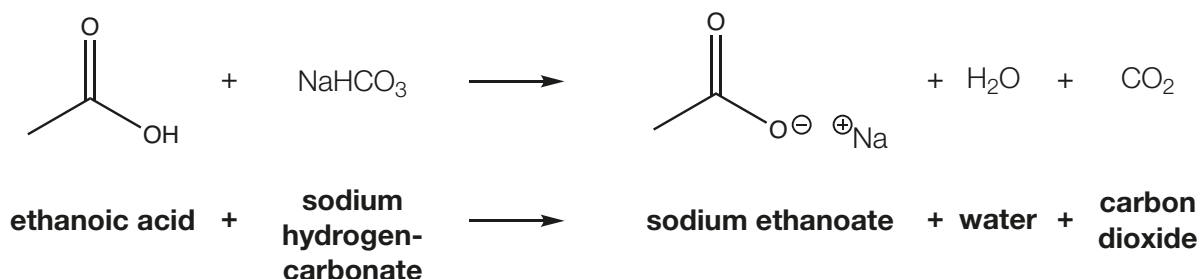
Example



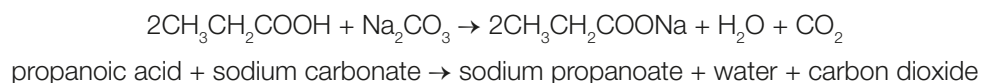
Reaction with carbonates and hydrogen-carbonates

Carboxylic acids react with carbonates and hydrogen-carbonates to produce water-soluble salts, water, and carbon dioxide gas. These reactions effervesce due to the production of gaseous carbon dioxide.

Example



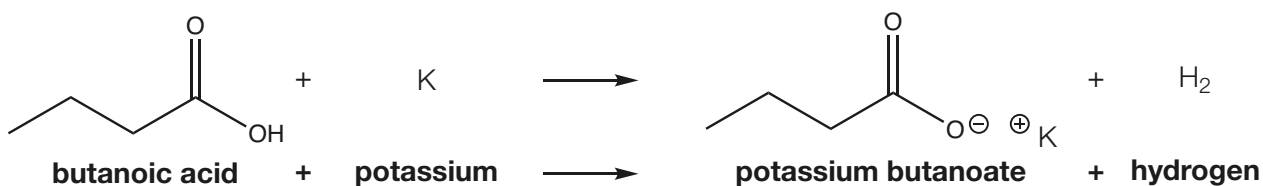
Example



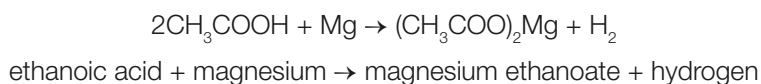
Reaction with metals

Carboxylic acids react with the more reactive metals to produce a salt and hydrogen gas.

Example



Example



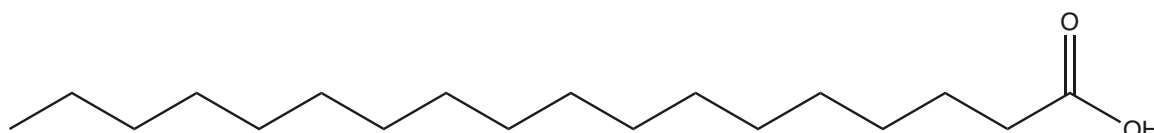
Solubility of carboxylate salts

Sodium and potassium carboxylate salts are *always soluble in water*, regardless of the solubility of the parent carboxylic acid.

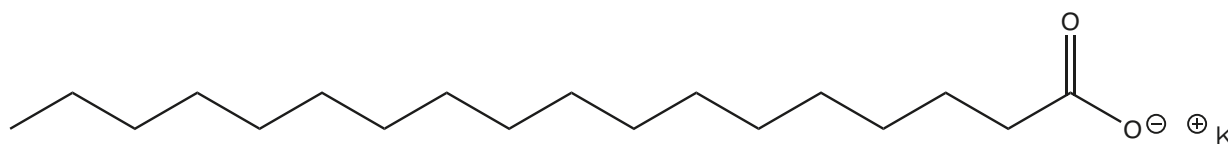
Carboxylic acids have *partial* charges on the polar hydroxyl group, which allows them to form hydrogen bonds with polar water. However, the solubility due to this hydrogen bonding decreases as the carbon chain length increases. When a carboxylate salt dissociates in water it forms the carboxylate anion, which has a *full* negative charge. The full charge on the ion allows for stronger ion-dipole interactions with water, and hence increased solubility.

Example

Stearic acid is a waxy, solid fatty acid. It is a long-chain carboxylic acid with 18 carbon atoms and is insoluble in water. However, its sodium salt (sodium stearate) is soluble.



stearic acid
(octadecanoic acid)
insoluble

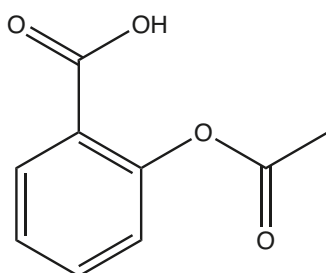


sodium stearate
(sodium octadecanoate)
soluble

Many pharmaceuticals contain carboxyl functional groups. However, because of their complex structures, they are insoluble in water and bodily fluids. Converting the drug to its carboxylate salt form allows it to dissolve and be more effective in the body.

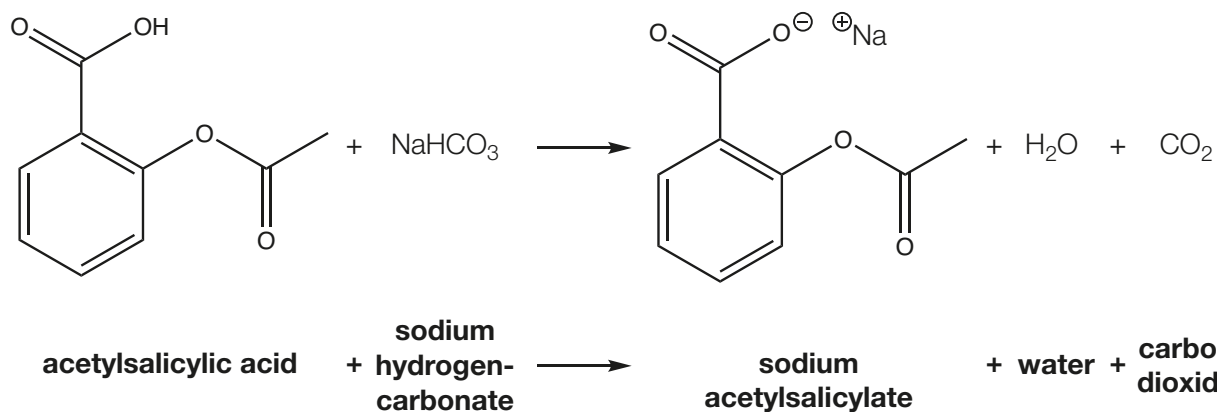
Example

Aspirin (acetylsalicylic acid) has the structure shown below. It is not very soluble in water or in the acids present in the stomach.



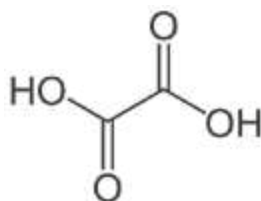
acetylsalicylic acid
(aspirin)
(2-acetoxybenzoic acid)

Sometimes aspirin is sold as “soluble aspirin”, which also contains sodium hydrogencarbonate (NaHCO_3). As the tablet dissolves, the aspirin and sodium hydrogencarbonate react to form the sodium salt of the aspirin, sodium acetylsalicylate. Like all sodium carboxylate salts, the sodium salt of aspirin is soluble in blood and other bodily fluids, as it will form strong ion-dipole interactions with water molecules.



Questions

9. Rhubarb is a pink vegetable commonly used to make tart-flavoured pies, jams, and sauces. The stalks are the only edible part of the rhubarb plant, as the leaves contain poisonous *oxalic acid*. The structural formula of oxalic acid is below:



- (a) Name oxalic acid systemically.

(2 marks) **KA4**

- (b) State the molecular formula of oxalic acid.

(2 marks) **KA4**

- (c) Predict what would be observed when each of the following procedures is carried out. Explain your prediction with the aid of equations.

- (i) Some solid oxalic acid is mixed with sodium hydroxide solution.

(3 marks) **KA1**

- (ii) Some solid oxalic acid is mixed with sodium carbonate solution.

(3 marks) **KA1**

- (d) Other carboxylic acids and their derivatives are used in the production of polymers, biopolymers, coatings, adhesives, and pharmaceutical drugs. They also can be used as solvents, food additives, antimicrobials, and flavourings.

- (i) Name the following carboxylic acids:

(1)		(2)	$\text{CH}_3\text{CH}_2\text{CH}_2\text{CO}_2\text{H}$	(3)	

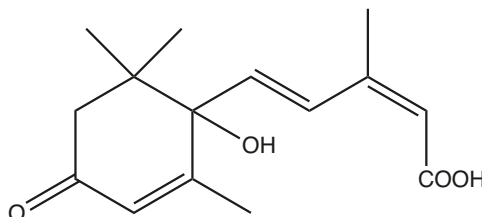
(6 marks) **KA4**

(ii) Draw the following carboxylic acids:

(1.)	hexanoic acid	(2.)	3-methylbutanoic acid	(3.)	octanedioic acid

(6 marks) **KA4**

10. Absciscic acid is a hormone found in plants that helps protect them against external stresses including drought, waterlogged soil, and pathogens. The structure of absciscic acid is shown below.



- (a) Write the molecular formula of absciscic acid.

(2 marks) **KA4**

- (b) Name three functional groups present in absciscic acid.

(3 marks) **KA1**

- (c) A sample of absciscic acid was subjected to several chemical tests. Complete the table below by writing any observations you would expect when the reactions are complete.

Absciscic acid tested with...	Observations
Bromine water (Br_2)	
Acidified dichromate ($\text{Cr}_2\text{O}_7^{2-}/\text{H}^+$)	
Tollens' reagent	
Sodium bicarbonate solution (NaHCO_3)	

(4 marks) **KA1**

- (d) Absciscic acid was reacted with concentrated sodium hydroxide solution.

- (i) Draw the structural product formed.

(2 marks) **KA4**

- (ii) Explain why the organic product of this reaction is more soluble in water than the acid.

(3 marks) **KA1**

11. Read the following article:

Eggs, steak, and butter on everything – it's not like most health food diets. But the high-fat “ketogenic” diet can be an effective last resort method of reducing seizures in people with epilepsy that doesn't respond to drugs, and may even help a range of other brain conditions. Now researchers may have figured out how it works – and how to make the method more palatable.

“All the time, you're looking at getting the fat in,” says Emma Williams, whose son Matthew used to eat like this. Breakfast might be scrambled eggs with lashings of butter, followed by a lunch of steak and salad, covered in oily dressing. “If we ate out, I'd take butter and oil with me,” says Williams. According to early-stage research, the high-fat ketogenic diet may also help several other brain conditions, including Alzheimer's disease and schizophrenia. The diet seems to have slowed or even stopped cancer growth in a few people with brain tumours who started to follow it to control seizures. When given to mice with tumours, it amplified the effects of radiotherapy. The results are so intriguing that a small trial of the diet in people with brain tumours is planned for next year.

But by far the most common use is for epilepsy. The ketogenic diet has been used in children with severe epilepsy since the 1990s. Two-thirds of those who try it see their number of seizures fall by half or more. In some cases, as happened for Matthew, children can later be weaned off the diet without their epilepsy becoming worse again. Until now, the mechanism behind these effects had been a mystery. Now researchers have discovered that one of the breakdown products of fat binds to molecules on the surface of brain cells, calming the storm of electrical activity that can cause epileptic seizures.

Calm the storm

Our cells usually get their energy from glucose, which comes from the carbohydrates we eat. But when these aren't available, the liver breaks down fat into fatty **acids** and ketones, so that our cells can burn ketones for energy instead. In epilepsy, the thinking has long been that these ketones somehow make neurons in the brain less likely to fire, preventing seizures.

But there was still a puzzle: higher blood ketone levels in those following the diet don't necessarily correlate with fewer seizures. Instead, it has been suggested that a fatty **acid** called **decanoic acid** is responsible for the effect. Previous work found that directly feeding this compound to mice with a version of epilepsy reduced their seizures.

Now lab tests using frog cells have shown that **decanoic acid** directly binds to a molecule that is found on the surface of brain cells and is known to be involved in spreading electrical impulses between different neurons (Brain, DOI: 10.1093/brain/awv325). When **decanoic acid** binds to it, it reduces the flow of electrical current into the cell via this molecule. “It reduces the chance of a neuron firing,” says Robin Williams of Royal Holloway, University of London.

His team's finding could lead to easier dietary regimes that get the same result. “It's a strong theory, and if it translates into practice it could use a more acceptable diet,” says Helen Cross of Great Ormond Street Hospital for Children in London, who wasn't involved in the research. She plans to trial giving **decanoic acid** directly to people.

This could enable more people with epilepsy to benefit from the diet's effects. The ketogenic regime seems to work for adults too, but few follow it because it's so hard to stick to. In the standard version, people have to make sure around three-quarters of their food is fat. “It can be daunting,” says Emma Williams. “You have to weigh every gram of food.”

But simply adding **decanoic acid** to food won't be enough. Under a typical high-carb diet, the body would still rely on glucose for energy, and store away the **decanoic acid** as fat. To make sure that the **decanoic acid** gets into the brain, people would still need a relatively low-carb diet – but not as low as the current ketogenic diet, says Robin Williams.

For instance, in Cross's trial, due to start next year, children with epilepsy will be given **decanoic acid** twice a day, in the form of a yogurt-like drink. They won't be able to eat sugary foods, but will be able to eat plenty of carbs like wholemeal bread and pasta, which release glucose into the blood more slowly. “It's a lot more acceptable,” says Cross. “And there's no measuring involved.”

New Scientist: “How high-fat diet for epilepsy affects the brain”. Clare Wilson. 28/1/2015, Vol. 228 Issue 3049, p12-13

With reference to the information presented in the article above, discuss and explain the importance of **Development** in Science as a Human Endeavour.

(3 marks) **KA1**

3

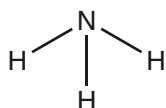
3.6 Amines

Science understanding

Amines are classified as primary, secondary, or tertiary.

© SACE 2025

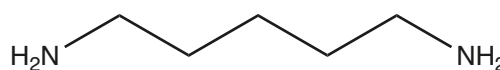
Amines are a class of organic compounds containing the **amino** functional group, which is a carbon bonded to a basic nitrogen with a lone pair. These compounds are derivatives of ammonia, NH_3 (although ammonia is not organic, as it contains no carbon). Amines are abundant in nature, and many have a characteristic unpleasant fishy odour. As their names suggest, the compounds *putrescine* and *cadaverine* are responsible for the *putrid* smell of *cadavers* (decaying animal tissue).



ammonia

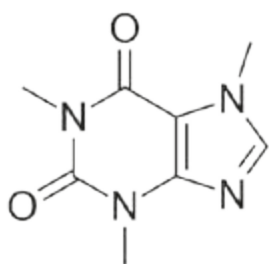


putrescine

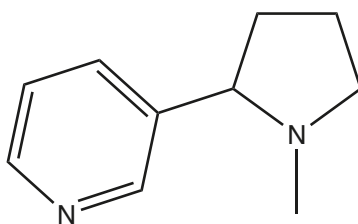


cadaverine

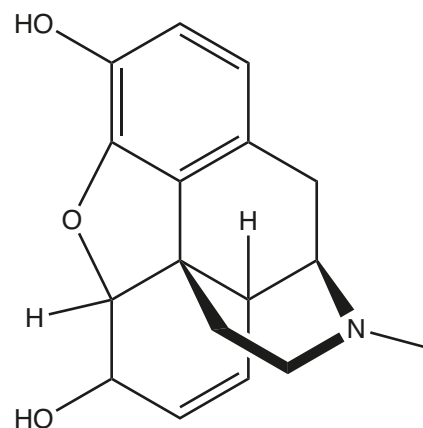
Many amines are extremely poisonous or can cause a variety of effects even in small doses. Some amines are extracted from plants, and commonly-known plant-based amines include caffeine, nicotine, and morphine.



caffeine



nicotine



morphine

Primary, secondary, and tertiary amines

Amines are classified as primary, secondary, or tertiary based on how many carbon atoms are directly connected to the nitrogen atom.

Primary (1°)		A primary amine has the nitrogen covalently bonded to <i>one</i> carbon.	 propanamine
Secondary (2°)		A secondary amine has the nitrogen covalently bonded to <i>two</i> carbons.	 N-methylethanamine
Tertiary (3°)		A tertiary amine has the nitrogen covalently bonded to <i>three</i> carbons.	 N,N-dimethylethanamine

Table 3.07: Amine classification

All amino groups have a trigonal pyramid geometry due to the presence of the lone pair of electrons.

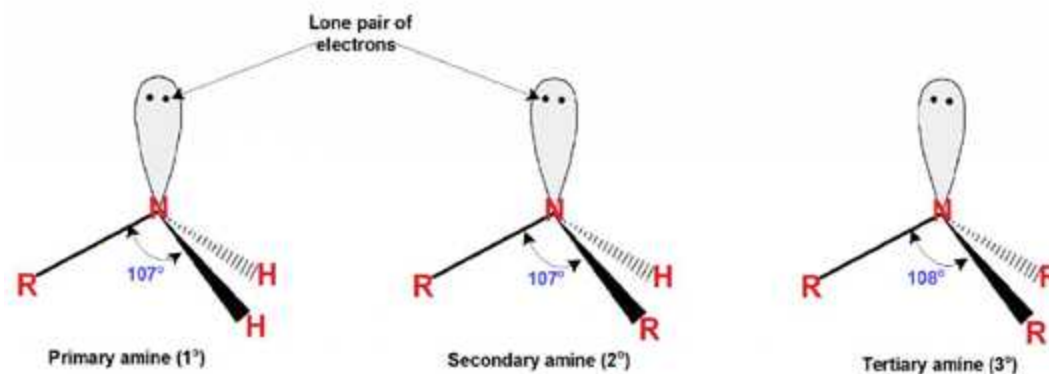


Figure 3.10: Spatial geometry of amino functional groups

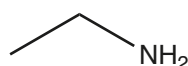
Amines have the general formula $R-NH_2$, R_2-NH , or R_3-N .

This course only requires the naming of primary amines.

- the -e is removed from the parent alkane and replaced with -amine.

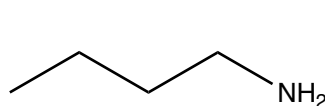
Example

Ethane becomes ethanamine.

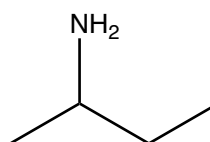


ethanamine

It is necessary to number the position of the functional group in the name, as it is non-terminal and can be placed in different positions.

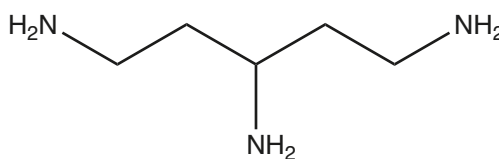


butan-1-amine



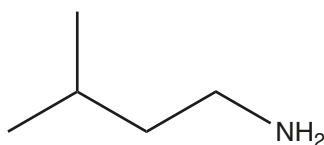
butan-2-amine

The prefixes *di-* and *tri-* are used before -amine if there are two or three amino functional groups. Remember to include numbers to indicate the position of the amino groups. The -e is included in the name of the parent alkane.



pentane-1,3,5-triamine

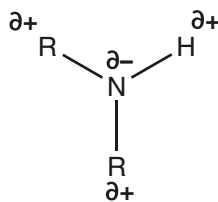
If there are branches, ensure the functional group is assigned the lowest number.



3-methylbutan-1-amine

Physical properties of amines

Both N–C and N–H bonds in amino functional groups are polar. However, because nitrogen is less electronegative than oxygen, the magnitude of the partial charges in amines is considerably less than in functional groups which contain oxygen.



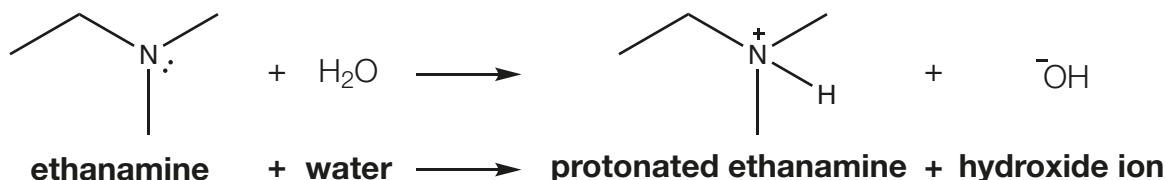
Both primary and secondary amines can form intermolecular hydrogen bonds. They have higher boiling points than alkanes of a similar molar mass, and they are soluble in water. However, as the carbon-chain length increases, the solubility of amines decreases.

Science understanding

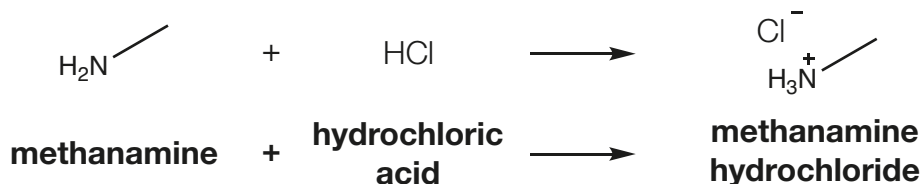
Amines act as bases.

© SACE 2025

The most important chemical property of amines is their basicity. The lone pair on the nitrogen can accept H^+ to form a **protonated amine**. Amines are weak bases; similar to carboxylic acids, they incompletely ionise in aqueous solution.



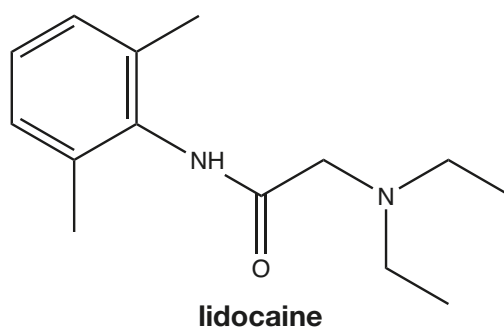
When amines react with acids, they form ionic salts. These ionic salts are water soluble.



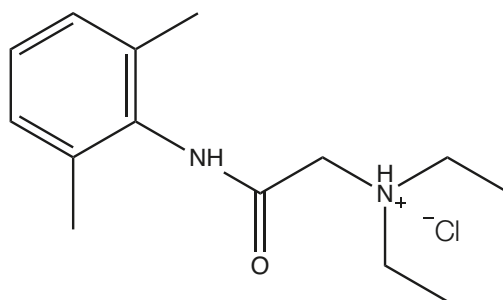
Many pharmaceutical drugs contain amino groups but are also large molecules with many non-polar components. They are administered as water-soluble salts because these amine salts can form strong ion-dipole interactions with polar water molecules. Ion-dipole interactions are stronger than hydrogen bonds; hence, the drugs dissolve more easily in bodily fluids.

Example

Lidocaine is a widely used local anaesthetic that was introduced in 1948. Its structural formula is below:



The molecule is quite big and has large non-polar sections, which makes it essentially insoluble in aqueous bodily fluids. Hence, it is administered in the form lidocaine hydrochloride (marketed under the name Xylocaine®).



lidocaine hydrochloride
(Xylocaine®)

Questions

12. Amines play an important role in biology: they are involved in the creation of amino acids, the building blocks of proteins in living beings. Many vitamins are also built from amino acids. Amines are also widely used in the preparation of medicines.

(a) Identify the functional group of each of the amines as primary, secondary, or tertiary.

(i)		(ii)		(iii)	$\text{H}_3\text{C}-(\text{CH}_2)_5-\text{NH}_2$
(iv)	$(\text{CH}_3)_3\text{N}$	(v)		(vi)	$(\text{CH}_3)_2\text{NH}$

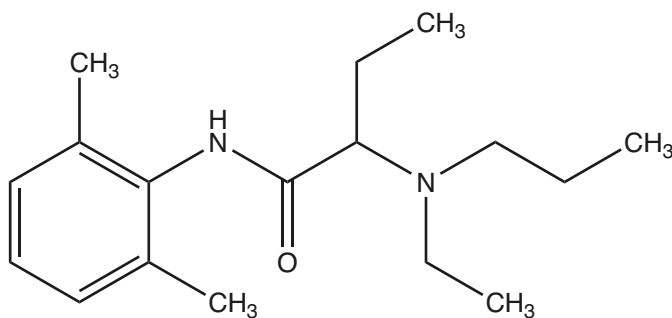
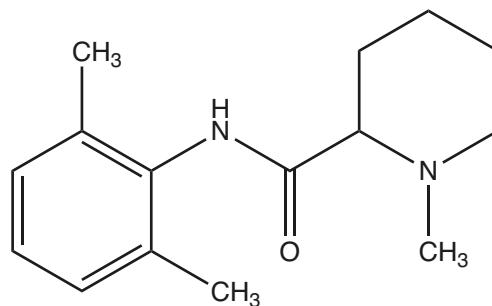
(12 marks) **KA4**

(b) Draw the structural formula of the following amines:

(i)	propan-1-amine	(ii)	methanamine	(iii)	ethane-1,2-diamine
(iv)	hexane-1,6-diamine	(v)	hexane-1,3,4-triamine	(vi)	butan-1-amine

(13 marks) **KA4**

13. Etidocaine and mepivacaine are two local anaesthetics: drugs that numb an area of the body to help reduce pain. Their structures are below.

**etidocaine****mepivacaine**

- (a) Circle the amino functional groups in each compound and classify them as primary, secondary, or tertiary.
(2 marks) **KA1**
- (b) Draw the structure of the protonated form of
- etidocaine; and
 - mepivacaine.

(4 marks) **KA4**

3.7 Esters

Science understanding

Carboxylic acids undergo condensation reactions with alcohols to form esters.

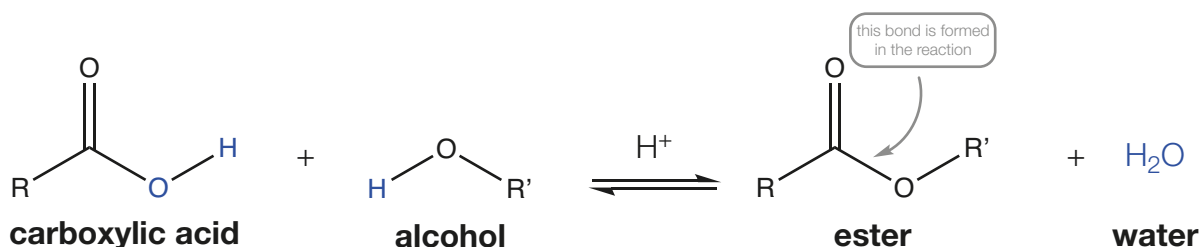
Condensation reactions occur when two organic molecules combine to form a larger molecule, also releasing another small molecule, such as water.

© SACE 2025

Esters are organic compounds that contain the **ester** functional group. Many esters, both natural and synthetic, are encountered in everyday life. They often have a sweet smell and can be used to add flavour or scent to foods and perfumes. Esters are found in:

- Fruits such as bananas, apples, pears, and raspberries
- Artificial flavourings
- Cosmetics, like nail polish remover
- Animal fats and vegetable oils
- Rum and wine

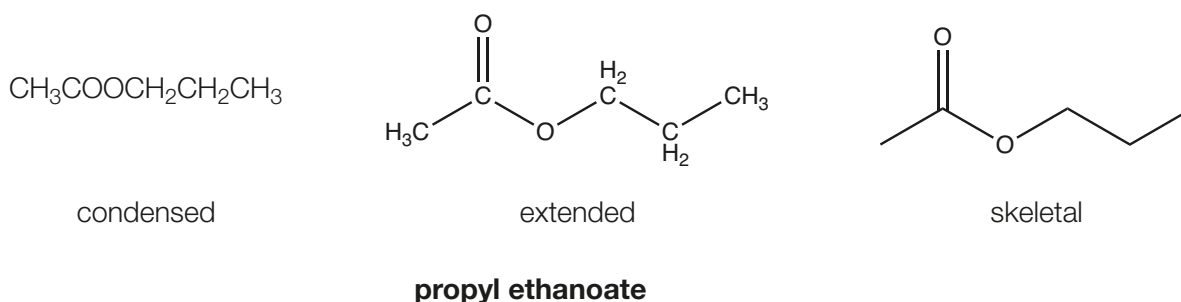
An ester can be prepared by reacting a carboxylic acid with an alcohol in the presence of an acid catalyst. It is a condensation reaction, as a water molecule is produced.



The functional group is called an **ester**. It can be written as **-COO-**.

Example

The ester that gives pears their flavouring is shown here in three different structural forms.



Science understanding

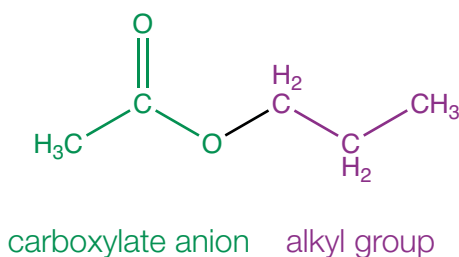
Identify, name systematically, and draw structural formulae of methyl and ethyl esters of acids containing up to eight carbon atoms in the main chain, with side chains limited to a maximum of two carbon atoms.

Draw the structural formula of the ester that could be produced by the condensation reaction between a carboxylic acid and an alcohol, given their structural formulae or vice versa.

© SACE 2025

Naming esters

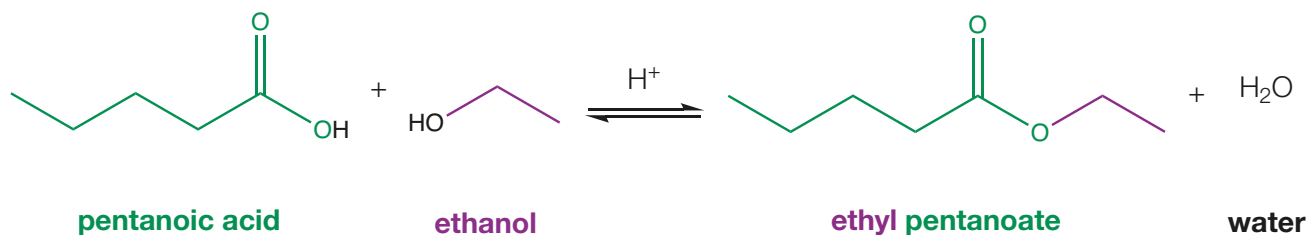
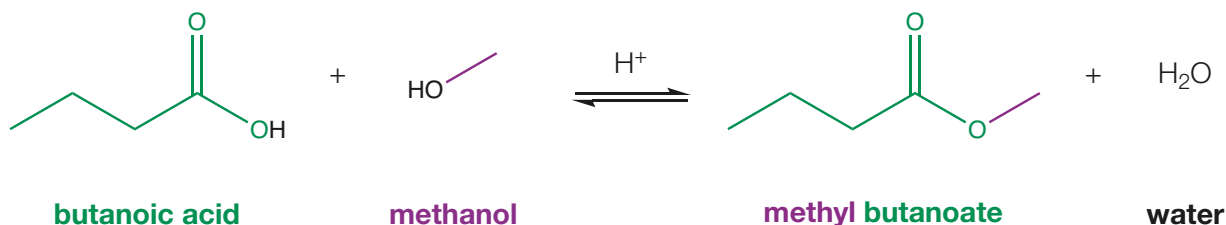
Esters are composed of two parts: the carboxylate ion and the alkyl group.



As such, there are two parts to the name of an ester.

- The first part is derived from the alkyl group. The alkane suffix *-an-* and the alcohol suffix *-ol* are removed and replaced with the ending that signifies a hydrocarbon fragment: *-yl*. For example, *methanol* becomes *methyl*, *ethanol* becomes *ethyl*, *propanol* becomes *propyl*, and so on.
- The second part of the name is simply the carboxylate anion. The carboxylic acid suffix is removed and replaced with *-oate*. For example, *methanoic acid* becomes *methanoate*, *ethanoic acid* becomes *ethanoate*, *propanoic acid* becomes *propanoate*, and so on.

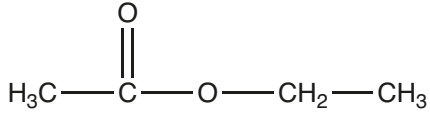
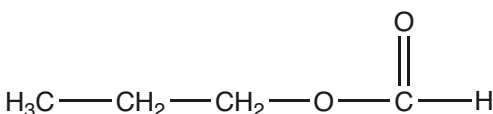
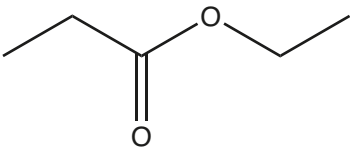
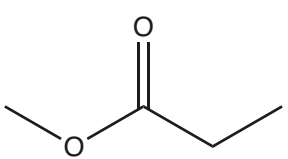
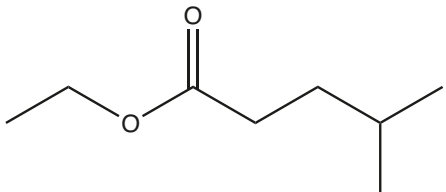
Example



Questions

14. Esters are found in food flavourings, perfumes, and in biological molecules such as triglycerides. Esters can also be used to make products such as soap and biodiesel.

(a) Name the following esters systematically and name the alcohol and carboxylic acid from which they are prepared.

i)		ii)	$\text{CH}_3\text{OOCCH}_2\text{CH}_2\text{CH}_3$
Name:		Name:	
Alcohol:		Alcohol:	
Carboxylic acid:		Carboxylic acid:	
iii)		iv)	
Name:		Name:	
Alcohol:		Alcohol:	
Carboxylic acid:		Carboxylic acid:	
v)		vi)	
Name:		Name:	
Alcohol:		Alcohol:	
Carboxylic acid:		Carboxylic acid:	

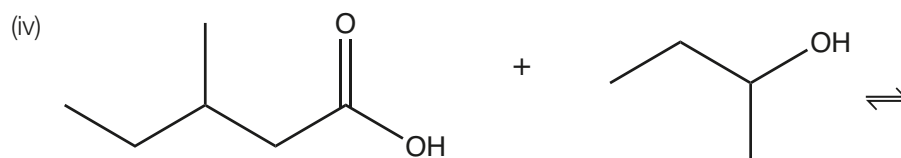
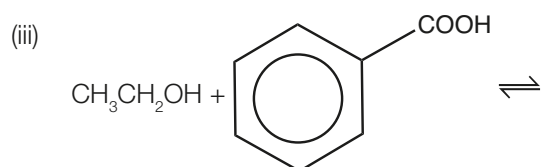
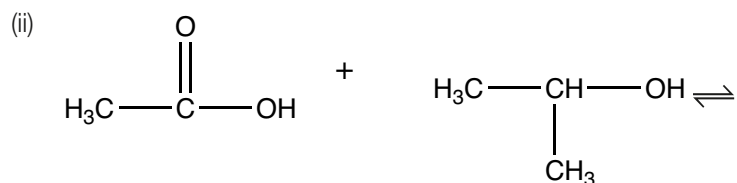
(24 marks) **KA4**

(b) Draw the following esters:

(i)	methyl hexanoate	(ii)	2-methylpropyl propanoate
(iii)	butyl butanoate	(iv)	propyl octanoate

(8 marks) **KA4**

(c) Draw the products of the following reactions:



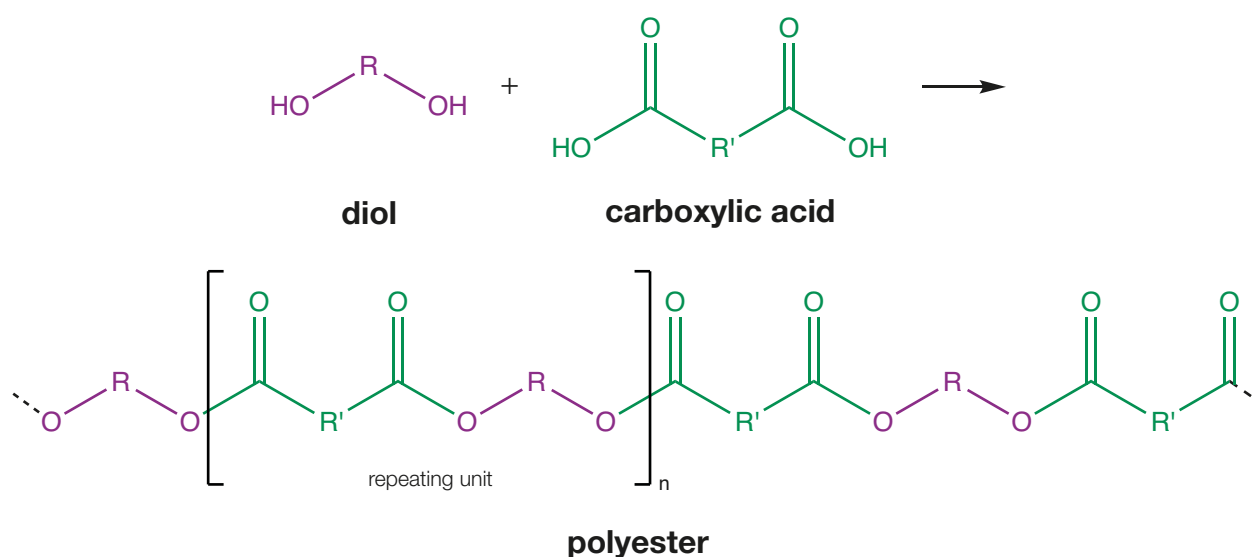
(8 marks) KA4

Science understanding

Draw the structural formula of a polyester, given the structural formula(e) of the monomer(s) or vice versa.

© SACE 2025

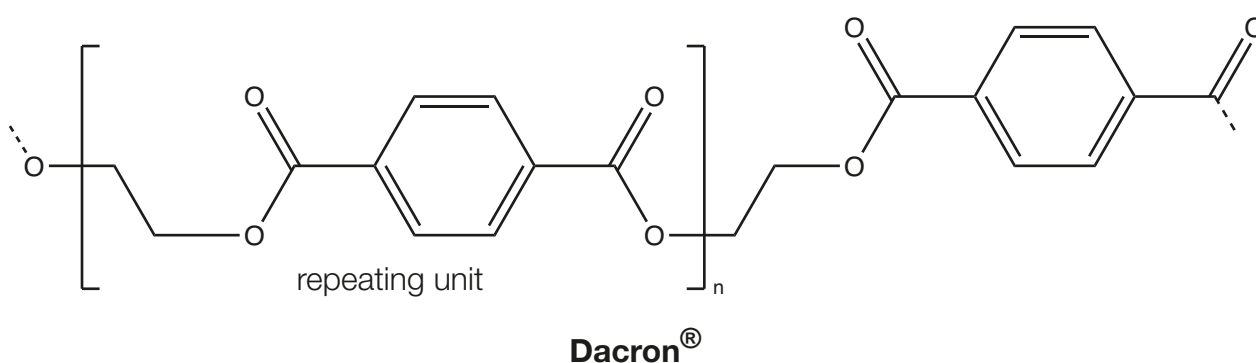
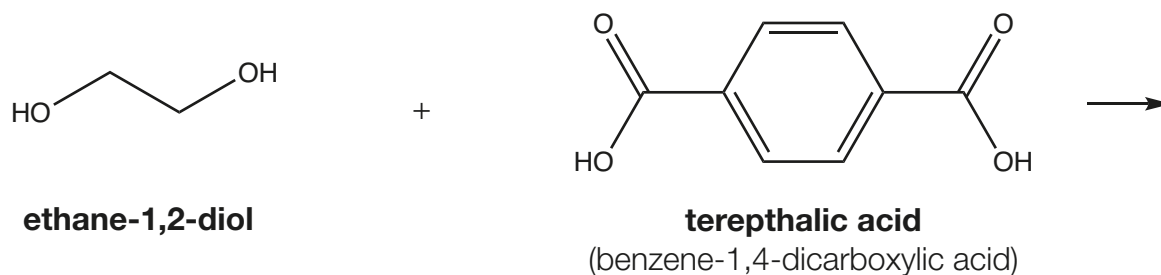
When a diol and a dicarboxylic acid react, they form a compound called a **polyester**. Two different monomers (the diol and dicarboxylic acid) have combined to form a polymer. *Polymers are discussed in more detail in Chapter 4.*



This is also a condensation reaction, as one water molecule is produced for each ester group. As there are many ester functional groups present, it is called polyester ("poly" meaning "many").

Example

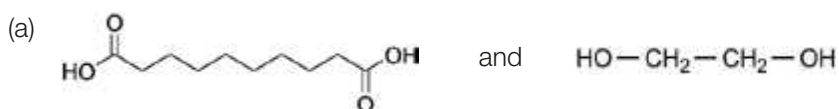
Dacron® is a polymer widely used in fibres for the manufacture of clothing. It is formed from the condensation reaction of ethane-1,2-diol and a dicarboxylic acid called terephthalic acid.



Thus, Dacron is a polyester.

Questions

15. Draw the structural formula of the polyesters that are formed in the reactions below. Show at least two repeating units. On the diagram, draw brackets around the repeating unit and circle the functional group.

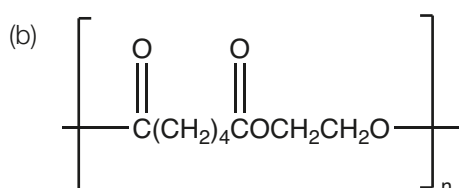
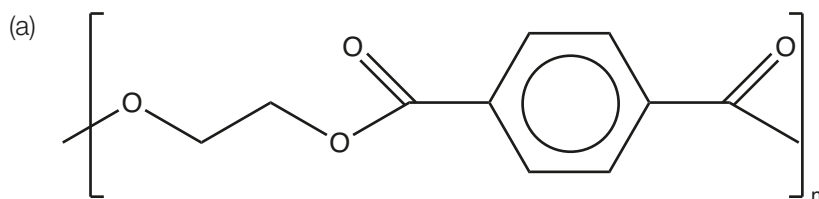


(4 marks) **KA4**

- (b) Butane-1,4-diol and hexanedioic acid

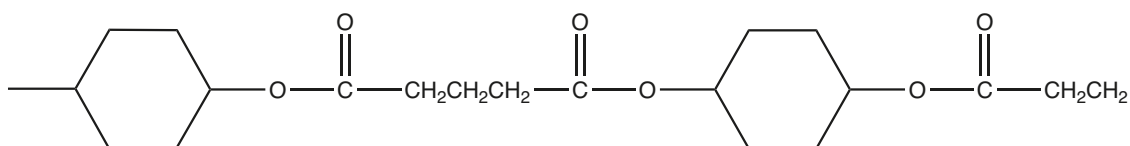
(4 marks) **KA4**

16. For the following polyesters, draw the two monomers from which it could be made.



(4 marks) **KA4**

(c) The following is the structural diagram of a polyester.



(i) Draw brackets around the repeating unit.

(1 mark) **KA1**

(ii) Draw the structural formulae of the two monomers from which this polymer could be made.

(4 marks) **KA4**

Science understanding

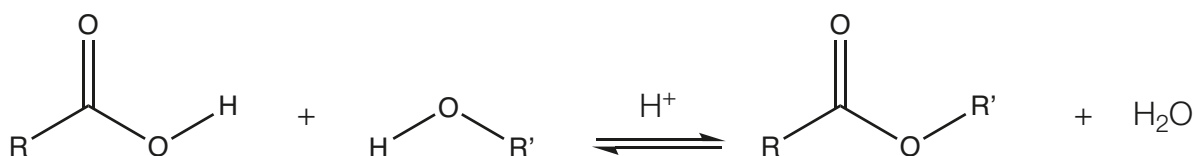
Condensation reactions are slow at 25°C.

Explain the use of heating under reflux, and the use of a trace of concentrated sulfuric acid in the laboratory preparation of esters.

© SACE 2025

Esterification

The reaction between a carboxylic acid and an alcohol in the presence of an acid catalyst, usually concentrated sulfuric acid, is called **Fischer esterification**, after the German chemist Emil Fischer.



The Fischer Esterification

Acid-catalysed esterification is reversible and will eventually reach a state of equilibrium. The equilibrium constant (K_c) is much less than 1, meaning the equilibrium favours the backward reaction. By controlling the reaction conditions, it is possible to shift the position of equilibrium to give a higher yield of ester. According to Le Châtelier's principle, an increase in the concentration of alcohol will drive the equilibrium to favour the forward reaction. *Equilibrium and Le Châtelier's principle are discussed in detail in Topic 2.2.*

Heating Under Reflux

Ester formation is very slow at 25°C, even with a catalyst, so it is important to heat the contents of the flask. However, the reactants and products are usually volatile, and the heating needs to be *controlled*. The apparatus used for heating the reaction mixture is shown below. It is called **reflux apparatus**.

When the mixture boils, the vapours rise up from the flask and enter the **condenser**. Cold water flows up from the bottom of the water jacket of the condenser and cools the vapours, which condense and run back into the flask. The heating must be controlled so the reactants do not boil so vigorously as to escape the flask. The solution should be simmering, the flask should not be filled more than halfway, and the condensing vapours should not reach higher than halfway up the condenser.

The use of reflux apparatus allows for extended boiling without evaporative loss of the reactants or products, which are often volatile liquids.

After an extended period of heating, the contents in the flask include the original alcohol, carboxylic acid, and sulfuric acid, as well as the ester and water. Reflux is usually followed by distillation to isolate the product(s).

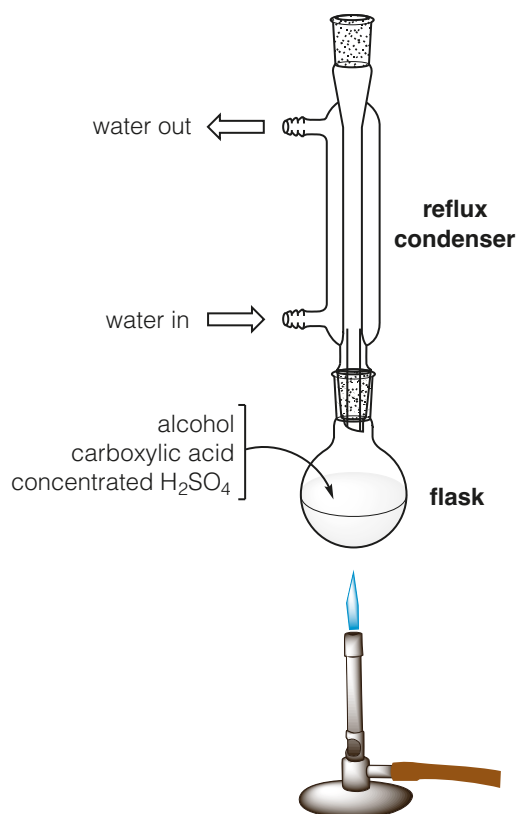
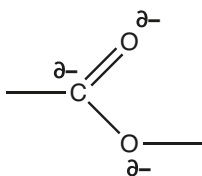


Figure 3.11: Reflux apparatus for esterification

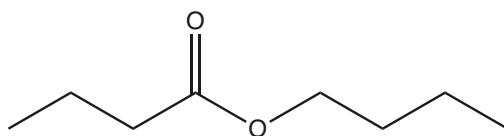
Physical properties of esters

Boiling point



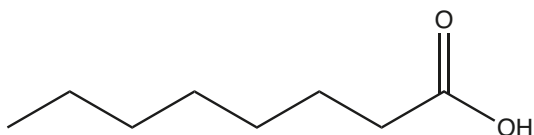
Esters have a polar functional group.

Unlike alcohols and carboxylic acids, ester molecules are unable to form hydrogen bonds between each other, instead experiencing dipole-dipole secondary interactions. This is because the carbon atom with a $\delta+$ charge is surrounded by other bulky atoms and cannot be accessed by $\delta-$ atoms in other molecules. The boiling points of esters are therefore significantly lower than carboxylic acids and alcohols with similar molar masses.



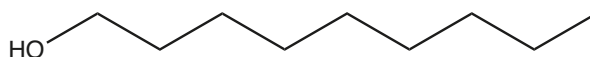
butyl butanoate

144.21 g/mol
boiling point: 77 °C



octanoic acid

144.21 g/mol
boiling point: 237 °C

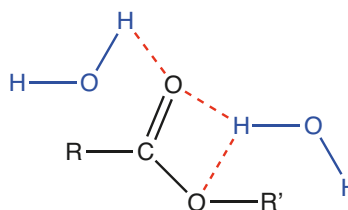
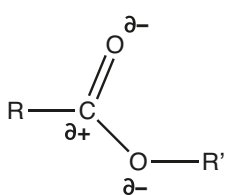


nonan-1-ol

144.26 g/mol
boiling point: 214 °C

Solubility in water

The ester functional group is polar. Hence, small esters are soluble in water as they can form hydrogen bonds with polar water molecules. However, solubility decreases with increasing carbon chain length, as the overall molecule becomes more non-polar.

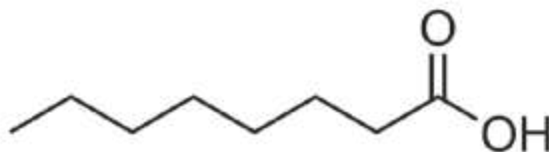


Ester	Solubility (g/L water)
ethyl methanoate	105
ethyl ethanoate	87
ethyl propanoate	17
ethyl butanoate	12
ethyl pentanoate	2

Table 3.08: Ester solubility

Questions

17. Caprylic acid is one of the acids found in coconut oil. It has some antibacterial properties and can be taken as a dietary supplement or used in cosmetics. Its structure is below.



- (a) State the systematic name of caprylic acid.

(2 marks) **KA4**

- (b) Caprylic acid can be refluxed with ethanol in the presence of concentrated sulfuric acid. It produces a compound that has a pleasant apple flavour and odour.

- (i) Draw the structural formula of the new compound.

(2 marks) **KA4**

- (ii) Write the systematic name of the new compound.

(2 marks) **KA4**

- (iii) State the purpose of adding concentrated sulfuric acid to the reaction.

(1 mark) **KA1**

- (iv) Explain why the contents of the flask are heated under reflux.

(2 marks) **KA1**

- (v) Explain why ethanol is added in excess in the esterification reaction.

(4 marks) **KA1**

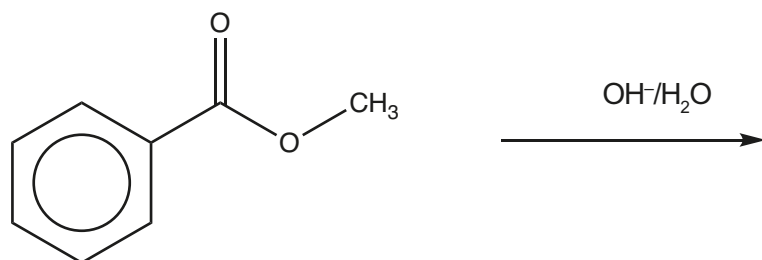
Esters may be hydrolysed under acidic or alkaline conditions.

© SACE 2025

Questions

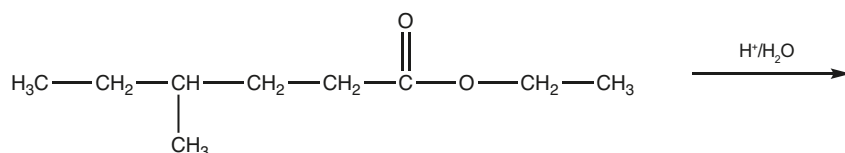
18. Complete the following ester hydrolysis reactions.

(a)



(4 marks) **KA4**

(b)

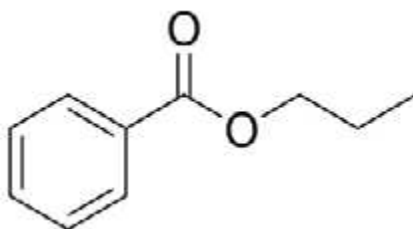


(4 marks) **KA4**

(i) Name the products in (b) systematically.

(2 marks) **KA1**

(c) The ester propyl benzoate is shown below.



Propyl benzoate

It can be hydrolysed with hot, concentrated sodium hydroxide solution.

(i) Draw the products below.

Carboxylate salt	Alcohol

(4 marks) **KA4**

(ii) Explain why the carboxylate salt is soluble in water while the original ester is not.

(3 marks) **KA1**

3.8 Amides

Science understanding

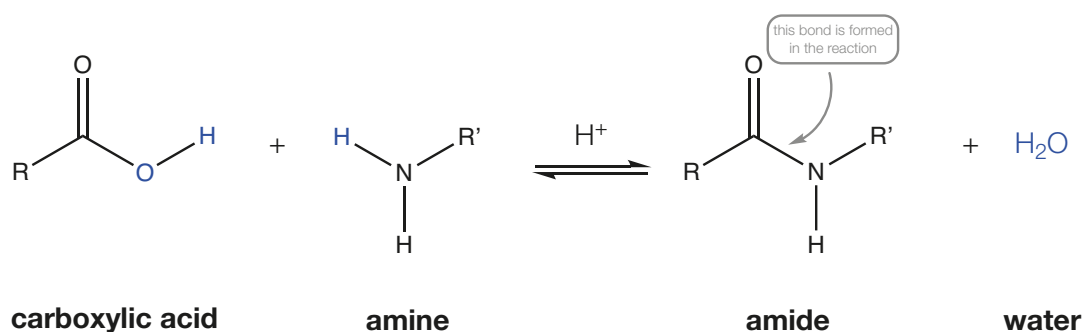
Carboxylic acids undergo condensation reactions with amines to form amides.

Draw the structural formula of the amide formed from a carboxylic acid and an amine, given their structural formulae or vice versa.

© SACE 2025

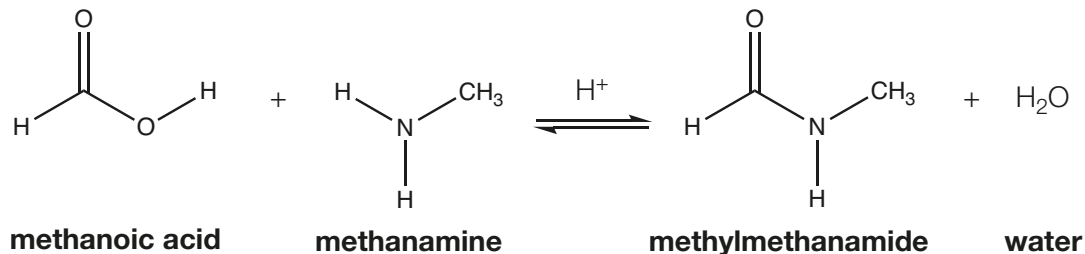
An amide is an organic compound formed by the condensation reaction between a carboxylic acid and an amine. The name of the functional group is also **amide**.

Example

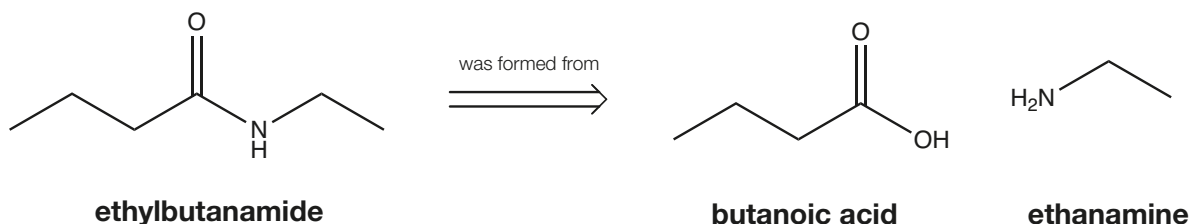


Example

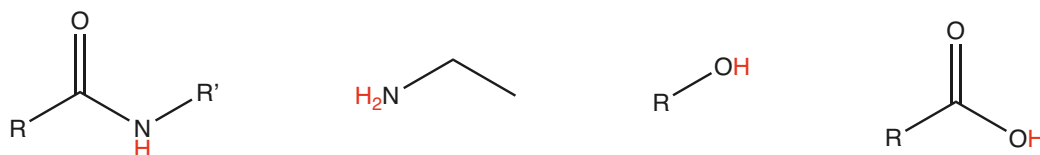
Methanoic acid reacts with methanamine to produce an amide and water.



The structural formula of the original carboxylic acid and amine can be determined from the amide.



When using skeletal formulas, only hydrogens bonded to carbon can be omitted. The hydrogen atom covalently bonded to the nitrogen within the amide functional group must always be drawn (similar to the hydrogen atom in hydroxyl groups).



Hydrogens that are not bonded to carbon are always drawn.

The naming of amides is not required for SACE Stage 2 Chemistry.

Questions

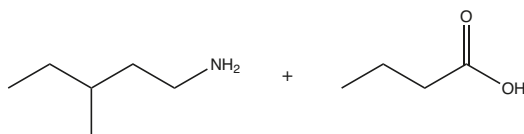
19. Amides are found in natural substances, from black pepper and caffeine to penicillin and anandamide found in chocolate.

(a) Draw the structural formulae for the amides that can be prepared from the following reagents:

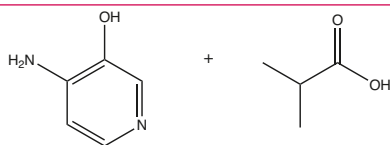
(i) Butan-1-amine and propanoic acid

(ii) Pentanoic acid and propan-2-amine

(iii)



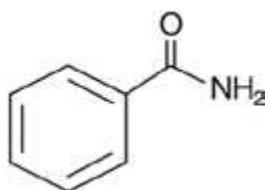
(iv)



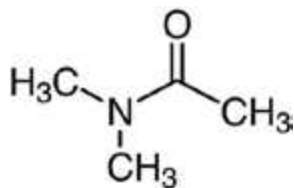
(8 marks) **KA4**

(b) Draw the structural formulae of the carboxylic acids and amines that react to form the amides below:

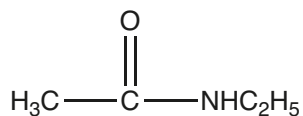
(i)



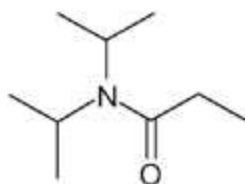
(ii)



(iii)



(iv)



(8 marks) **KA4**

Primary, secondary, and tertiary amides

Amides are classified as primary (1°), secondary (2°), or tertiary (3°) based on how many carbon atoms are directly bonded to the nitrogen atom.

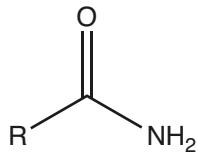
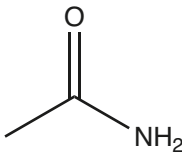
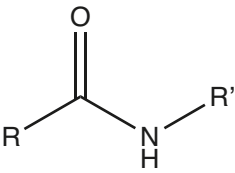
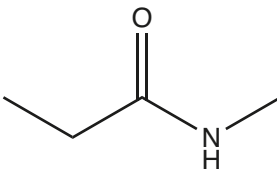
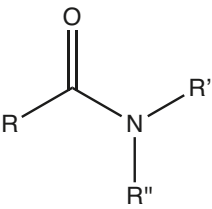
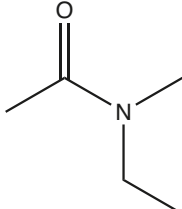
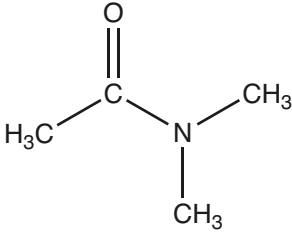
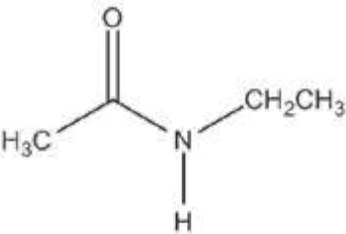
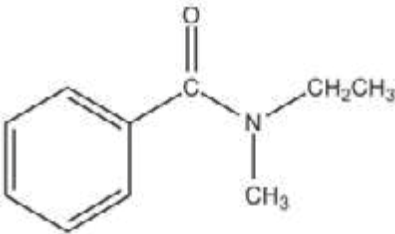
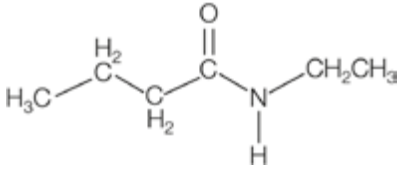
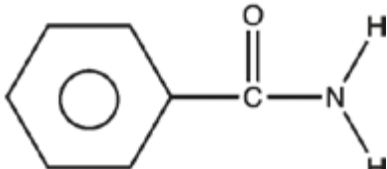
			Examples
Primary (1°) amide		One carbon covalently bonded to the nitrogen atom.	
Secondary (2°) amide		Two carbons directly covalently bonded to the nitrogen atom.	
Tertiary (3°) amide		Three carbons directly covalently bonded to the nitrogen atom.	

Table 3.09: Amide classification

Questions

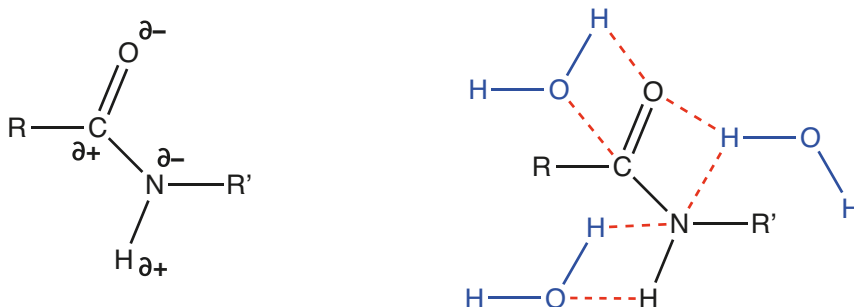
20. Identify the following amides as primary, secondary, or tertiary.

		
(i)	(ii)	(iii)
		
(iv)	(v)	

(5 marks) **KA1**

Solubility of amides

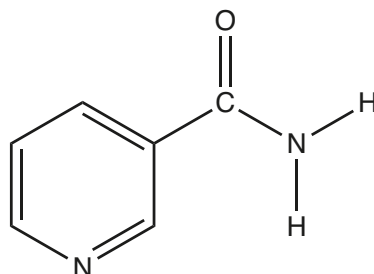
The amide functional group is polar. It can form hydrogen bonds with water.



As with esters, small amides are soluble, but solubility decreases as the lengths of the carbon chains increase.

Questions

21. Niacinamide, shown below, is becoming quite popular in the skincare industry, with many facial cleansers boasting this “miracle ingredient”.



Niacinamide molecule

Explain why niacinamide is soluble in water and on the skin.

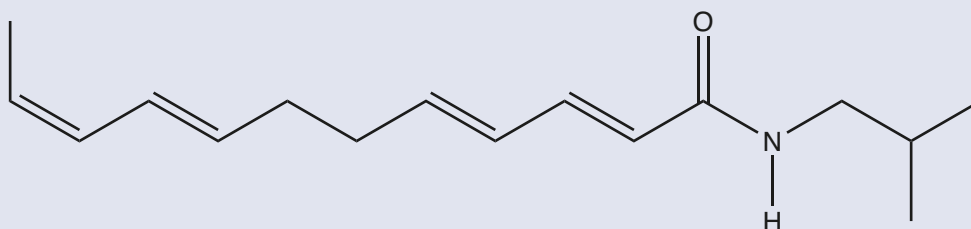
(3 marks) **KA1**



Science as a human endeavour

Plant based insecticides

Rather than using synthetic insecticides, scientists are turning towards plant-derived substances. Many plants have developed their own chemicals that protect them from insects, and one such plant has a particular amide in its leaves that kills *Aedes aegypti*, the yellow fever mosquito. Scientists are hoping that these plant extracts can help rural communities by treating small pools of water which are breeding grounds for these disease-bearing mosquitoes.

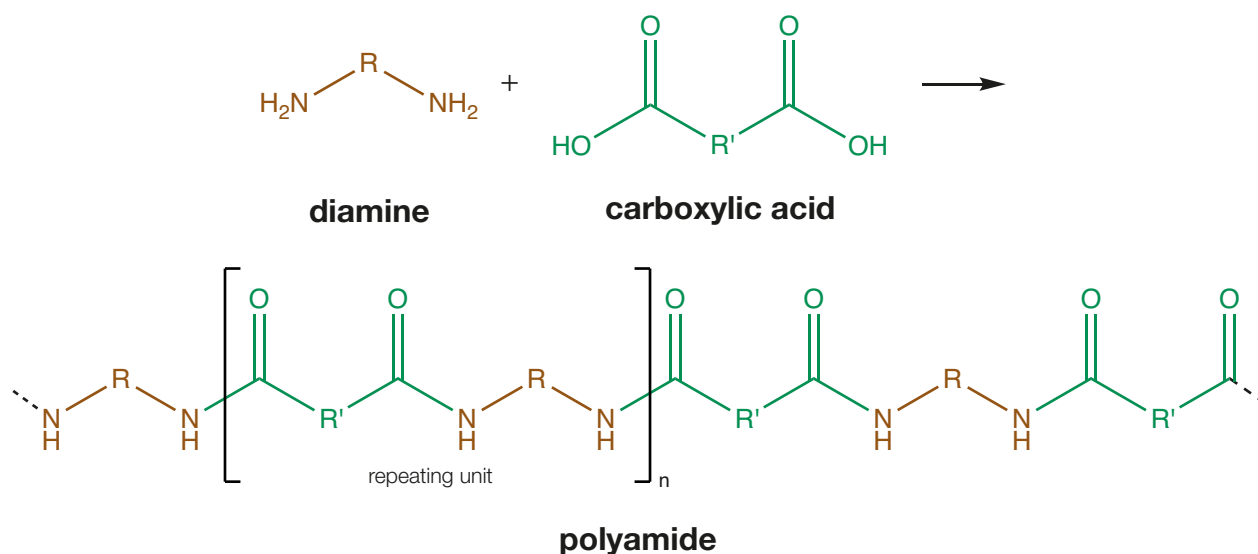


Science understanding

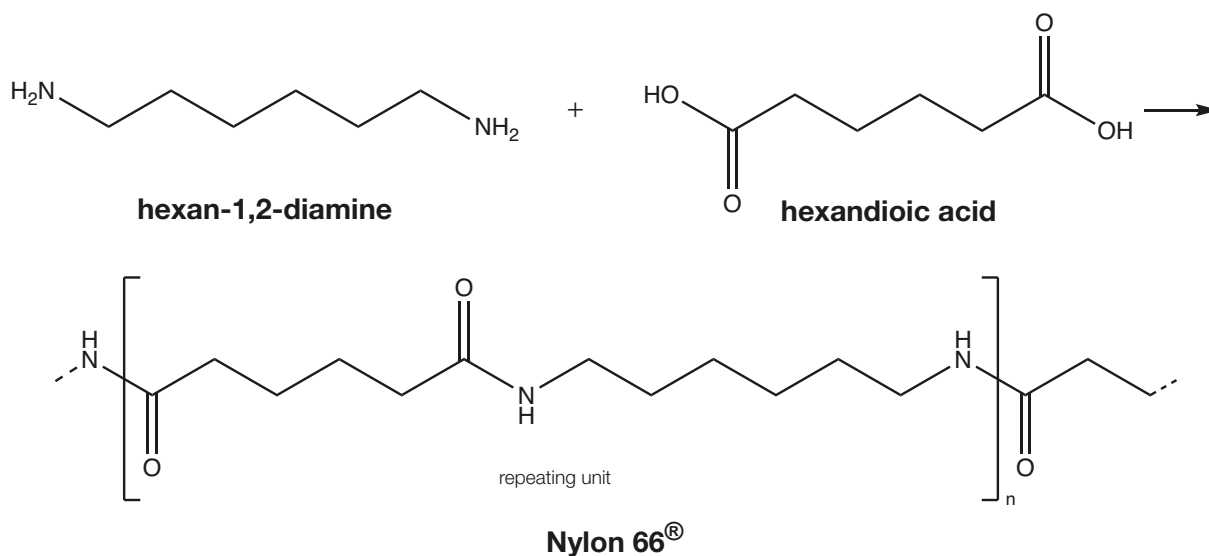
Draw the structural formula of a polyamide, given the structural formula(e) of the monomer(s) or vice versa.

© SACE 2025

Polyamides are polymers formed in the condensation reaction between a dicarboxylic acid and a diamine.

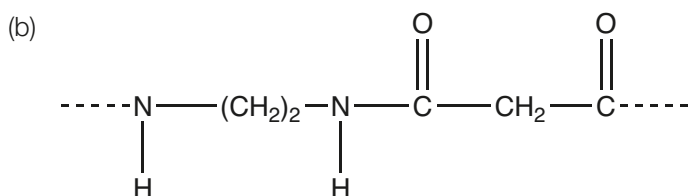
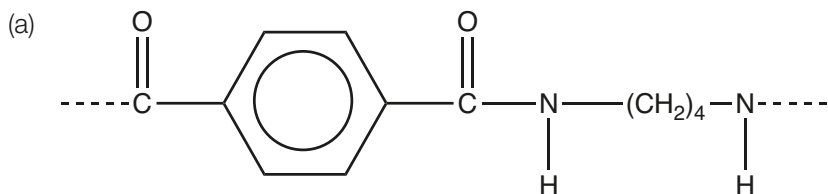


Nylon 66 is a polyamide used in fibres for textiles and carpets. It is formed from the reaction between hexan-1,6-diamine and hexandioic acid.



Questions

22. For the following polymers, draw the structural formula of the monomers.



(8 marks) **KA4**

(c) Draw the structural formula of the polyamides that are formed in the reactions below.

(i) Ethanediamine and propanedioic acid

(ii) Decanedioic acid and butane-1,4-diamine

(4 marks) **KA4**

Science understanding

Amides may be hydrolysed under acidic or alkaline conditions.

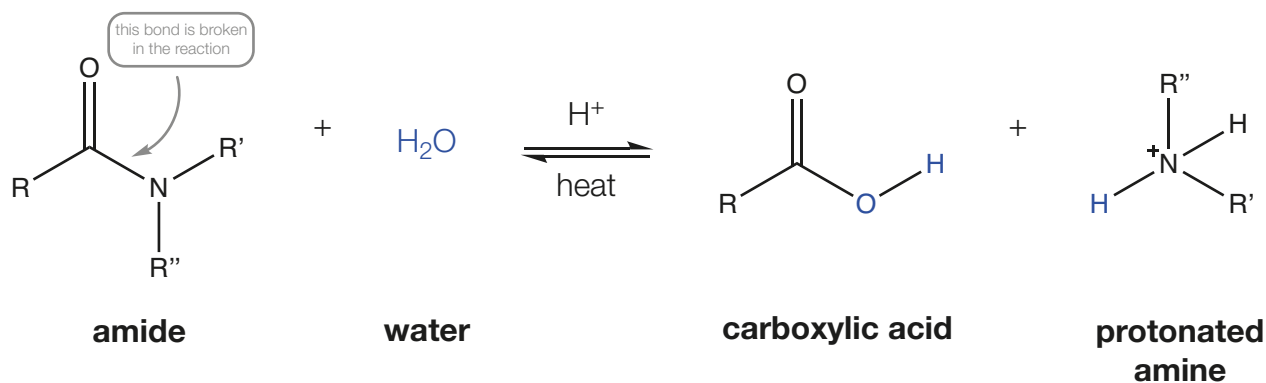
Identify the products of acidic or alkaline hydrolysis of an amide or polyamide, given the appropriate structural formula.

© SACE 2025

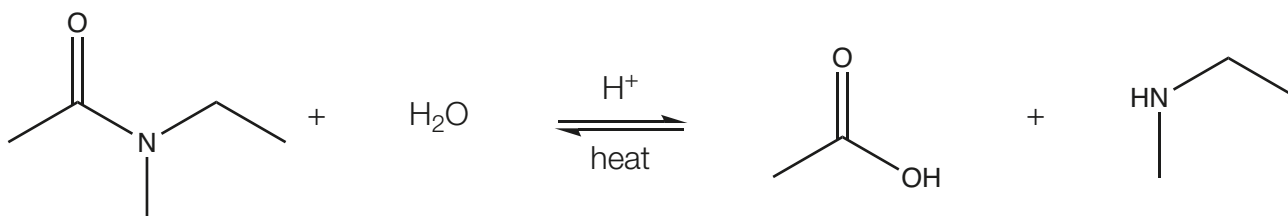
Amides can undergo hydrolysis in acidic or alkaline conditions. They require more vigorous conditions for hydrolysis than esters. The products of hydrolysis are different, depending on the pH of the reaction. Amide hydrolysis is a common reaction in biological systems; it is the initial step in the digestion of protein.

Acidic hydrolysis

If an amide is refluxed with water using a hot, aqueous acid, the products are the original carboxylic acid and a **protonated amine**. This reaction is reversible.

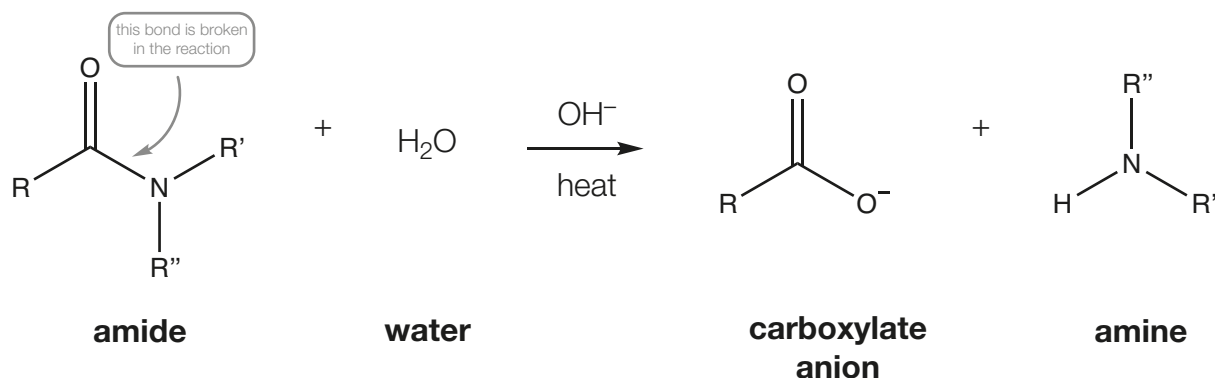


Example

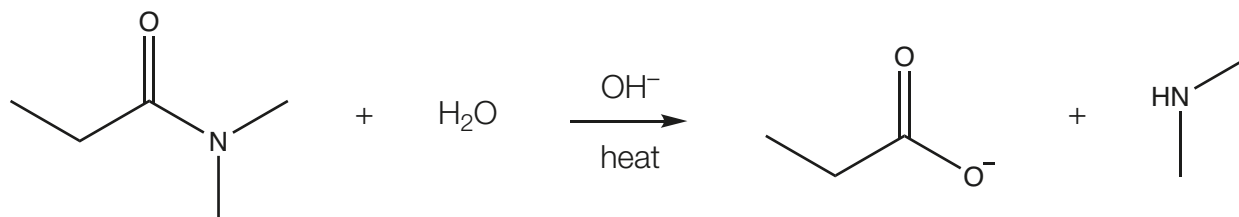


Alkaline hydrolysis

When an amide is refluxed with water using a strong base, such as NaOH, the products are a **carboxylate anion** and an amine. This hydrolysis reaction is driven to completion as the carboxylate anion forms a salt with the spectator cation from the catalytic base.

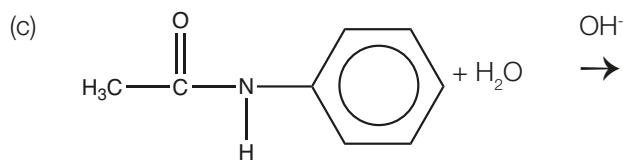
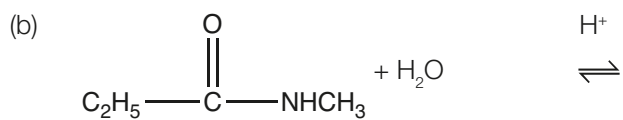
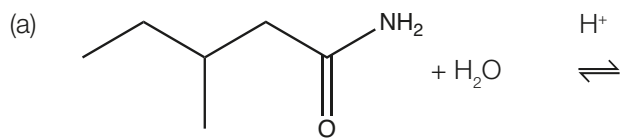


Example



Questions

23. Draw the structural formulae of the products of the following amide hydrolysis reactions.



(12 marks) **KA4**

3

3.9 Triglycerides

Science understanding

Edible oils and fats are esters of propane-1,2,3-triol (glycerol) and various carboxylic acids.

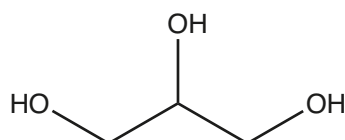
Draw the structural formula of an edible oil or fat, given the structural formula(e) of the carboxylic acid(s) from which it is derived.

© SACE 2025

Fats and oils, like those that come from animal fats, fish oils, and vegetable oils, are naturally occurring esters. The esters are made from one molecule of propane-1,2,3-triol, called **glycerol**, and three long-chain carboxylic acids, called **fatty acids**.

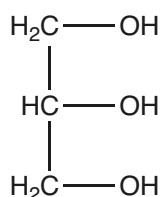
Glycerol

Glycerol is the common name for propane-1,2,3-triol, a small molecule with three hydroxyl groups.



glycerol
(propane-1,2,3-triol)

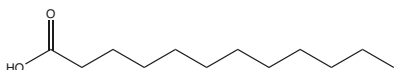
Because there are three hydroxyl groups in the glycerol molecule, three fatty acid molecules can be covalently bonded to one glycerol molecule. Glycerol is often drawn in such a way that the long-chain fatty acids can be conveniently drawn to the right.



glycerol
(propane-1,2,3-triol)

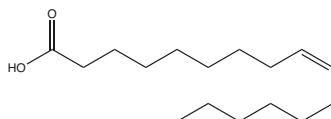
Fatty acids

Fatty acids are long-chain carboxylic acid molecules found in fats. The chains are unbranched and usually contain an even number of carbon atoms in the range 12–22. The chains can be **saturated** (only single bonds between carbon atoms) or **unsaturated** (at least one double or triple bond between carbon atoms). Unsaturated fatty acids with one double or triple bond are called **monounsaturated**. Unsaturated fatty acids with more than one double or triple bond are called **polyunsaturated**.



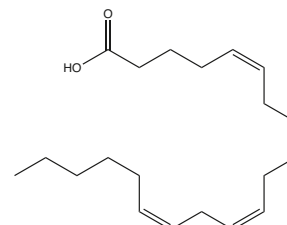
lauric acid
(dodecanoic acid)

a saturated fatty acid



palmitoleic acid
(hexadec-9-enoic acid)

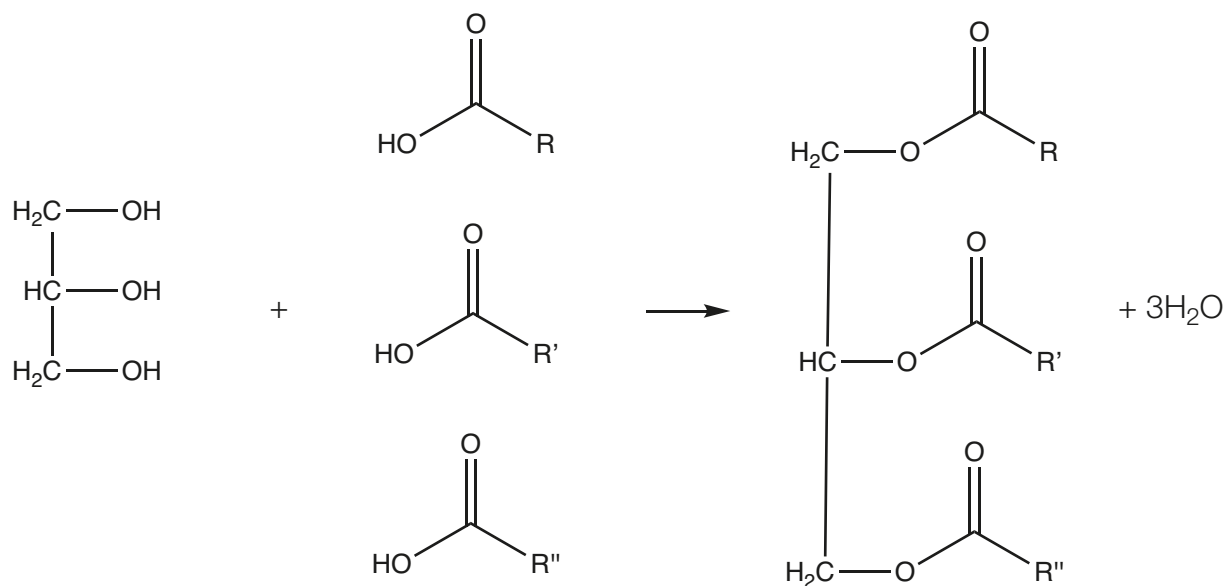
a monounsaturated fatty acid



arachidonic acid
(icosa-5,8,11,14-tetraenoic acid)

an polyunsaturated fatty acid

One molecule of glycerol reacts with three fatty acids to form a compound with three ester groups. Hence, these fats and oils are called **triesters** or **triglycerides**. As with any reaction involving an alcohol and a carboxylic acid, one molecule of water is produced for every ester group formed. For a triglyceride, three molecules of water are produced. The three fatty acids in the triglyceride are not necessarily the same.



3

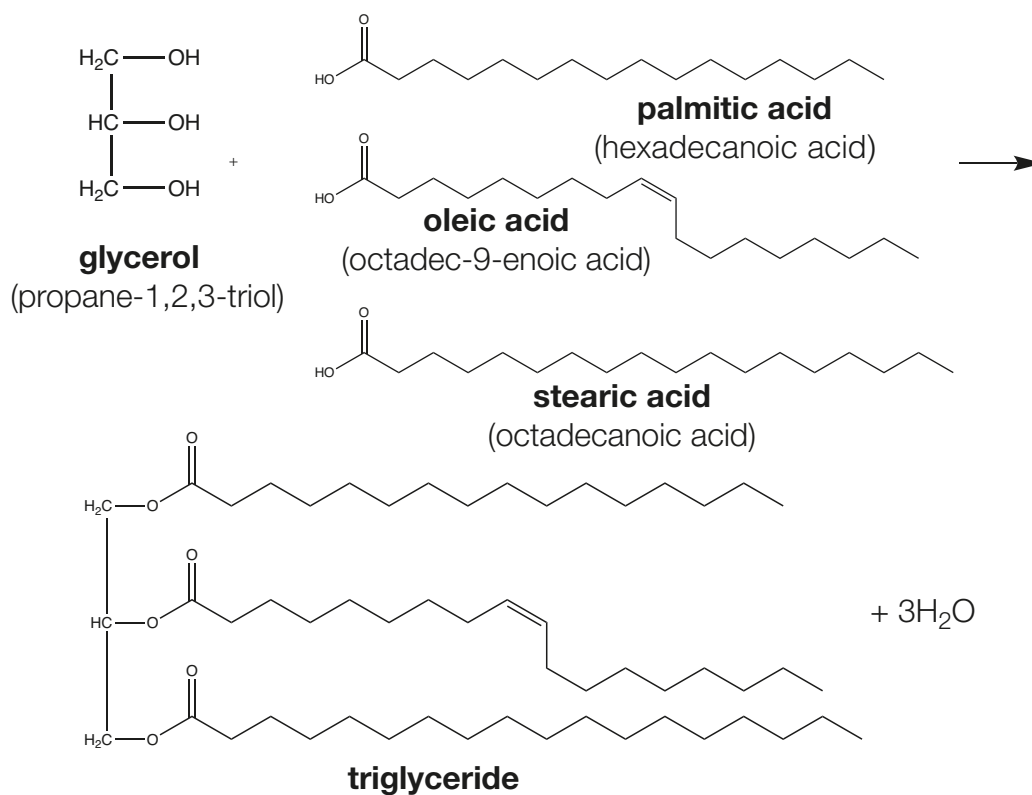
glycerol
(propane-1,2,3-triol)

three fatty acids

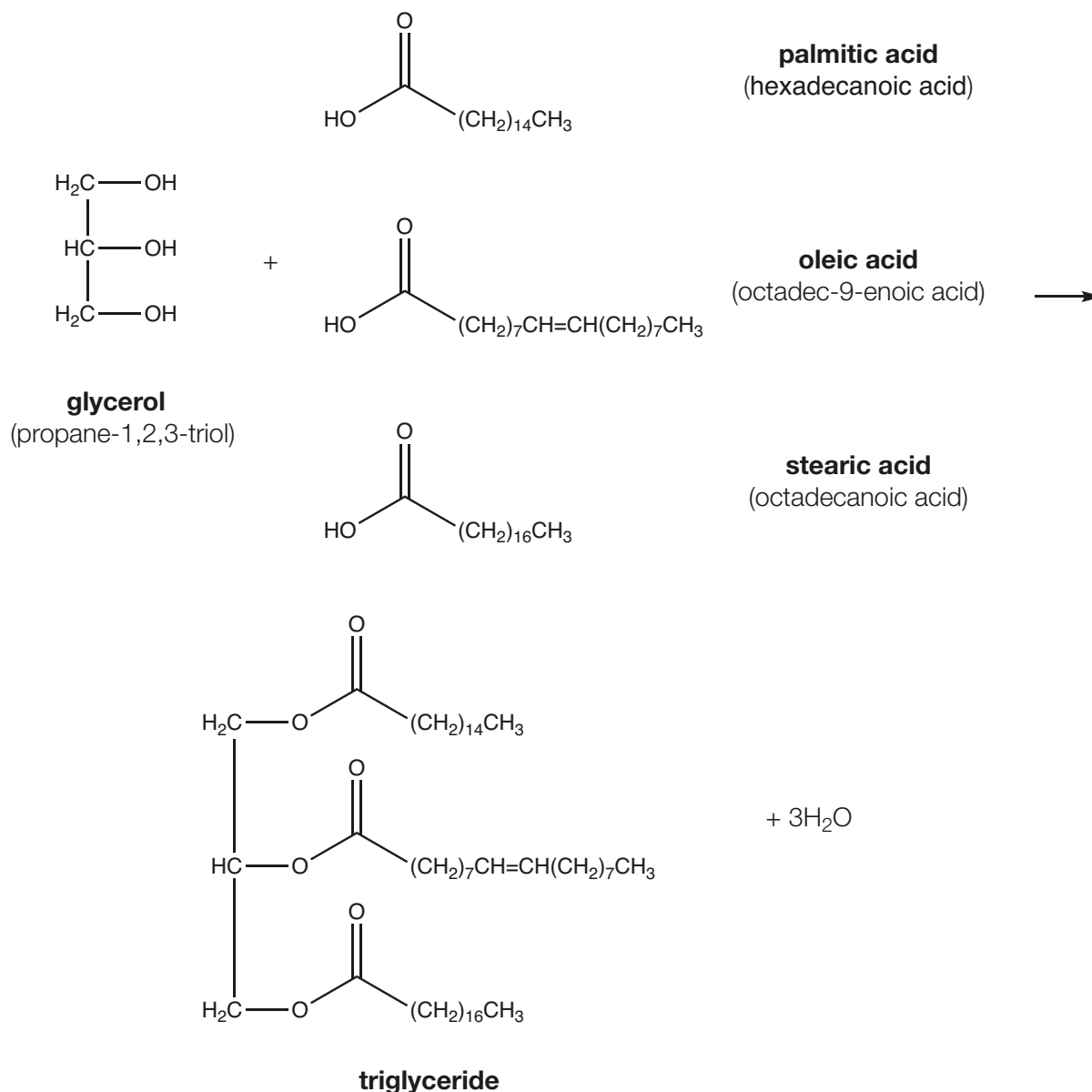
triglyceride

water

Palmitic acid, oleic acid, and stearic acid are the three most abundant fatty acids in the biological world. When one molecule of glycerol reacts with these three fatty acids, the following triglyceride is formed.



Triglycerides can also be represented using condensed structural formula, with CH=CH representing a double bond in the fatty acid molecule. The reaction above can be written as:



Science as a human endeavour

Protesting whaling with butter?

Butter is a solid triglyceride, which must be refrigerated to ensure its safe consumption. If correct storage conditions are not maintained the butter can become “rancid”. Chemically rancidity is the process by which the triglyceride hydrolyses and releases butanoic acid. Butanoic acid is the putrid smell that is present in both vomit and body odour.

In pursuit of Japanese whaling ships between 2005 and 2010, anti-whaling activists threw rancid butter onto the decks of the whaling ships (Figure 3.12).

These objects were deemed “butter bombs”, though activists claimed they were merely throwing harmless food material at the manned whaling ships.



Figure 3.12: “Butter bombs” thrown by activists onto the deck of a whaling ship.

Questions

24. Animal fat contains a high proportion of stearic acid, $\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$. Draw the structural formula of the triglyceride formed from glycerol and three stearic acid molecules.

(2 marks) **KA4**

25. Draw the triglyceride formed from the three fatty acids below



(2 marks) **KA4**

Science understanding

Triglycerides can be hydrolysed to produce propane-1,2,3-triol and various carboxylic acids.

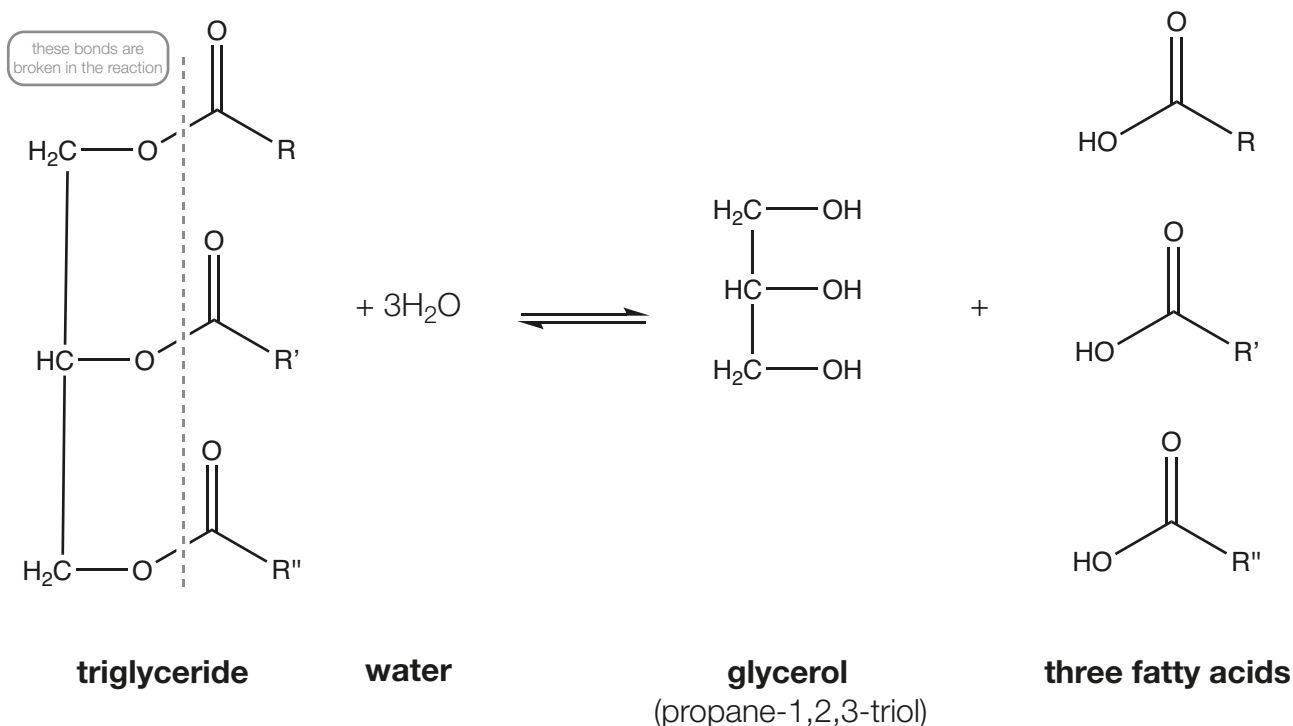
Identify and draw the structural formulae of the alcohol and acid(s) from which a triglyceride is derived, given its structural formula.

© SACE 2025

Like other esters, triglycerides can undergo hydrolysis in acidic or alkaline conditions to recover the reactants of the condensation reaction. Hydrolysis of triglycerides occurs inside the cells of living organisms. It is catalysed by the enzyme **lipase** (triglycerides are **lipids**), which is found in saliva and digestive secretions.

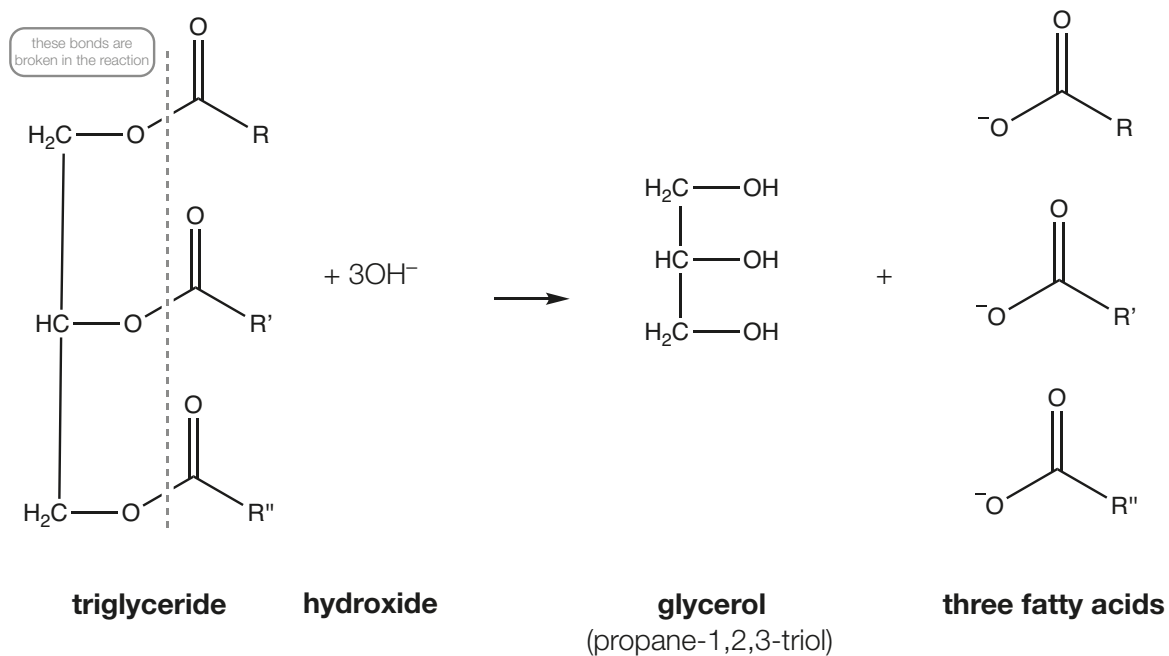
Acidic hydrolysis

In an acidic solution, triglycerides are hydrolysed to produce glycerol and free fatty acids. This process is reversible.



Alkaline hydrolysis

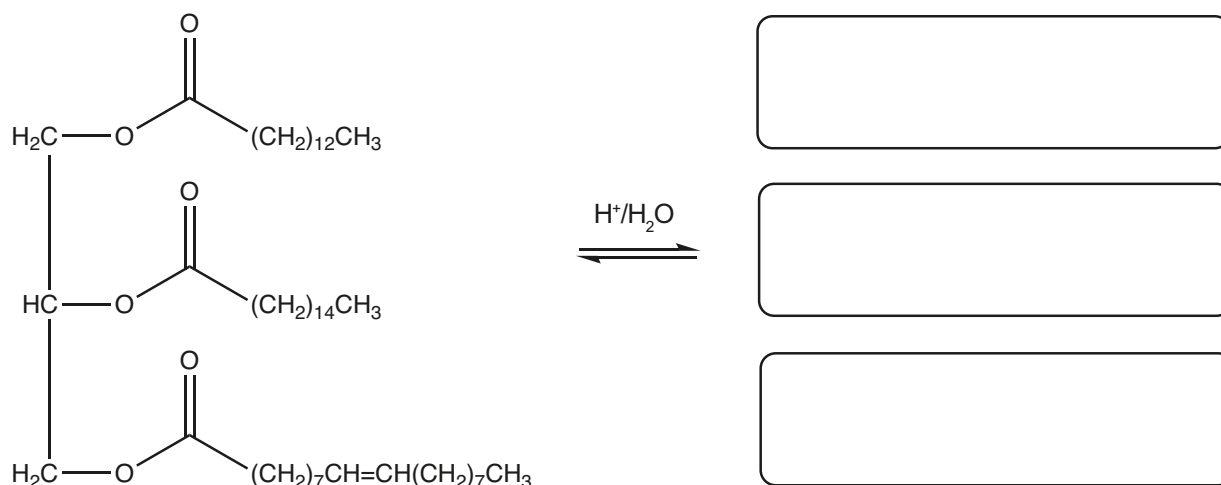
In an alkaline solution, triglycerides hydrolyse to produce glycerol and the carboxylate anions. Alkaline hydrolysis is not reversible, so the reaction is driven to completion.



Questions

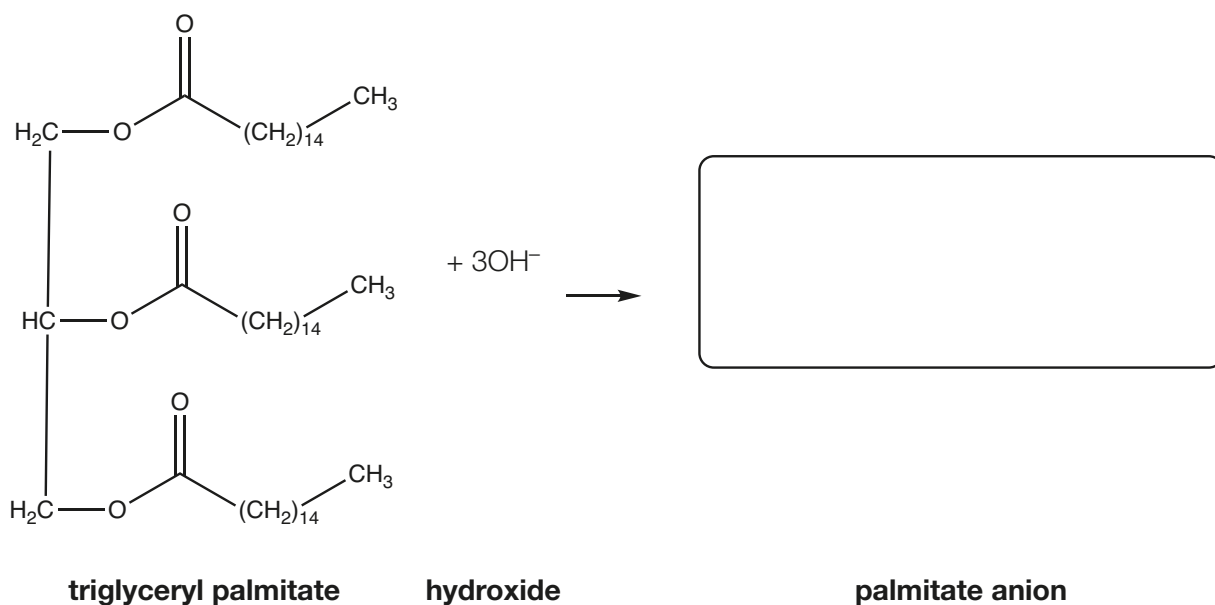
26. Fats and oils are the most abundant lipids in nature. They provide energy for living organisms, insulate body organs, and transport fat-soluble vitamins through the blood.

- (a) Draw the structural formula of the three fatty acids formed from the acidic hydrolysis of the following triglyceride:



(6 marks) **KA4**

- (b) The triglyceride glyceryl tripalmitate can undergo alkaline hydrolysis to form the palmitate anion. Draw the structural formula of the palmitate anion.



(2 marks) **KA4**

Science understanding

Triglycerides may be saturated or unsaturated.

Describe and explain the use of a solution of bromine or iodine to determine the degree of unsaturation of a compound. Draw the structural formula of the reaction product.

Explain how the degree of unsaturation causes differences in the melting points of edible oils and fats.

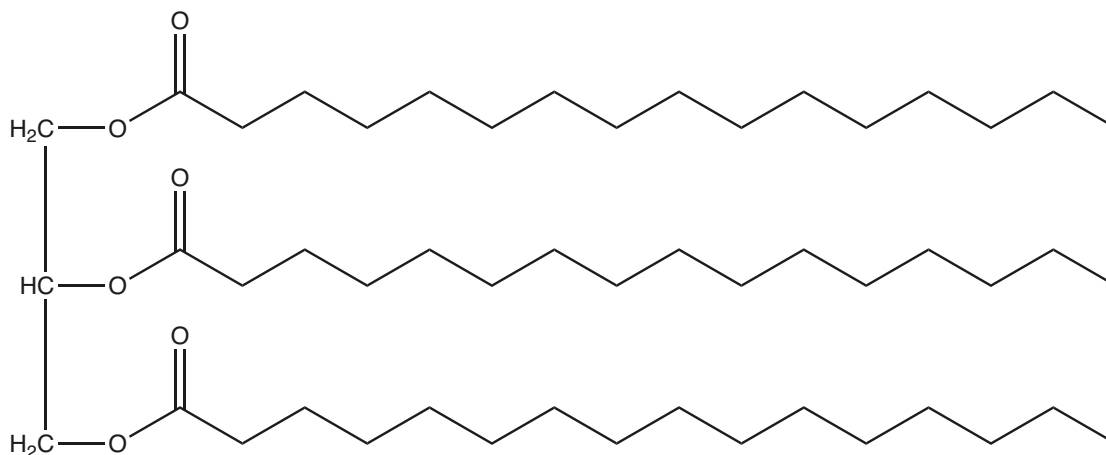
© SACE 2025

Physical properties

The melting point of triglycerides is related to the saturated and unsaturated fatty acid components within the molecule, and the strength of the intermolecular forces.

Saturated Triglycerides

In a saturated triglyceride, the geometry around the carbon atoms in the fatty acid chain is tetrahedral. As such, the hydrocarbon chains lie parallel to each other, stacking neatly, and giving the molecule an ordered shape. This increases the strength of the intermolecular dispersion forces between the chains and thus the lattice structure of the solid is formed.

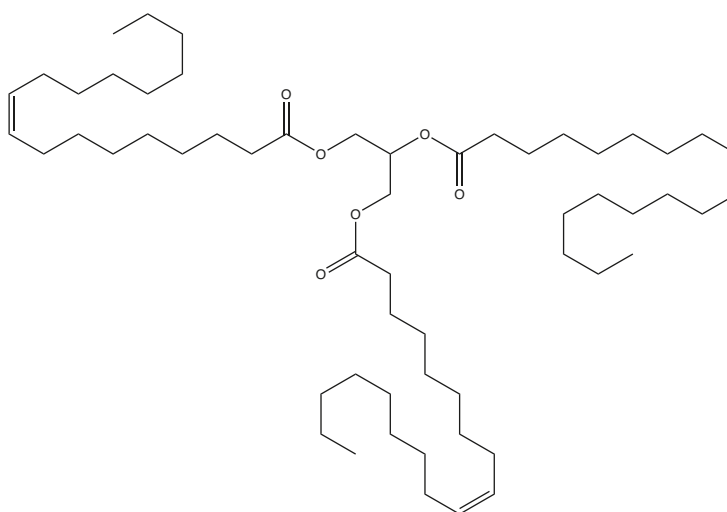


tripalmitin
saturated triglyceride

melting point: 66 °C

Unsaturated Triglycerides

In an unsaturated triglyceride, the geometry around the carbon atoms in the fatty acid chain is a combination of tetrahedral and trigonal planar. The double bonds force the carbon chains to twist at certain points. As such, the hydrocarbon chains have a less-ordered structure and do not stack as neatly or compactly together. The intermolecular dispersion forces are weaker, and thus unsaturated triglycerides have lower melting points and are usually liquids at room temperature.



triolein
unsaturated triglyceride

melting point: 5 °C

Triglycerides rich in saturated fatty acids are generally solids at room temperature and are called **fats**, while those rich in unsaturated fatty acids are liquids at room temperature and are called **oils**. Other than their state at room temperature, fats and oils are chemically indistinguishable (chemists use the word **triglycerides** to include both groups).

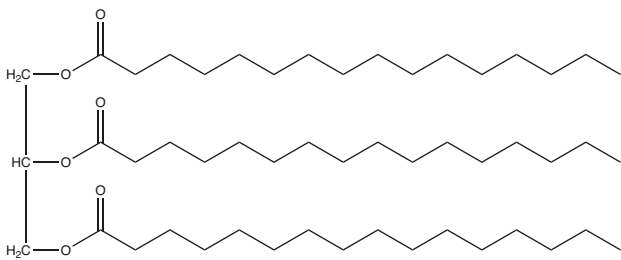
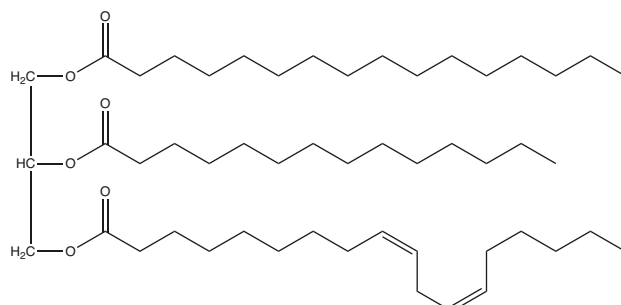
Edible fats	Edible oils
Solids at room temperature (25°C).	Liquids at room temperature (25°C).
Triglyceride molecules contain mainly saturated fatty acid substituents.	Triglyceride molecules contain one or more unsaturated fatty acid substituents.
Generally derived from land animals.	Generally derived from plants.
Fats of land animals usually contain 40-50% saturated fatty acids.	Most plant oils contain 80% or more unsaturated fatty acids.
	

Table 3.10: Properties of edible fats and oils

Table 3.11 shows the percentage of saturated and unsaturated fatty acid content of triglyceride of common fats and oils.

Derived from	Fat or oil	Saturated fatty acids (% of total fat)	Unsaturated fatty acids (% of total fat)
Animals	Beef fat	52	48
	Butter fat	66	34
Plants	Olive oil	15	85
	Sunflower oil	10	90

Table 3.11 - percentage of saturated and unsaturated fatty acid content of triglyceride of common fats and oils.

Degree of unsaturation

The general formula for a *saturated* fatty acid is $C_nH_{2n}COOH$. Given the formula of any fatty acid, this general formula can be used to determine whether it is saturated or unsaturated.

Example

Linoleic acid has the formula $C_{18}H_{32}COOH$.

If saturated, the acid would fit the formula $C_{18}H_{(2 \times 18)}COOH$, which is $C_{18}H_{36}COOH$. The acid is therefore *unsaturated*.

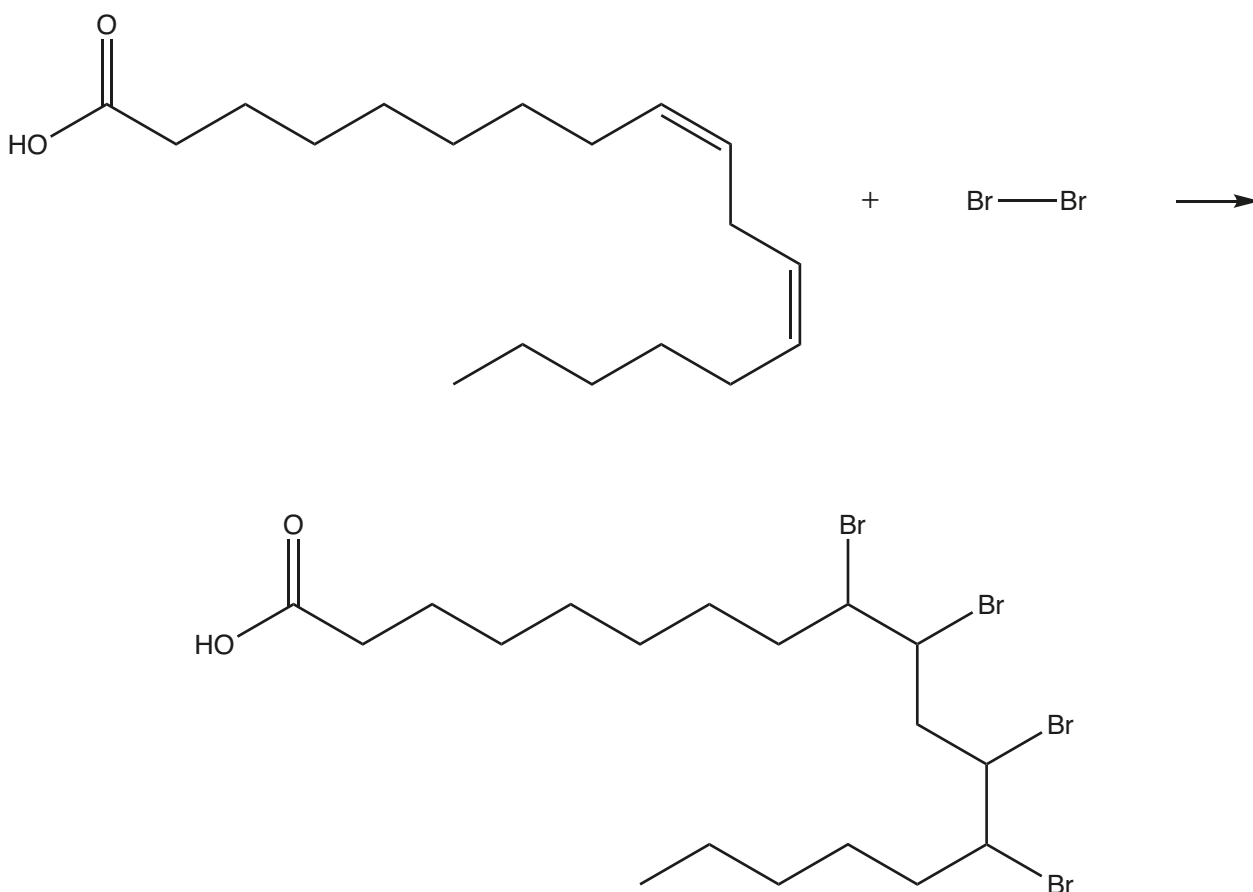
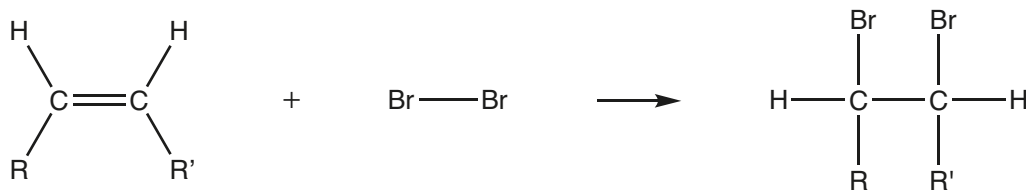
To determine how many double bonds it contains, calculate how many hydrogens are missing.

$$36 - 32 = 4$$

Linoleic acid has four fewer hydrogens than the corresponding saturated fatty acid. Each double bond displaces two hydrogens, one from each carbon in the bond, so linoleic acid has two double bonds.

Bromine / Iodine number

Alkenes are unsaturated and contain the C=C functional group. They undergo addition reactions with small diatomic halogen molecules such as bromine (Br₂) or iodine (I₂). Unsaturated fatty acids and triglycerides contain the C=C functional group and will also undergo this addition reaction.



The mass of bromine or iodine that reacts with exactly 100 g of the compound is called the **bromine number** or **iodine number**.

Example

Determining Iodine Number

Linoleic acid has an M_r of 280.5 g mol^{-1} and the formula $\text{CH}_3(\text{CH}_2)_4\text{CH}=\text{CHCH}_2\text{CH}=\text{CH}(\text{CH}_2)_7\text{COOH}$ (or $\text{C}_{18}\text{H}_{32}\text{O}_2$).

One mole of linoleic acid has two double bonds; therefore, 2 mol of iodine will react.

$$\begin{aligned} M_r(\text{I}_2) &= 253.8 \text{ g mol}^{-1} \\ \text{mass}(\text{I}_2) &= n \times M_r \\ &= 2 \text{ mol} \times 253.8 \text{ g mol}^{-1} \\ &= 507.6 \text{ g} \end{aligned}$$

The mass of 1 mol of iodine is 507.6 g.

$$\begin{aligned} \text{mass}(\text{linoleic acid}) &= n \times M_r \\ &= 1 \text{ mol} \times 280.5 \text{ g mol}^{-1} \\ &= 280.5 \text{ g} \end{aligned}$$

The mass of 1 mol of linoleic acid is 280.5 g.

If 507.6 g of iodine reacts with 280.5 g linoleic acid, and x grams of iodine reacts with 100 g linoleic acid, then:

$$\begin{aligned} \frac{x}{507.6} &= \frac{100}{281} \\ x &= \frac{100}{281} \times 507.6 \\ x &= 180.6 \text{ g} \end{aligned}$$

Therefore, the iodine number of linoleic acid is 181.

Example

Determining Number of Double Bonds

2.8 g of linoleic acid will react with 5.0 g of I_2 .

1 mol of I_2 reacts with 1 mol of double bonds.

$$\begin{aligned} n(\text{I}_2) &= \frac{m}{M_r} = \frac{5.0 \text{ g}}{(2 \times 126.9) \text{ g/mol}} \\ &= 0.020 \text{ mol} \end{aligned}$$

5.0 g of I_2 is 0.020 moles.

$$\begin{aligned} n(\text{linoleic acid}) &= \frac{m}{M_r} = \frac{2.8 \text{ g}}{((18 \times 12.01) + (30 \times 1.01) + (2 \times 16.00)) \text{ g/mol}} \\ &= 0.010 \text{ mol} \end{aligned}$$

2.8 g of linoleic acid is 0.010 moles.

If 0.020 mol of iodine reacts with 0.010 mol of linoleic acid, and x mol of iodine reacts with 1 mol of linoleic acid, then

$$\begin{aligned} \frac{x}{1} &= \frac{0.020}{0.010} \\ x &= \frac{0.020}{0.010} \times 1 \\ x &= 2 \text{ mol} \end{aligned}$$

2 moles of iodine are needed for every 1 mole of linoleic acid. Therefore, linoleic acid has 2 carbon-carbon double bonds

Questions

27. Ricinoleic acid has a molar mass of $298.46 \text{ g mol}^{-1}$ and an iodine number of 85. Determine the number of double bonds in ricinoleic acid.

(3 marks) KA4

Science understanding

Liquid triglycerides can be converted into triglycerides of higher melting point.

Explain the role of pressure, temperature, and a catalyst in the hydrogenation of liquid triglycerides to form triglycerides of higher melting point.

© SACE 2025

Liquid oil triglycerides can be converted to solid fats by a process called **hydrogenation**, where hydrogen is added across $\text{C}=\text{C}$ double bonds.



Science as a human endeavour

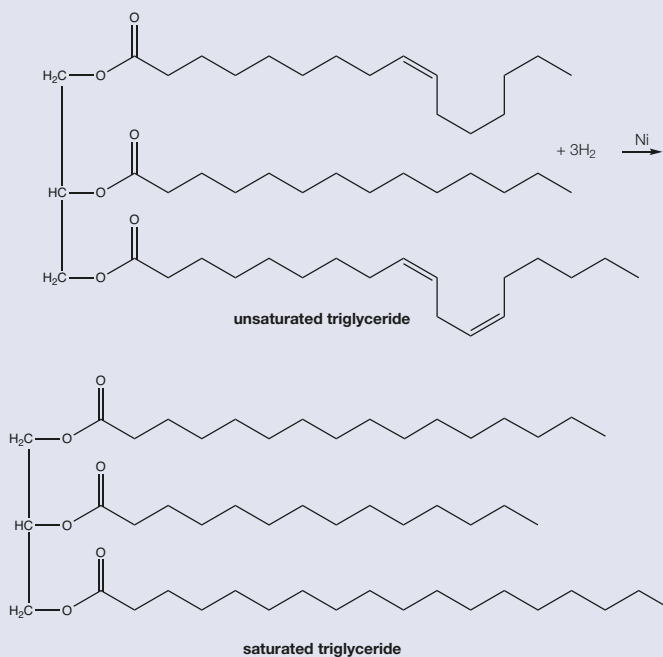
Hydrogenation

In 1869, when fats and oils were scarce in Western Europe, French chemist Hippolyte Mège-Mouriès invented margarine from animal fats. He won a prize from Emperor Napoleon III for “a satisfactory butter substitute”. Today, margarine is prepared from vegetable oils including corn, soy, and sunflower, using the hydrogenation process. The vegetable oil is heated to a high temperature with hydrogen gas under pressure in the presence of a nickel catalyst.

The hydrogens add across the double bonds to increase the degree of saturation, changing the $\text{C}=\text{C}$ double bonds to $\text{C}-\text{C}$ single bonds. This changes the geometry around the carbon atoms from trigonal planar to tetrahedral, allowing the chains to stack more neatly and form a product that is solid at room temperature.

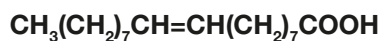
The use of high temperature, high pressure, and a powdered catalyst such as nickel are all required to increase the rate of reaction.

- The catalyst provides an alternate pathway where the activation energy is lower. It is in a powdered form to increase the surface area.
- Increasing the temperature increases the kinetic energy of the particles, so more particles will have energy greater than or equal to activation energy. This leads to more successful collisions per unit time.
- Increasing the pressure increases the concentration of the gaseous hydrogen. There is less space for the particles to occupy and an increased total number of particle collisions per unit time.



Questions

28. Sunflower oil contains oleic acid and linoleic acid, whose structures are shown below.



Oleic acid



Linoleic acid

(a) Write the molecular formula for each acid.

(i) Oleic acid:

(ii) Linoleic acid:

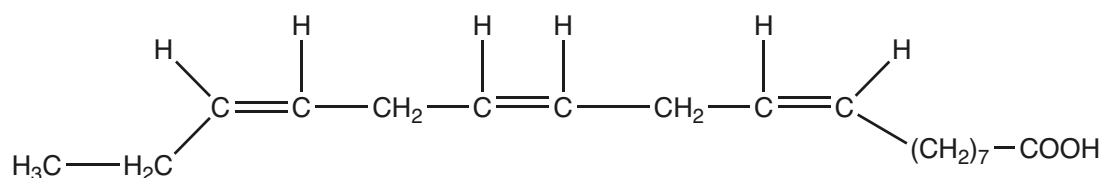
(4 marks) **KA1**

(b) Draw the molecule of sunflower oil formed from two linoleic acid molecules and one oleic acid molecule.

3

(2 marks) **KA4**

(c) Many margarine companies are using flaxseed oil to promote a “healthier” alternative product. One of the fatty acids in flaxseed oil is linolenic acid, shown below. Note that **linolenic** acid is a different compound to **linoleic** acid.



Draw the structural formula of the oil formed only from linolenic acid molecules.

(2 marks) **KA4**

(d) List the reagent required to convert flaxseed oil into margarine.

(1 mark) **KA1**

(e) List three reaction conditions required to convert flaxseed oil into margarine.

(3 marks) **KA1**

(f) Describe the difference in physical properties between flaxseed oil and margarine.

(1 mark) **KA1**

(g) Explain why margarine has a higher melting point than the oils from which it is prepared.

(4 marks) **KA1**

Science understanding

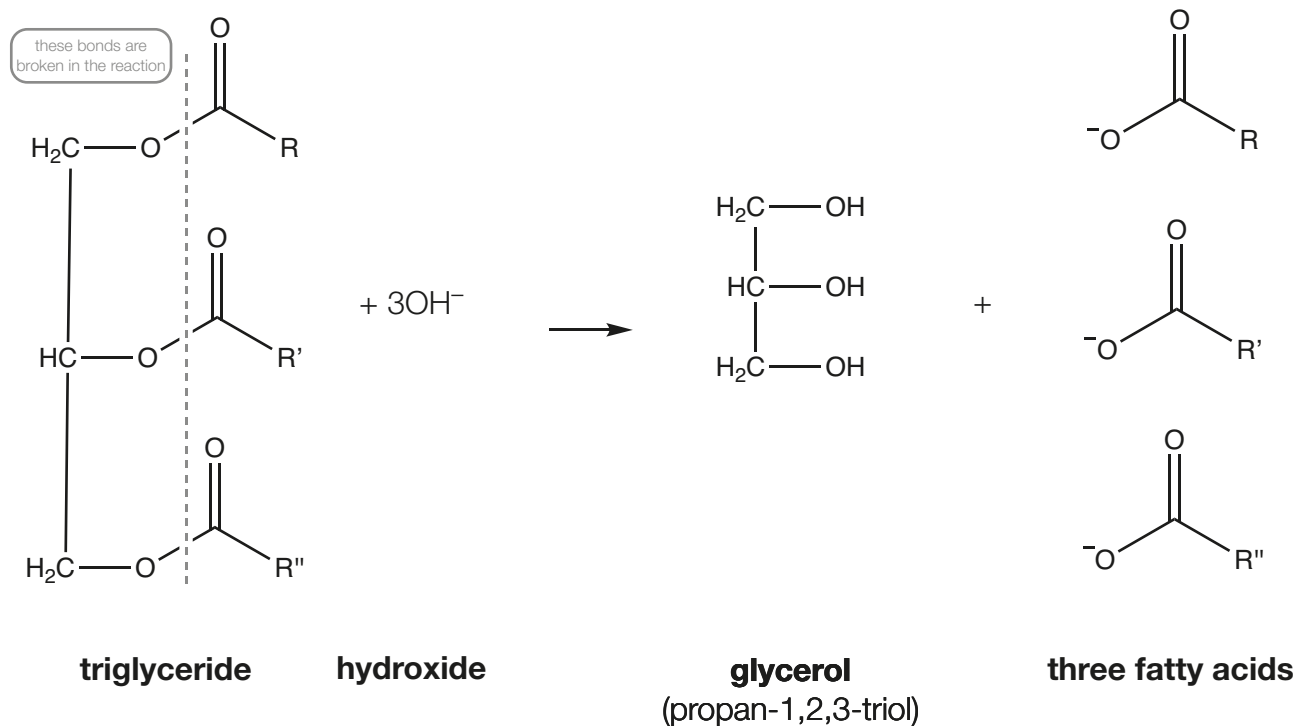
Alkaline hydrolysis of triglycerides produces carboxylate ions, which have both hydrophilic and hydrophobic regions.

Explain how such particles form micelles in solutions.

Explain how micelles can dissolve and move non-polar substances through an aqueous medium or vice versa.

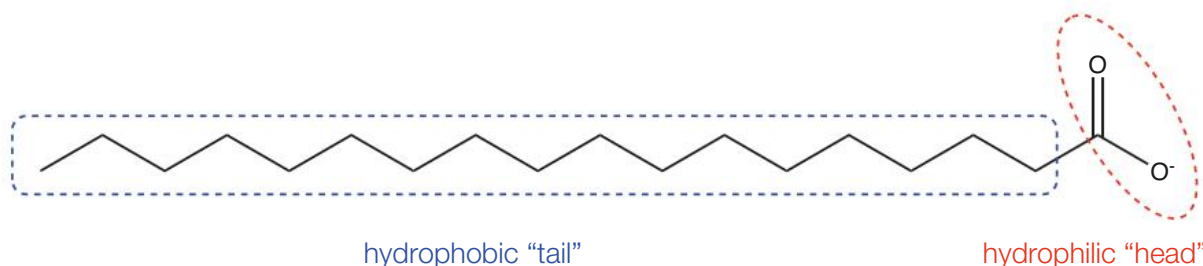
© SACE 2025

When triglycerides undergo hydrolysis in alkaline solution, carboxylate anions are formed.



The carboxylate anions, or “fatty acid anions”, that are produced are composed of two parts:

- A non-polar “tail”. This long hydrocarbon chain is **hydrophobic** (‘water-hating’) as it cannot form secondary interactions with water.
- An ionic “head”. This carboxylate functional group is **hydrophilic** (‘water-loving’) as it can form strong ion-dipole secondary interactions with water.



When these carboxylate anions are dispersed in water or aqueous solution, they form **micelles**. The non-polar hydrocarbon chains cluster in the centre of the micelle, and the hydrophilic anionic heads are on the surface of the micelle, pointing outwards to interact with polar water molecules.

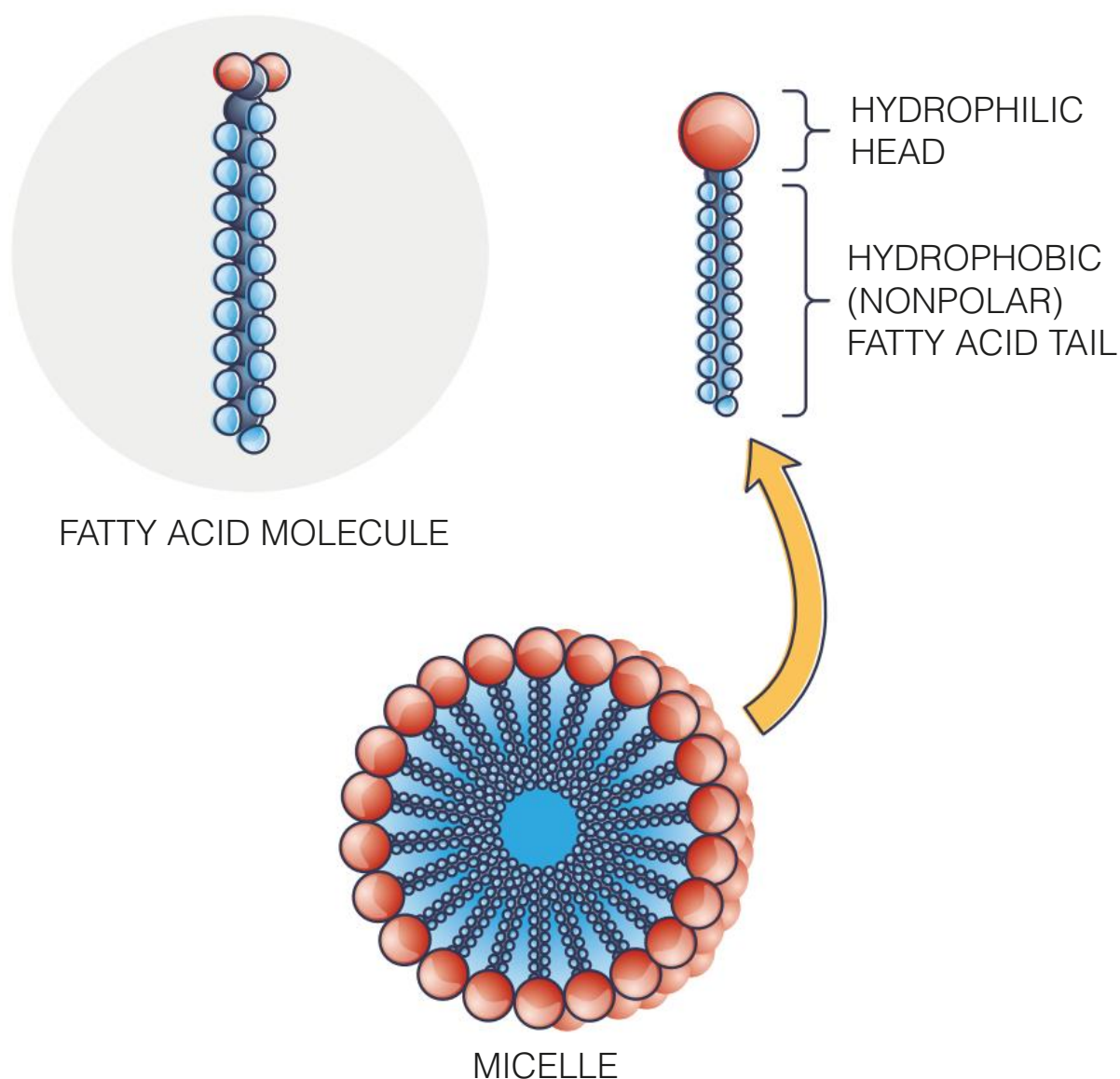


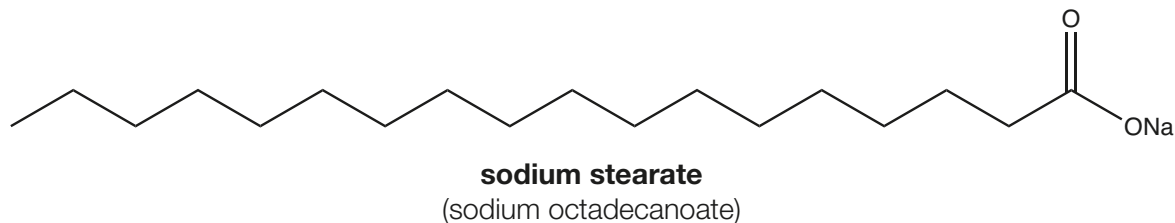
Figure 3.13 - Carboxylate anions form micelles in aqueous solution

Micelles are nanoscopic (1–100 nanometres in size). They allow non-polar substances to mix with polar substances such as water.

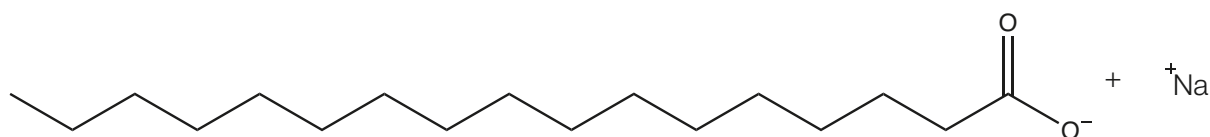
Applications of micelles

Soap micelles

In pure form, carboxylate salts of sodium are waxy white solids with the common name **soap**. Non-polar substances such as grease, oil, and fat stains are removed from fabric or surfaces by the action of soap micelles, which allow these substances to mix more readily with water and thus be washed away. The most common soap is sodium stearate.



When soap dissolves in water, the ions dissociate.



When soap is mixed with grease and water, like in a washing machine or dishwasher, the anions cluster into micelles with the non-polar grease molecules in the centre. The non-polar hydrocarbon tails “dissolve” the non-polar grease molecules.

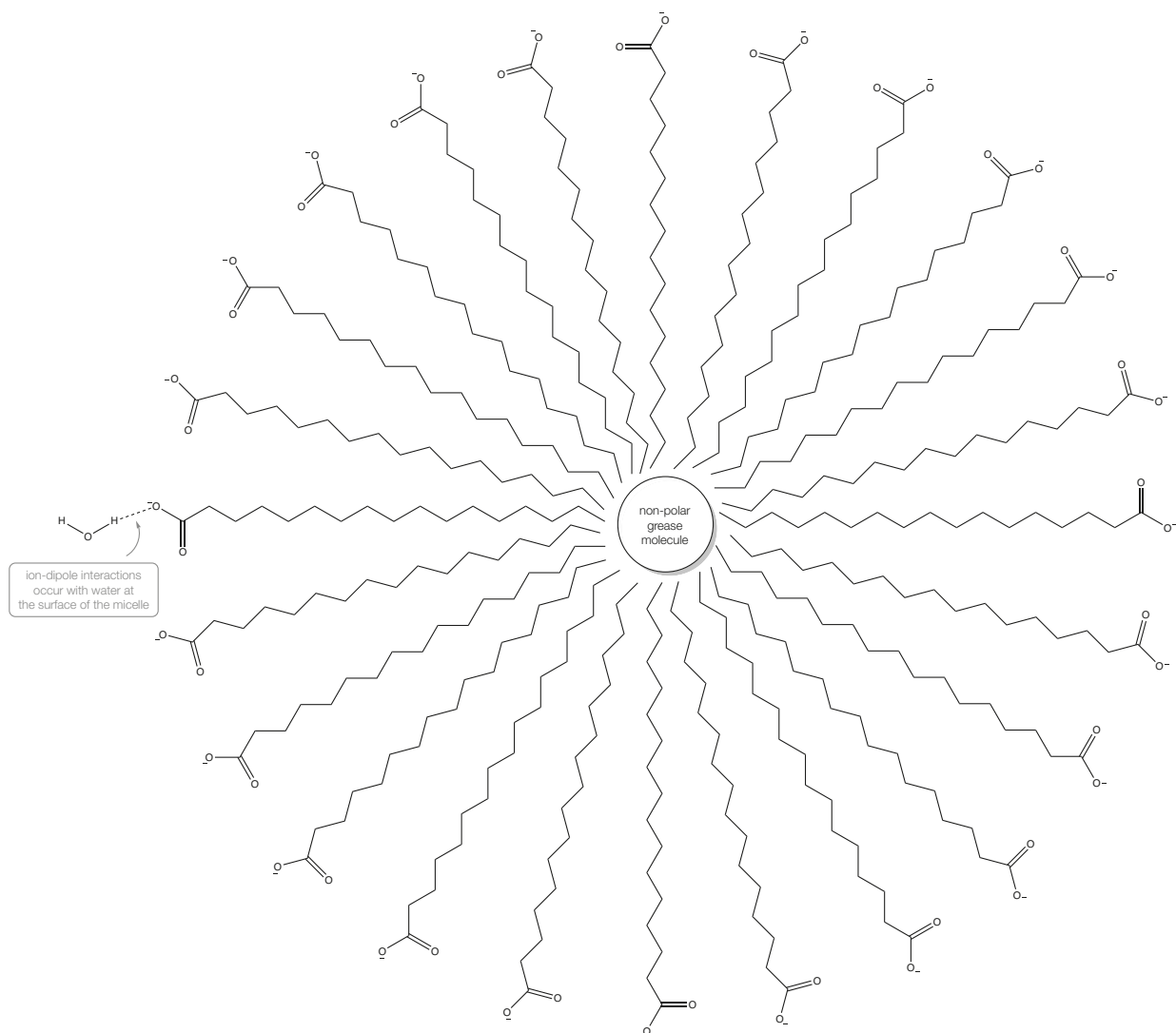


Figure 3.14- A soap micelle with “dissolved” grease in the centre

With agitation, grease lifts off the surface. The micelles repel each other, and they are washed away in the polar water.

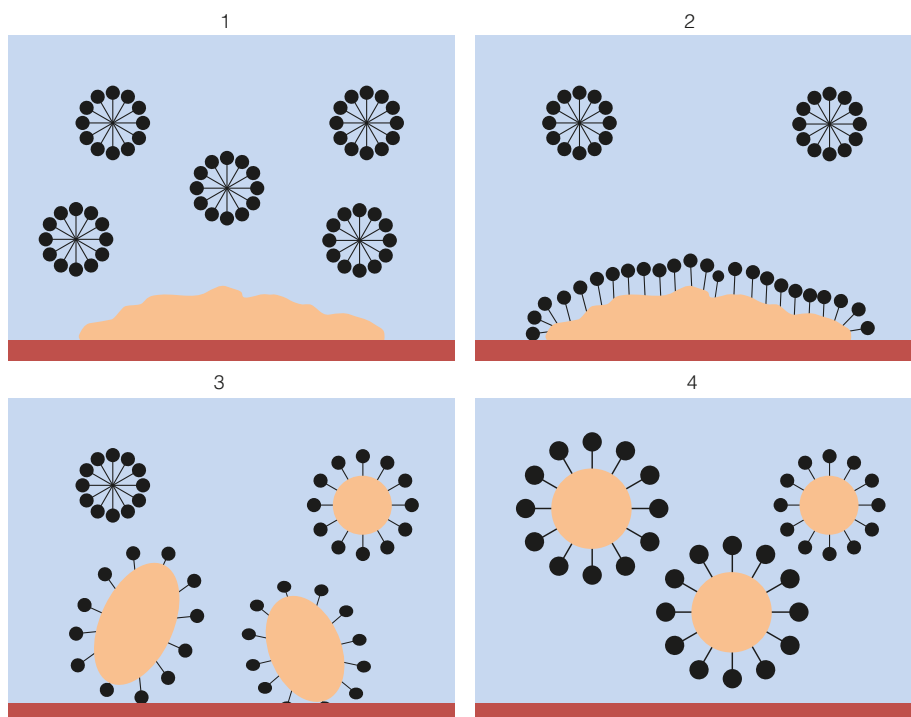


Figure 3.15: Soap molecules removing grease/dirt from a surface

3



Science as a human endeavour

Biocompatible Polymers

Non-polar, hydrophobic drugs, such as those used in cancer treatment, can be delivered around the body with nanoscopic **polymeric micelles**, also called **biocompatible polymers**.

The monomers that make up the polymer in the polymeric micelle have hydrophobic and hydrophilic parts:

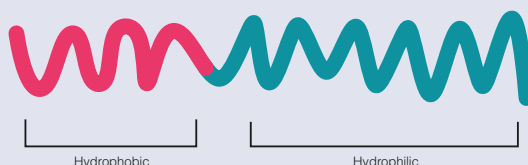


Figure 3.16 - Hydrophobic and hydrophilic parts of a polymeric micelle monomer

These monomers assemble themselves so that the hydrophobic parts face towards the centre, forming a spherical core, while the hydrophilic parts form the shell.

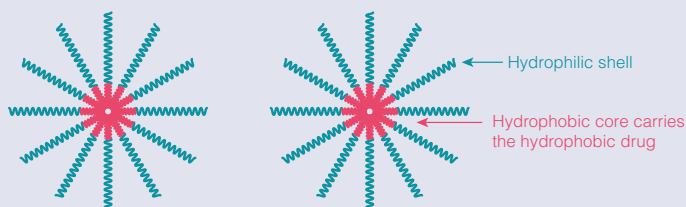


Figure 3.17: Polymer micelles

The hydrophobic core carries and protects the drug. The hydrophilic shell supports and stabilises the core in the aqueous medium, enabling it to be soluble in water.

Drugs that were originally insoluble now become soluble in water and bodily fluids, and therefore they are more readily available for the sites that require targeting. These polymeric micelles are biodegradable, so they can be excreted from the body without causing harmful side effects.

Polymeric micelles are being used in a variety of medicinal fields, including cancer treatments, oestrogen therapy, and flu prevention.

Questions

29. Read the article below:

“Self-assembled amphiphilic core-shell nanocarriers in line with the modern strategies for brain delivery”

“Disorders of the central nervous system (CNS) represent increasing social and economic problems all over the world which makes the effective transport of drugs to the brain a crucial need. In the last decade, many strategies were introduced to deliver drugs to the brain trying to overcome the challenge of the blood brain barrier (BBB) using both invasive and non-invasive methods. Non-invasive strategy represented in the application of nanocarriers became very common. **One of the most hopeful nanoscopic carriers for brain delivery is core-shell nanocarriers or polymeric micelles (PMs).** They are more advantageous than other nanocarriers. They offer small size, ease of preparation, ease of sterilization and the possibility of surface modification with various ligands.” <https://pubmed.ncbi.nlm.nih.gov/28648865/>

With reference to the information presented in the article above, discuss and explain the importance of **Application and Limitation** in Science as a Human Endeavour.

(2 marks) **KA3**

3.10 Proteins

Science understanding

Proteins are polymers of amino acids.

Amino acids contain a carboxyl group and an amino group.

Write the general formula of amino acids and recognise their structural formulae.

© SACE 2025

Proteins are natural polymers that make up about 15% of the human body and carry out many important functions, including:

- transporting and storing oxygen and nutrients
- acting as catalysts for biological reactions
- fighting off foreign objects that invade the body
- serving as hormones to regulate body processes
- providing structural integrity and strength for tissue
- forming skin, hair, nails, and cartilage

The monomers of all proteins are compounds called **amino acids**. Although there are many types of amino acids, α -amino acids are the most significant in the biological world as they are the backbone of all proteins. The α -amino acids will be the focus of this chapter in terms of their structure, function, properties, and reactions.

Amino acids

Amino acids contain:

- A carboxyl group ($-\text{COOH}$)
- An amino group ($-\text{NH}_2$)
- An “R” group, called a side chain
- A hydrogen atom

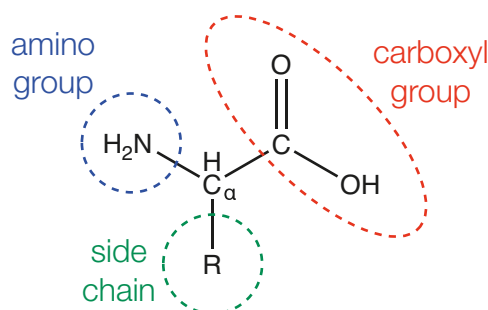
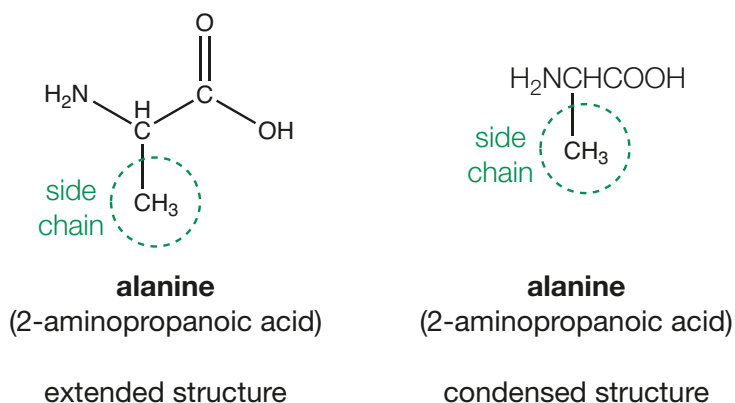


Figure 3.17 - General structural formula for an amino acid

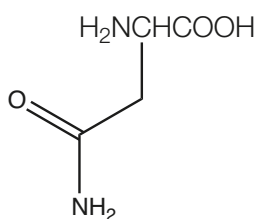
These are called ‘ α -amino acids’ because the side chain is attached to the α -carbon. (Larger amino acids have more carbons which are labelled β , γ , and so on). Different α -amino acids vary only by what is attached at the position marked ‘side chain’.

Alanine is one of the simplest amino acids. It has a methyl group ($-\text{CH}_3$) side chain. Because only the side chain varies between different amino acids, they are often drawn in a condensed format.



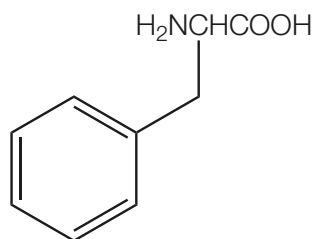
Polarity of amino acids

There are 20 different amino acids present in most proteins, each having a unique side chain. These unique side chains determine the overall polarity of the amino acids. Polar side chains contain nitrogen and oxygen atoms and are hydrophilic (water loving). Non-polar side chains contain mostly carbon and hydrogen atoms and are hydrophobic (water hating).



glutamine
(2,5-diamino-5-oxopentanoic acid)

polar side chain



phenylalanine
(2-amino-3-phenylpropanoic acid)

non-polar side chain

The polarity of the side chains affects the secondary interactions that can form between the chains, and thus impacts the three-dimensional structure and shape of the protein polymer.

Essential amino acids

Of the 20 unique amino acids, only 10 can be synthesised by the human body. The other 10 cannot be made by the body and must be ingested; these are called *essential amino acids*. Essential amino acids are a necessary part of the human diet.

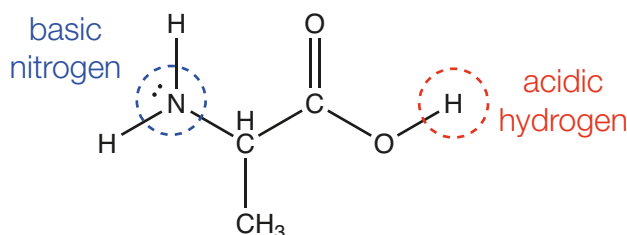
Science understanding

Amino acids have both acidic and basic properties.

Draw the structural formula of the product formed when an amino acid self-ionises, given its structural formula.

© SACE 2025

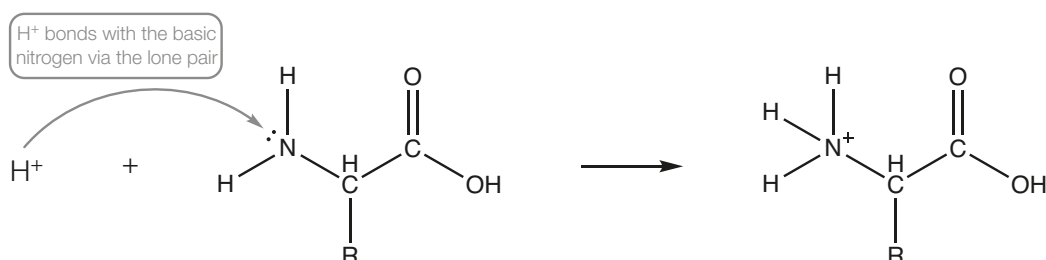
Amino acids have a carboxyl group with an acidic hydrogen that can be donated. They also contain an amino group, which has a basic nitrogen that can accept a proton due to its lone pair of electrons. These groups exist within the same molecule.



Amino acids are **amphiprotic**. Because amino acids contain both an acidic group and a basic group, amino acids can act as proton donors or proton acceptors depending on the pH of the solution.

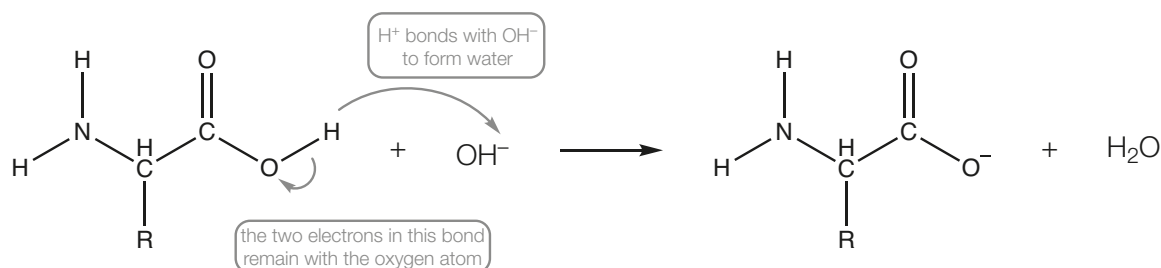
Acidic solution, pH < 7

An acidic solution contains free protons (H^+ ions). In an acidic solution, the amino group accepts an H^+ and forms a protonated amine.



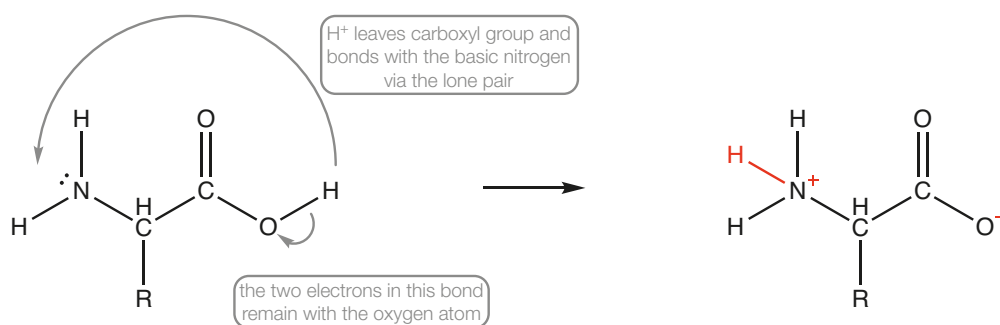
Alkaline solution, pH >7

An alkaline solution contains hydroxide ions (OH^-). In an alkaline solution, the carboxyl group donates its acidic hydrogen and forms a deprotonated amine.



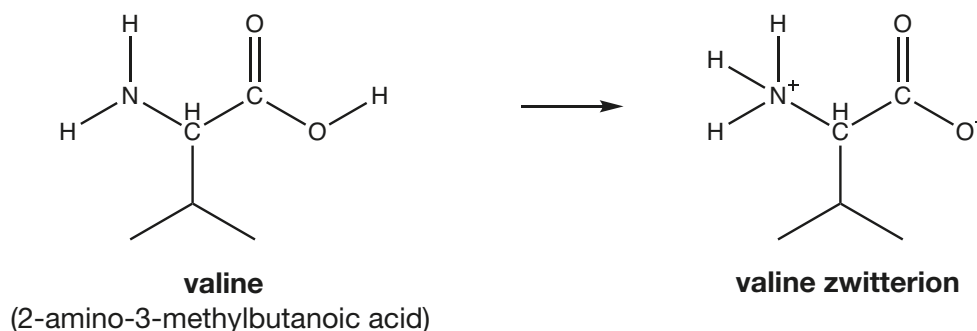
Neutral solution, pH $\approx$ 7

In water, or any near-neutral aqueous solution, these acidic and basic groups react with each other; the carboxyl group donates a proton to the amino group. This forms a **zwitterion**: a molecule with positively and negatively charged functional groups, but no overall charge.



zwitterion

The following diagrams show the structure of valine, an essential amino acid, and its zwitterion form.

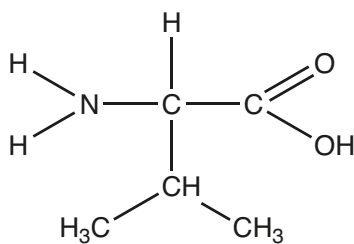


Properties of zwitterions

Amino acids exist as zwitterions, even in their solid state. Due to their ionic dipole, zwitterions are also called “internal salts” of amino acids. They have many of the same properties as salts, including high melting points, forming crystalline solids, and being generally soluble in water (depending on the polarity of the side chain).

Questions

30. Valine is an amino acid that assists in muscle tissue recovery and repair. Its structure is below.



Valine

(a) State the name of the functional group that is a proton donor.

(1 mark) **KA1**

(b) State the name of the functional group that is a proton acceptor.

(1 mark) **KA1**

(c) Draw the structure of the amino acid when:

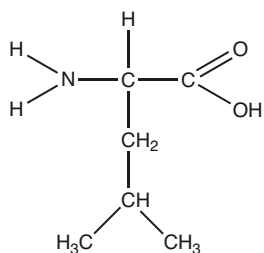
(i) It is placed in a solution of pH 3

(2 marks) **KA4**

(ii) It is a zwitterion in neutral solution

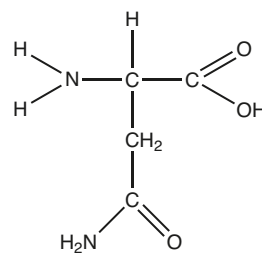
(2 marks) **KA4**

(d) The structures and molar masses of two amino acids are shown below. Explain why leucine is insoluble in water while asparagine is soluble.



Leucine

Molar mass: 131.17 g mol⁻¹



Asparagine

Molar mass: 132.12 g mol⁻¹

(4 marks) **KA1**

Science understanding

Amino acids can undergo condensation to form protein chains.

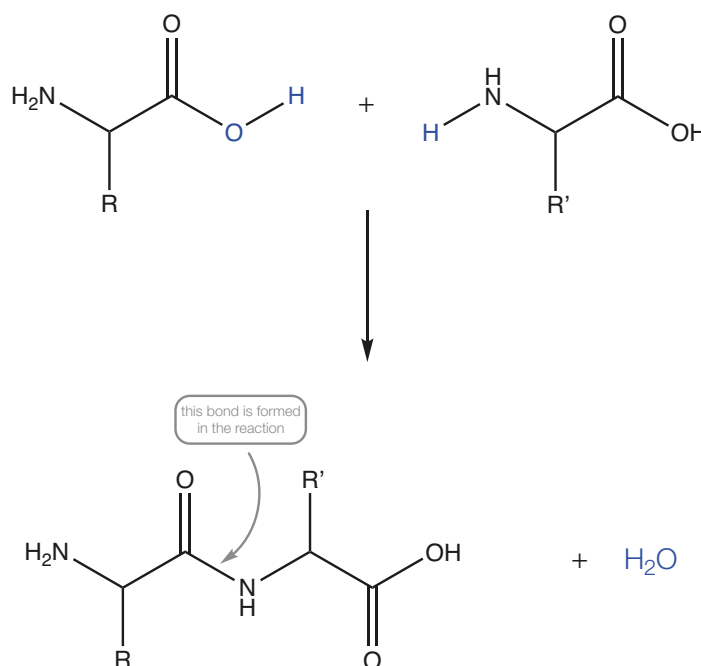
The amide groups within proteins are also known as 'peptide links'.

Draw the structural formula of a section of a protein chain that could be formed from amino acids, given their structural formulae or vice versa.

© SACE 2025

Amino acids undergo condensation reactions to form a protein polymer chain. The amino group from one amino acid reacts with the carboxyl group from another amino acid. The side chains do not react.

Example



Amino acids are joined together by the **amide functional group**.

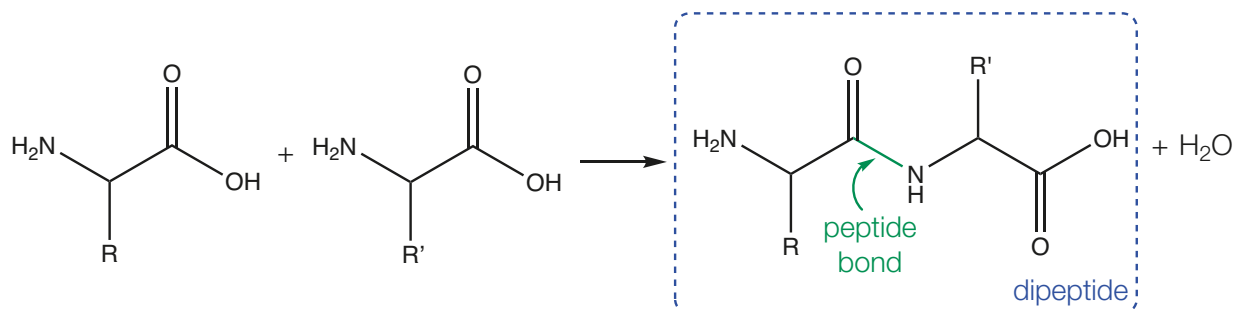
Biologists and biochemists also call this a **peptide bond** or **peptide linkage** when it appears in the context of amino acids and proteins.



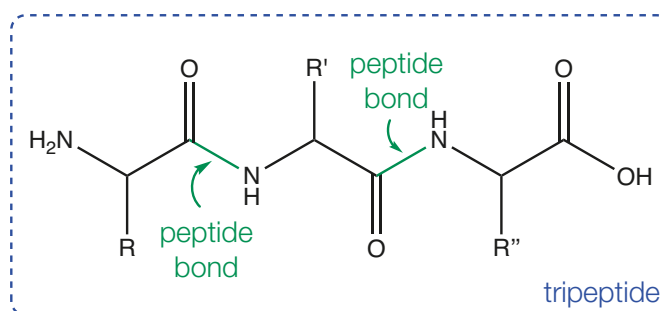
amide functional group

Dipeptides, tripeptides, and polypeptides

When **two amino acids** join via a condensation reaction, they produce a **dipeptide**. There is one peptide link.



When **three amino acids** join together they produce a **tripeptide**. There are two peptide links.

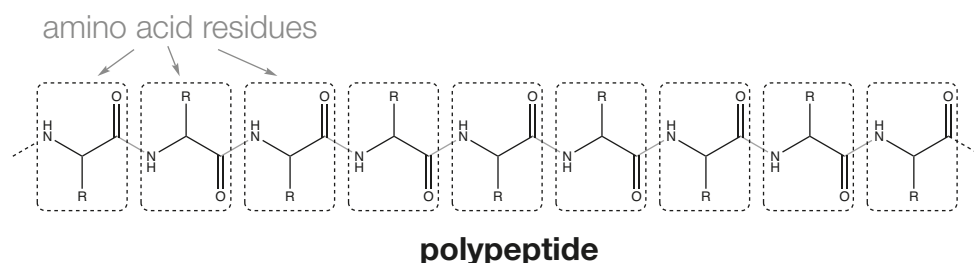


Hence, the prefix for a peptide depends on the number of amino acids that form it.

The part of the amino acid that remains after water is removed and which is incorporated into the polymer is called an **amino acid residue**.

Amino acids can join together in condensation reactions to produce chains of almost any length. Peptides made from fewer than 20 amino acid monomers are called **oligopeptides** ('oligo' meaning few), while peptides with greater than 20 amino acid monomers are called **polypeptides** ('poly' meaning many).

Proteins are polypeptides.

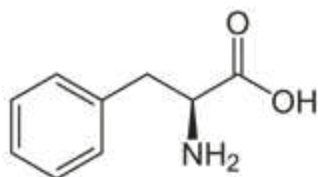


When drawing a **polypeptide** (or, equivalently, a section of a **protein chain**), appropriate notation (i.e., a squiggly or dotted line) is used to show that the chain continues at either end.

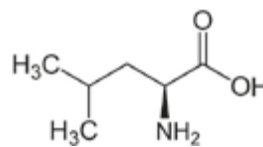
Questions

31. Peptide synthesis is characterized as the formation of a peptide bond between two or more amino acids via a condensation reaction.

(a) Draw the dipeptide that is formed from the following amino acids.



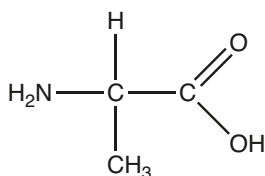
Phenylalanine



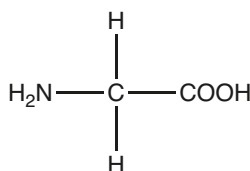
Leucine

(2 marks) **KA4**

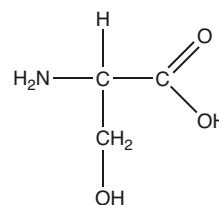
(b) Draw the polypeptide that is formed from the following amino acids.



Alanine



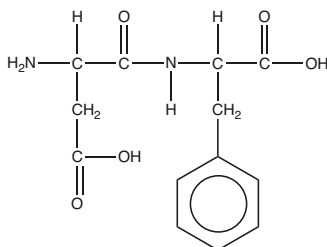
Glycine



Serine

(2 marks) **KA4**

(c) Aspartame is an artificial sweetener that contains the dipeptide of aspartic acid and phenylalanine. Given the structure of the dipeptide below, draw the two amino acids that form it.



Aspartame

(4 marks) **KA4**

Science understanding

The unique spatial arrangement of a protein depends on secondary interactions between sections of the chain and, in aqueous environments, between the chain and water.

Identify where secondary interactions can occur, given the structural formula of a section of a protein chain.

The biological function of a protein is a consequence of its spatial arrangement.

© SACE 2025

Primary structure of proteins

Proteins are composed of 20 unique amino acids that can be arranged in any order, which means there are many, many possible protein structures. This versatility has allowed organisms to evolve specific proteins for various functions.

The order in which the amino acid residues are connected along a protein chain is called the protein's **primary structure**. The residues are joined together by **peptide bonds**, which are covalent bonds.

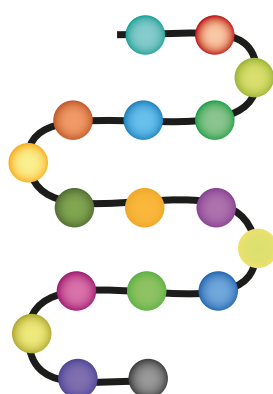
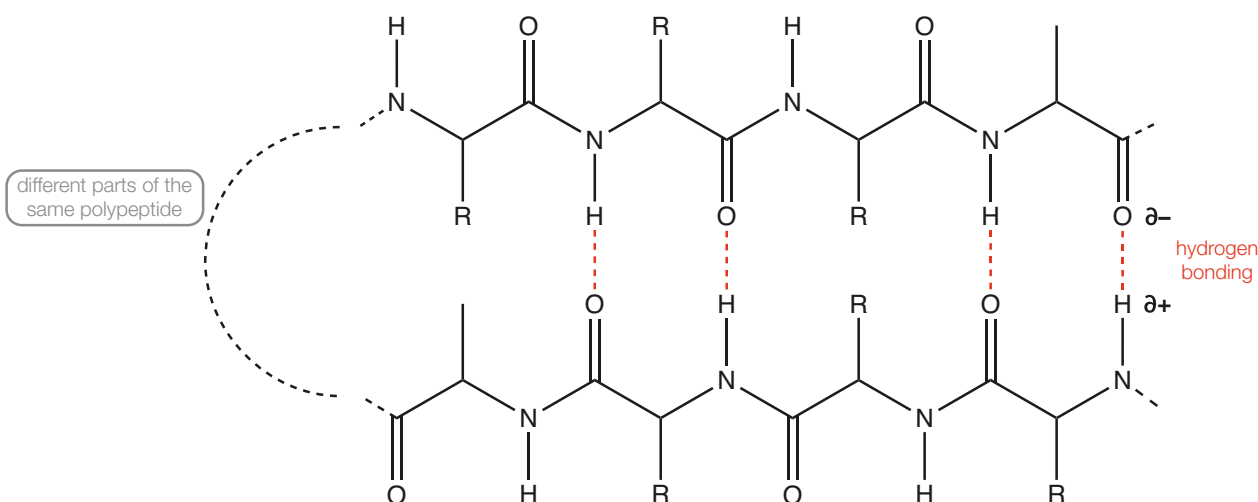


Figure 3.18 - The “primary” structure of a protein refers to the order in which the amino acids are joined

The primary structure is responsible for the protein's unique identity. A change in one amino acid can completely alter the biochemistry of the protein. For example, sickle-cell anaemia is a genetic disorder caused by one amino acid with a hydrocarbon side chain being replaced by an amino acid with an acidic side chain. Another example is oxytocin and vasopressin. Oxytocin is a hormone that triggers milk secretion, while vasopressin regulates the flow of urine from the kidneys. Their polypeptide primary structure only differs by two amino acids, yet these proteins have vastly different functions.

Secondary structure of proteins

In aqueous solution, protein chains fold and coil in specific ways; this is referred to as the protein's **secondary structure**. The secondary structure is determined by the hydrogen bonding between non-adjacent amide functional groups. The hydrogen in the amino group of one residue forms a hydrogen bond with the oxygen in the carbonyl group of another residue.



When hydrogen bonding can occur regularly between the N–H of each amino acid residue and the C=O located four residues earlier in the sequence, a coiled structure called an **alpha helix** (or α -helix) forms. This structure is the most common type of secondary protein structure and can be predicted from the sequence of amino acid residues.

In diagrams showing the structure of a whole protein, α -helices are represented using a curled ribbon.

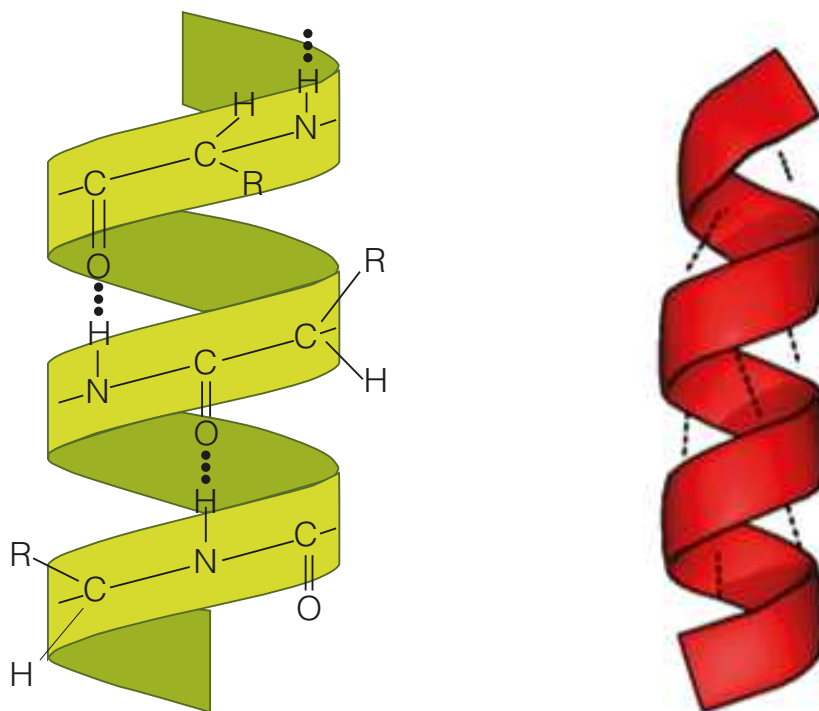


Figure 3.19 - a short section of α -helix secondary structure

When hydrogen bonding occurs between different parts of the protein chain, they form a pleated plane called a **beta sheet** (or β -sheet). This arrangement is also an extremely common motif of protein secondary structure.

In diagrams showing the structure of a whole protein, β -sheets are represented using wide flat arrows.

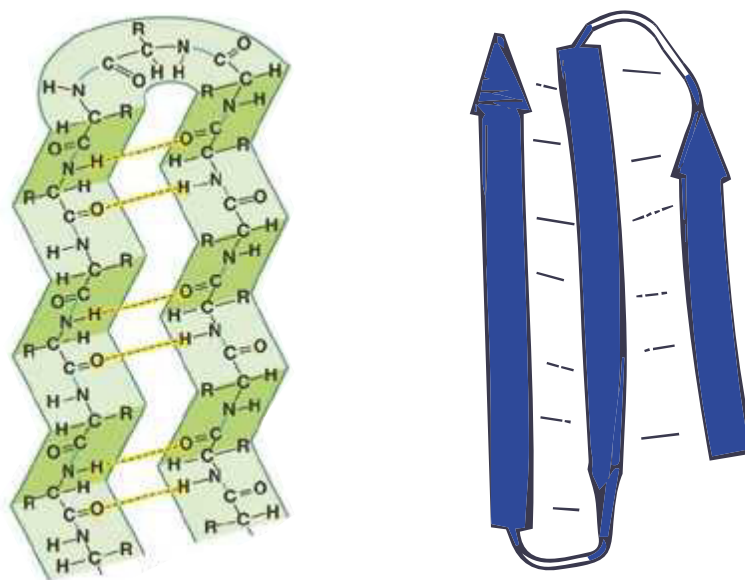
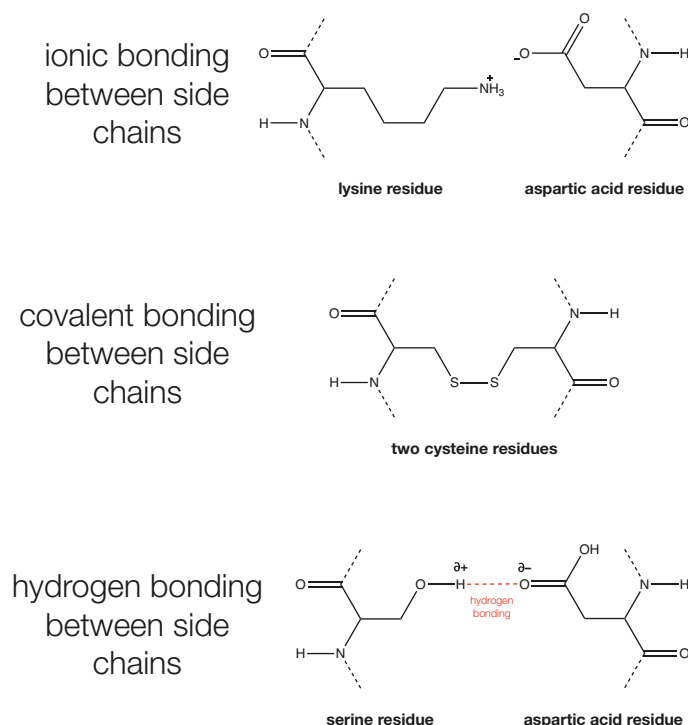


Figure 3.20 - a short section of β -sheet secondary structure

Some proteins are soluble in water because hydrogen bonding secondary interactions can form between the polar groups in the amide link and polar water.

Tertiary structure of proteins

The overall shape of a protein is called the **tertiary structure**. It refers to the way all atoms of the polypeptide chain arrange themselves in a three-dimensional shape. The tertiary structure of a protein depends largely on the particular side chains of the amino acid residues and how they interact with one another. Various side chains can form primary bonds (ionic or covalent) as well as secondary bonds, including ion-dipole, dipole-dipole, hydrogen bonding, and dispersion forces.



Interactions can occur between side chains of residues that are far apart in the sequence, but which happen to be near one another when the protein is folded.

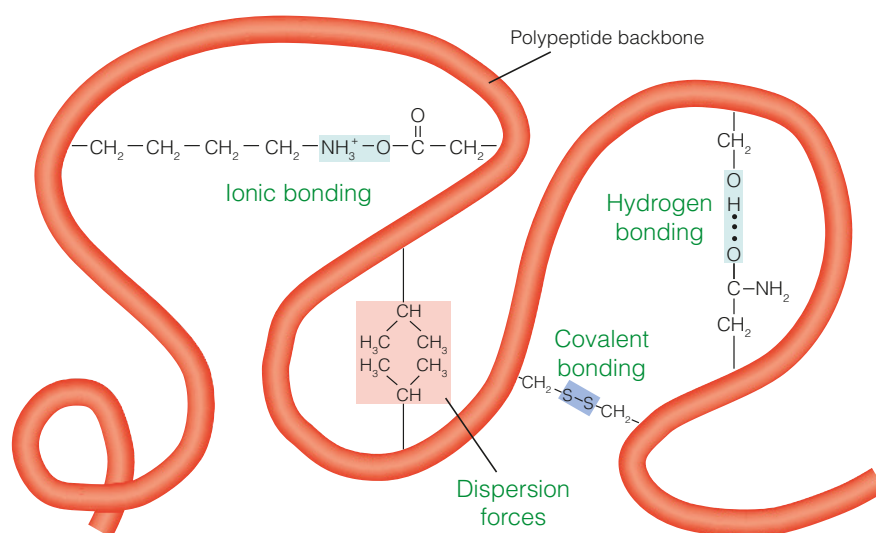


Figure 3.21 - Tertiary structure results from complex interactions between many parts of the protein

Quaternary structure of proteins

Some proteins do not function as single units; they combine with copies of themselves to create a symmetrical **protein complex**. This is called the **quaternary structure**. Each **subunit** is a large, but distinct, polypeptide molecule.

Example

Haemoglobin, the protein which transports oxygen in blood, is made up of four subunits arranged in a roughly tetrahedral structure.

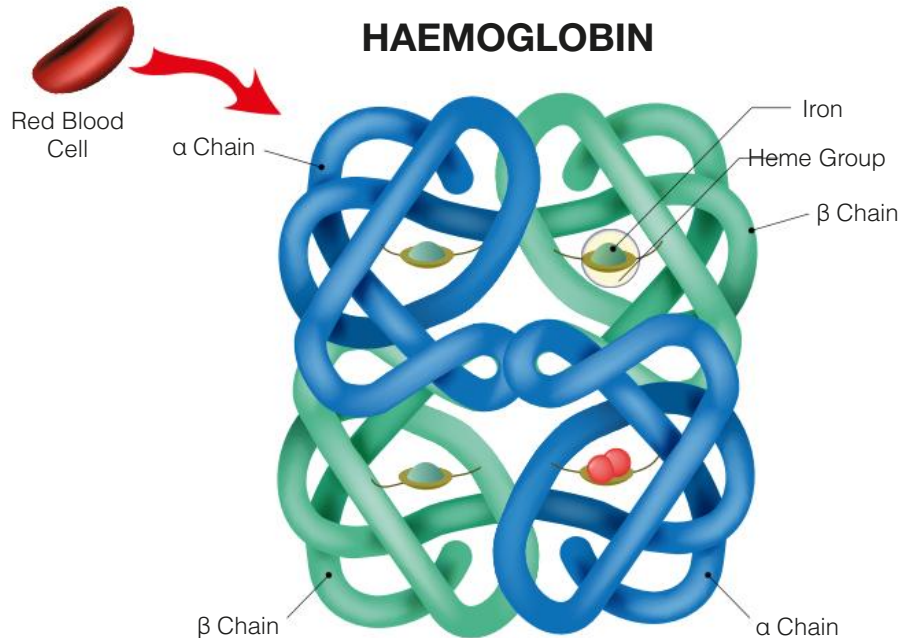


Figure 3.22 - Haemoglobin protein complex forms from four haemoglobin subunits

Protein Structure Summary

Proteins have at least three, and often four, levels of structure. The **primary structure** of a protein is its amino acid sequence. The **secondary structure** is the initial folding of the sequence into alpha helices and beta sheets. The **tertiary structure** is a more complex folding of the protein upon itself. **Quaternary structure** is the combination of two or more of the same protein.

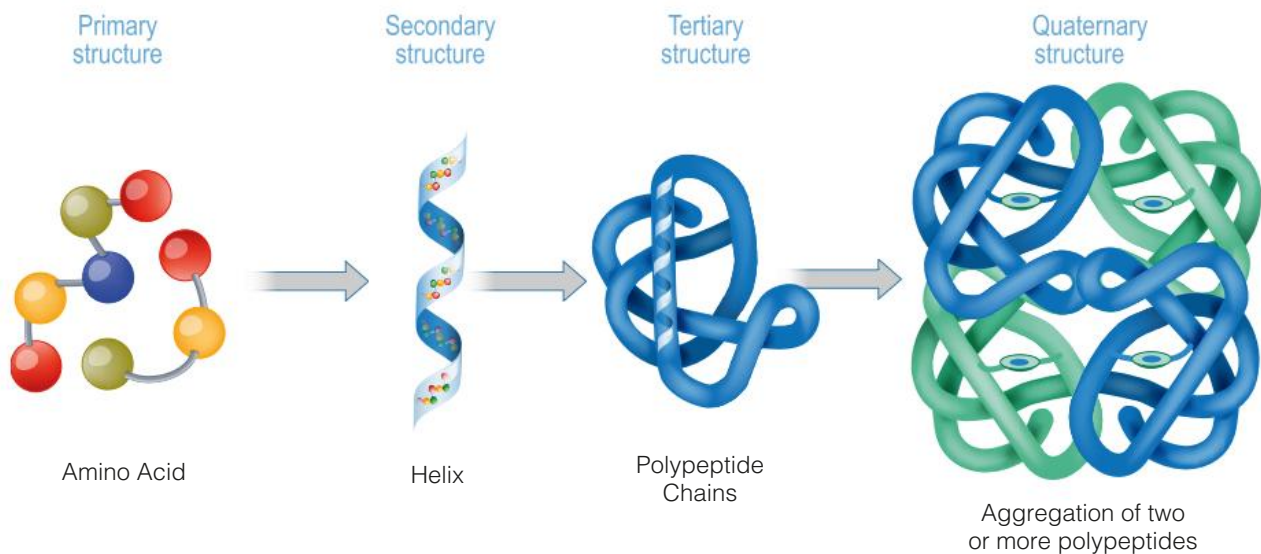


Figure 3.23 - Proteins have multiple levels of structure

Science understanding

Explain why the biological function of a protein (e.g. an enzyme) may be affected by changes in pH and temperature.

© SACE 2025

The three-dimensional structure of a protein is crucial to its function. If a protein's structure is changed such that the protein no longer functions, the protein is **denatured**. Even small changes can result in a protein losing all functionality. Two major factors that affect protein structure, and hence function, are **heat** and **pH**.

Effect of heat on protein structure

When proteins are heated to high temperatures, there is sufficient thermal energy to break secondary or even primary bonds. This disrupts the tertiary structure of the protein, and can also lead to a change in the macroscopic properties of the substance.

Example

Albumen is the main protein found in egg white. Albumen is water soluble but becomes insoluble when cooked. This is because the heat allows individual protein chains to change shape and form new primary bonds with other protein chains, creating a tangled web of cross-linked polypeptides.



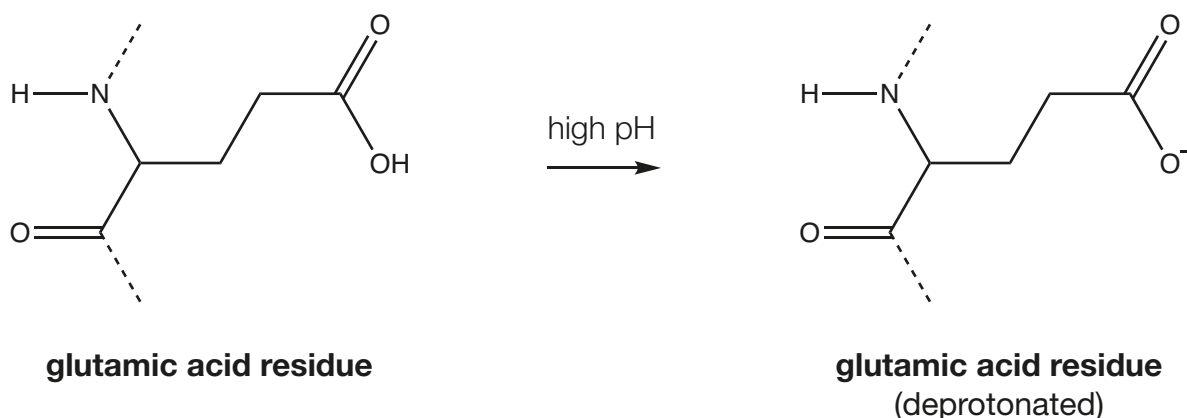
Figure 3.23 - Proteins can change drastically when heated

Effect of pH on protein structure

Many amino acid side chains are either acidic or basic; they can donate or accept protons. The pH of the solution will affect how these side chains are able to form bonds.

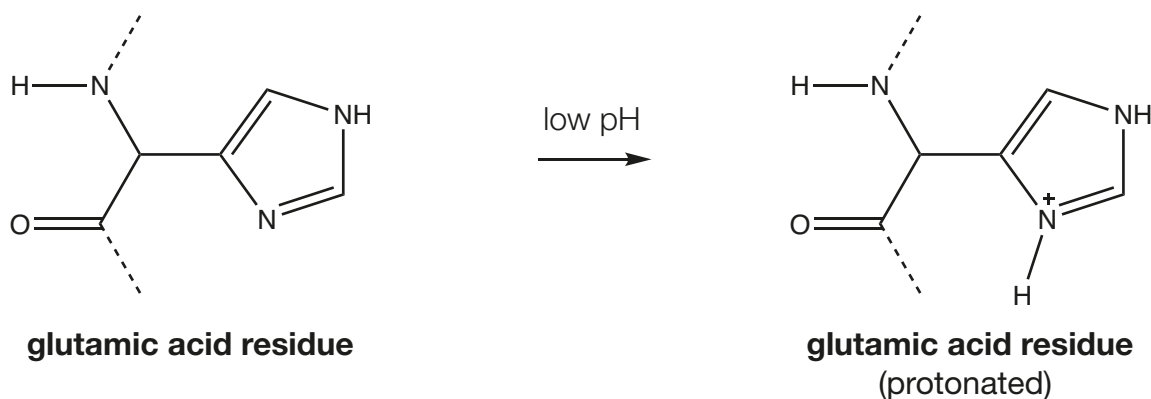
Acidic side chains will donate a proton when the pH increases.

Example



Example

Basic side chains will accept a proton when the pH decreases.



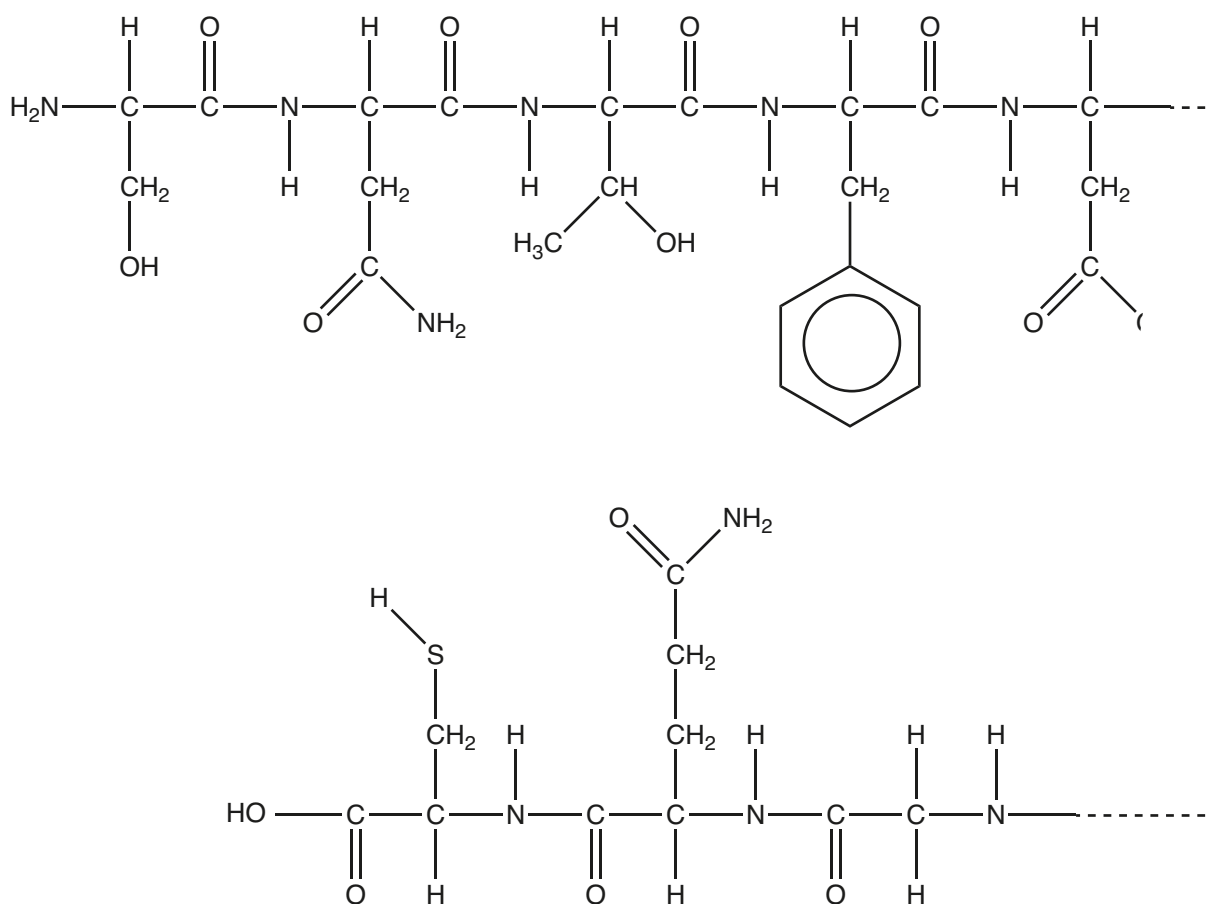
If the secondary interactions change, the protein molecule unfolds and denatures. Because the structure has changed, the protein is no longer able to function.

Enzymes

Enzymes are an important class of proteins. They are large molecules that act as natural catalysts for very specific reactions. Without enzymes, life would not be sustainable. As with all proteins, enzymes require specific temperature and pH ranges to function correctly. This is the primary reason that organisms die when they are too cold or too warm.

Questions

32. A part of a protein chain is shown below.



(a) Circle one peptide link in the chain above.

(1 mark) KA1

(b) Draw the structural formula for one amino acid that forms this protein chain.

(2 marks) **KA4**

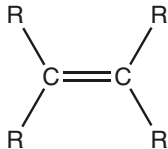
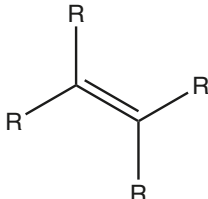
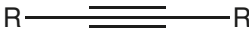
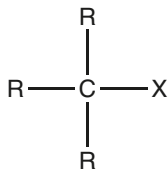
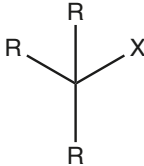
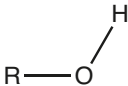
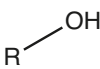
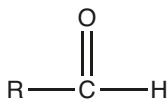
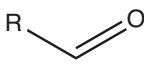
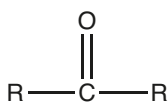
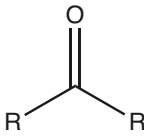
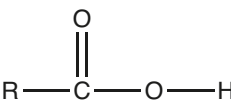
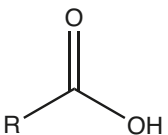
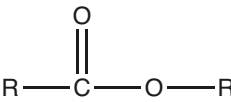
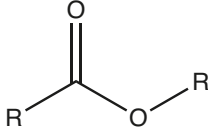
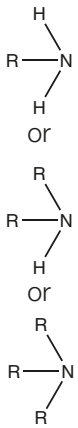
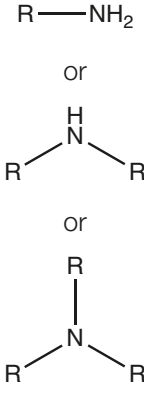
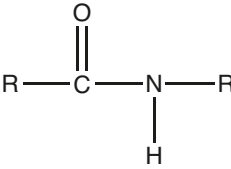
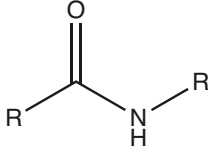
(c) Indicate sites for hydrogen bonding with water.

(1 mark) **KA1**

(d) With reference to the protein chain shown above, explain the effect of decreasing the pH on the secondary interactions in the protein and hence its function.

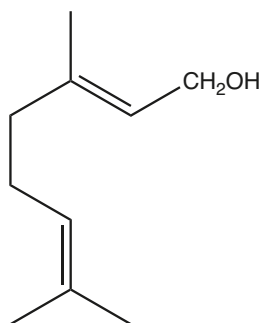
(4 marks) **KA1**

Chapter 3 functional groups summary

Homologous series	Functional group	Extended Structure	Skeletal Structure	Suffix or prefix
Alkene	Alkene			-ene
Alkyne	Alkyne	$R-C\equiv C-R$		-yne
Haloalkane (or halogenalkane or alkyl halide)	Halogen	 $X = \text{halogen}$		halo- e.g., fluoro-, chloro-
Alcohol	Hydroxyl			-ol
Aldehyde	Aldehyde (terminal carbonyl)			-al
Ketone	Ketone (non-terminal carbonyl)			-one
Carboxylic acid	Carboxyl			-oic acid
Ester	Ester			-yl -oate
Amine	Amino			-amine
Amide	Amide			-amide

Summary test 3: Organic and biological chemistry

1. Geraniol is a chemical compound found within many essential oils of fruits. It has a pleasant odour and can also be used as a natural insect repellent. Its structure is below.



- (a) Write the molecular formula of geraniol.

(1 mark) **KA1**

- (b) Geraniol can be partially oxidised with an oxidising agent. Draw the product.

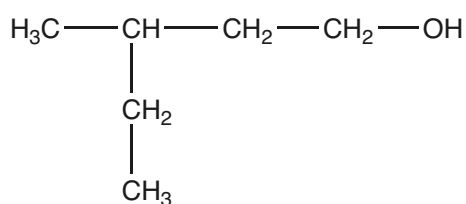
(2 marks) **KA4**

- (c) Many alcohols can also be used as fuels to provide energy.

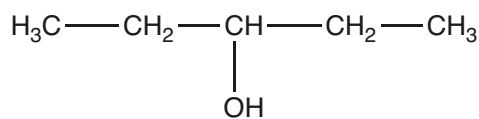
- (i) Write an equation for the complete combustion of ethanol.

(2 marks) **KA4**

- (ii) Classify the following alcohols as primary, secondary or tertiary.



(i)



(ii)

(2 marks) **KA1**

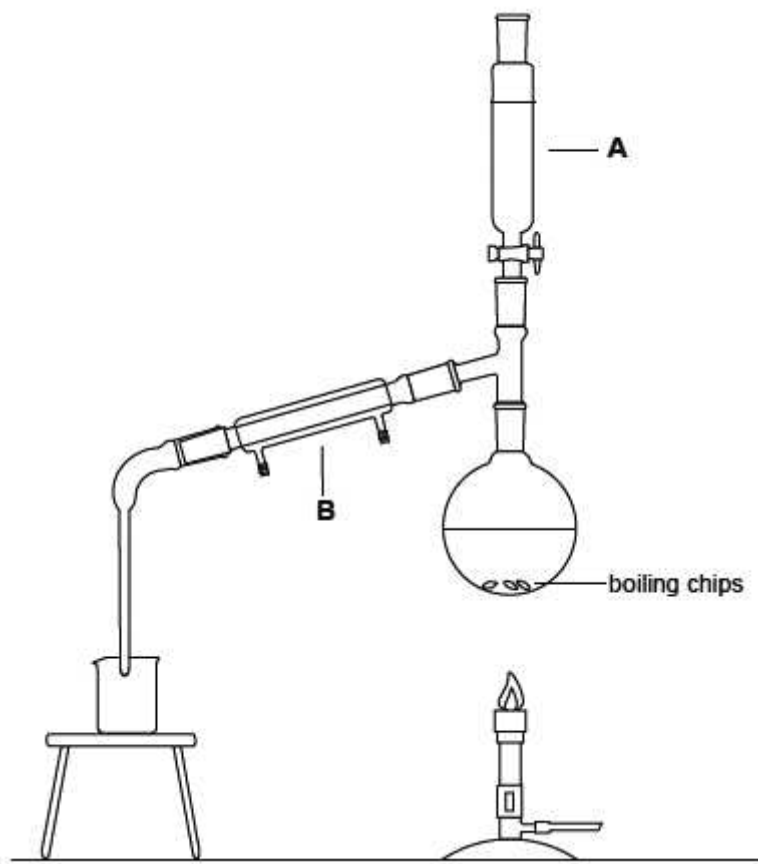
- (iii) Determine the organic product formed when each of the compounds is heated under reflux with excess acidified dichromate added dropwise. If no reaction occurs, write NR.

Compound	Organic product
$\text{CH}_3\text{CH}_2\text{CH}(\text{OH})\text{CH}_3$	
$\text{CH}_3\text{CH}_2\text{COCH}_3$	
$\text{CH}_3\text{CH}_2\text{CH}_2\text{OH}$	
$\text{CH}_3\text{CH}_2\text{CH}_2\text{CHO}$	

(4 marks) **KA1**

Aldehydes are used in many ways. Some aldehydes are found in natural materials, while others are made synthetically.

An aldehyde can be prepared from an alcohol, using the apparatus shown below:



- (iv) Name the pieces of glassware labelled **A** and **B**.

A is

(1 mark) **KA1**

B is

(1 mark) **KA1**

- (v) On the diagram above, show the direction of the water flow on the glassware labelled **B**.

(1 mark) **KA1**

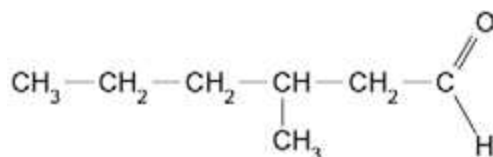
- (vi) The glassware labelled **A** contained acidified dichromate ($\text{Cr}_2\text{O}_7^{2-}/\text{H}^+$). When it reacted with the alcohol, the $\text{Cr}_2\text{O}_7^{2-}$ ions converted to Cr^{3+} ions. Write the half-equation for this conversion.

(2 marks) **KA1**

- (vii) Name the functional group that would be formed if the alcohol, acidified dichromate ($\text{Cr}_2\text{O}_7^{2-}/\text{H}^+$) and H_2SO_4 were refluxed together rather than reacted in the apparatus shown.

(1 mark) **KA1**

- (d) The structural formula of one aldehyde is shown below:



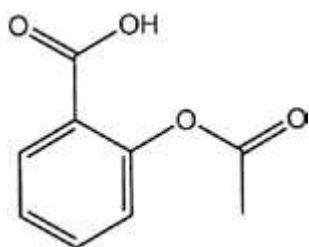
- (i) Give the systematic name of the aldehyde shown above.

(2 marks) **KA1**

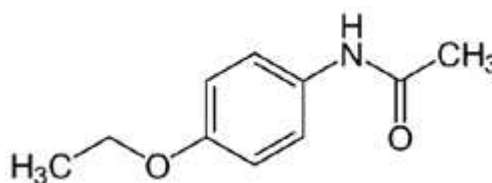
- (ii) Draw the structural formula of the ketone that is a functional group isomer of the aldehyde shown in (d).

(2 marks) **KA4**

2. The following compounds are the active ingredients in over-the-counter drugs used as analgesics.



Compound A



Compound B

- (a) Name two functional groups in Compound A.

(2 marks) **KA1**

- (b) Describe and explain a chemical test that could be undertaken in a laboratory to distinguish between Compound A and Compound B.

(3 marks) **KA1**

- (c) Explain why Compound B is slightly soluble in water.

(3 marks) **KA1**

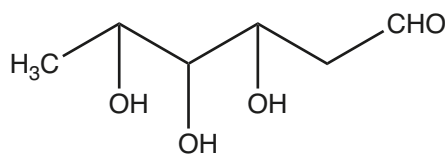
- (d) Draw the products formed when Compound B undergoes hydrolysis at pH 3.4.

(2 marks) **KA4**

- (e) Draw the products formed when Compound B undergoes hydrolysis at pH 11.8.

(2 marks) **KA4**

3. Carbohydrates are often found in nature. The purple foxglove plant produces important cardiac medication that reduces pulse rate, regulates heart rhythm, and strengthens heartbeat. When hydrolysed, it produces the monosaccharide shown below, labelled Monosaccharide A:



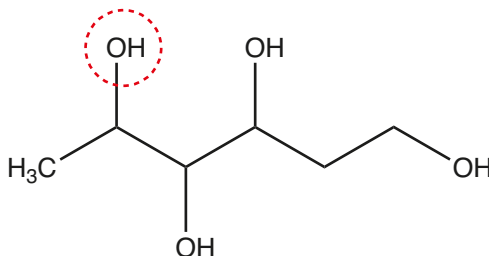
Monosaccharide A

- (a) Write the molecular formula of Monosaccharide A.
- (b) Explain why Monosaccharide A is classified as a carbohydrate.

(1 mark) **KA1**

(2 marks) **KA1**

- (c) An isomer of Monosaccharide A is shown below, labelled Monosaccharide B.



Monosaccharide B

- (i) Name monosaccharide systemically.
- (ii) Explain what is meant by the term "isomer".
- (iii) Classify the hydroxyl group that is circled as primary, secondary, or tertiary.
- (iv) Describe and explain a chemical test that could be performed in a laboratory to distinguish between Monosaccharide A and Monosaccharide B.

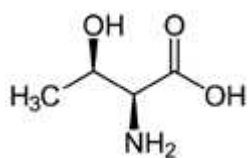
(2 marks) **KA1**

(1 mark) **KA1**

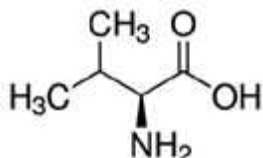
(1 mark) **KA1**

(4 marks) **KA1**

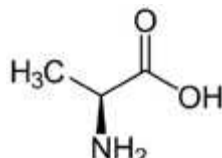
4. Questions (a) to (c) relate to the amino acids shown below.



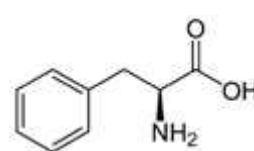
Threonine



Valine



Alanine



Phenylalanine

(a) Name the functional groups present in each of the amino acids.

(2 marks) **KA1**

(b) State which of the amino acids contain side chains that can form hydrogen bonds.

(2 marks) **KA1**

(c) Draw a section of a protein chain formed from the amino acids valine, phenylalanine, and threonine.

(2 marks) **KA4**

(d) Draw the structure of alanine when placed in a solution of the following pH:

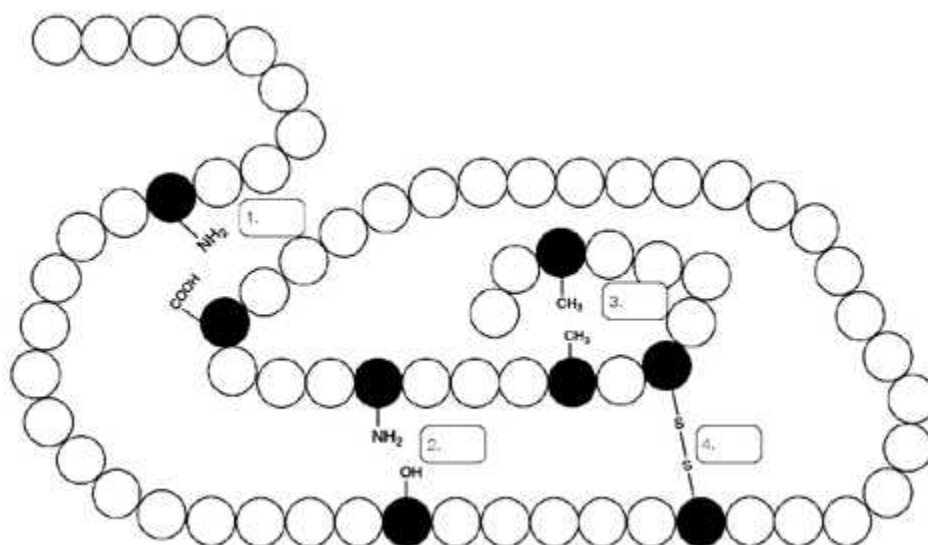
(i) pH 2.5

(ii) pH 7.1

(iii) pH 10.6

(6 marks) **KA4**

- (e) Protein X is shown below with various interactions occurring between parts of the chain.



Protein X

- (i) Identify the types of interactions occurring between parts of the protein chain.

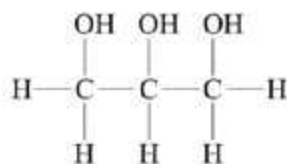
1.	
2.	
3.	
4.	

(4 marks) **KA1**

- (ii) The optimal pH for Protein X is 6.8. State and explain what would happen to this protein if it were placed in an alkaline environment.

(4 marks) **KA1**

5. The structural formula of compound **B** is shown below:

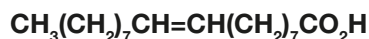


Compound **B**

- (a) Write the systematic name of compound **B**.

(2 marks) **KA1**

- (b) The structural formula of compound **C** is shown below.



When compound **B** reacts with compound **C**, a triglyceride, **D**, is formed.

- (i) Draw the structural formula of triglyceride **D**.

(2 marks) **KA4**

- (ii) Identify the other product of this reaction.

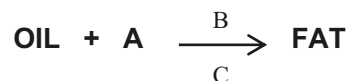
(1 mark) **KA1**

- (iii) Triglyceride **D** is a liquid at room temperature.

State whether **D** is more likely to come from a plant or a land animal.

(1 mark) **KA1**

- (iv) When heated, liquid oils may be converted into solid fats, as shown below:



Identify the required reagent A, the substance B, and the condition C necessary for the conversion to occur.

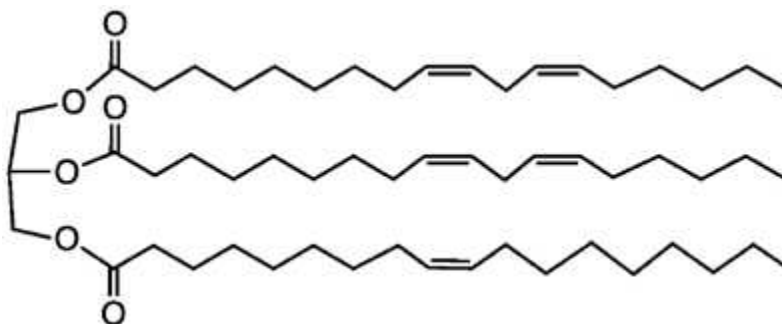
A:

B:

C:

(3 marks) **KA1**

- (c) The structural formula of another triglyceride is shown below:



0.1 g of this triglyceride was shaken in a non-polar solvent and reacted completely with iodine solution.

- (i) Calculate the number of moles of triglyceride in the 0.1 g, given that its molar mass is $876.16 \text{ g mol}^{-1}$.

(2 marks) **KA3**

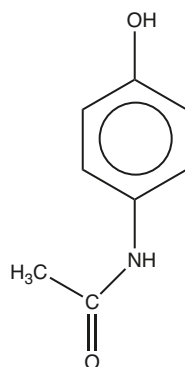
- (ii) Calculate the moles of iodine solution required to react completely with the triglyceride.

(1 mark) **KA3**

- (iii) Given the concentration of the iodine solution is 0.01 mol L^{-1} , calculate the volume of iodine solution required to react completely with the triglyceride.

(2 marks) **KA3**

6. The compound acetaminophen is used in over-the-counter medication such as paracetamol to relieve pain and fever. Its structure is below.



Acetaminophen (paracetamol)

- (a) State the functional groups present in acetaminophen.

(1 mark) **KA1**

- (b) Studies show that the protonated form of acetaminophen allows it to be more soluble in water.
- (i) Draw the protonated form of acetaminophen.

(2 marks) **KA4**

- (ii) Explain why the protonated form is more soluble than the molecular form.

(4 marks) **KA1**

- (c) The following excerpts are from the article “The Fever Paradox”, which discusses how paracetamol, fever, and COVID-19.

Geddes, Linda; New Scientist; 4/11/2020; Vol 246; Issue 3277; p39-41

AS NEWS about coronavirus spread around the world, paracetamol soon began to disappear from shop shelves as people stocked up at home. In some places, the price of the drug shot up. That probably comes as little surprise given that one of the key symptoms of the infection is a fever. We tend to routinely use drugs such as paracetamol or ibuprofen to try to bring down a high temperature. Yet mounting evidence suggests that fever may, in fact, be a strategy the body uses to ramp up its defences. This new understanding of what is going on when we are burning up could help us come up with better approaches to fighting infection altogether.

Daniel Davis, an immunologist at the University of Manchester, UK, says that, “by increasing your body temperature, you may be slowing down the ability of a virus to multiply.”

Mark Peters, from the UCL Great Ormond Street Institute of Child Health in London, suggests fever might not be all bad. “Things that have a very high metabolic cost would not be preserved throughout evolutionary history unless they came with a clear survival advantage.” We currently have no effective drugs for pneumonia triggered by the new coronavirus, and so Peters speculates that mild fever could be helpful in such a situation.

“Fever may be a deliberate strategy to bolster our immune defences in the face of infection,” says Mike White at the University of Manchester. “It suggests that the immediate immune response is that bit faster at higher temperatures.”

However, Edward Walter, an intensive care doctor at Royal Surrey County Hospital in Guildford, UK, says, “The question isn’t whether we should treat fever, but in which patients we should do it.”

Not everyone agrees. “You cannot really say fever is good, period, or fever is bad, period,” says Andrej Romanovsky at the University of Arizona, who edits the journal *Temperature*. “The only practical way to answer how we should treat fever is to run clinical trials in specific populations suffering from a specific disease and using specific (fever-reducing) drugs.”

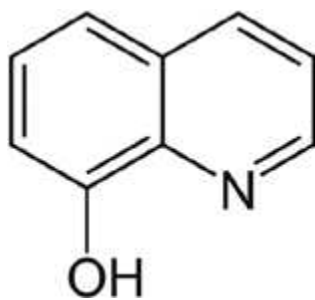
In the meantime, the UK’s National Institute for Health and Care Excellence (NICE) is reviewing evidence on ibuprofen to try to clarify whether it is safe for treating the symptoms of covid-19 infections, after French health officials controversially urged people with symptoms to avoid the drug. The current advice from the World Health Organization is that either paracetamol or ibuprofen can be used to treat symptoms of the illness.

With reference to the information presented in the article above, discuss and explain the importance of **Communication and Collaboration** in Science as a Human Endeavour.

(4 marks) **KA1**

7. "Bag Balm" is a medical ointment that is used to soothe dry, cracked skin on humans. It was originally developed in 1899 to soothe irritation on cows' udders after milking.

(a) One of the active ingredients in Bag Balm is shown below, labelled Compound A:



Compound A

- (i) Write the molecular formula of Compound A.

(1 mark) KA4

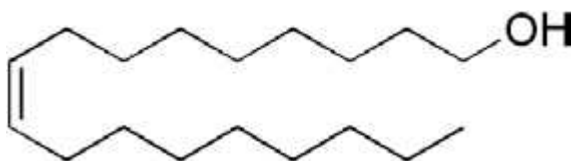
- (ii) Name the functional group in Compound A that contains nitrogen and identify it as primary, secondary, or tertiary.

(2 marks) KA4

- (iii) Explain why Compound A is only slightly soluble in cold water.

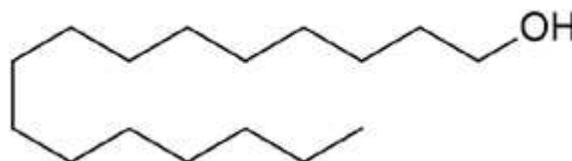
(3 marks) KA1

- (b) Two other ingredients in Bag Balm are shown below. Use this information to answer the questions that follow.



Compound B

Formula: $C_{18}H_{36}O$



Compound C

Formula: $C_{16}H_{34}O$

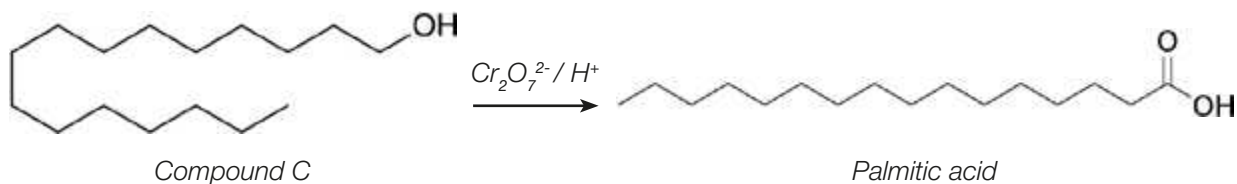
- (i) State and explain which compound is unsaturated.

(2 marks) KA4

- (ii) Describe a chemical test that can be performed in the lab to distinguish between Compound B and Compound C. Include relevant reagents, equations, and observations.

(4 marks) KA1

- (c) **Compound C** converts to palmitic acid in the presence of acidified dichromate, shown below.



- (i) State the name of this type of reaction.

(1 mark) **KA4**

- (ii) State the colour change that occurs.

(1 mark) **KA4**

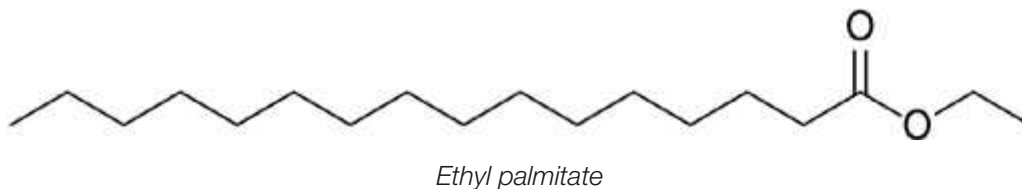
- (iii) State and explain whether you would expect palmitic acid to be solid or liquid at room temperature.

(3 marks) **KA1**

- (iv) Draw the triglyceride formed with three palmitic acid molecules.

(2 marks) **KA4**

- (v) Palmitic acid can undergo a condensation reaction to produce ethyl palmitate, shown below.



- (1) State the functional group in ethyl palmitate.

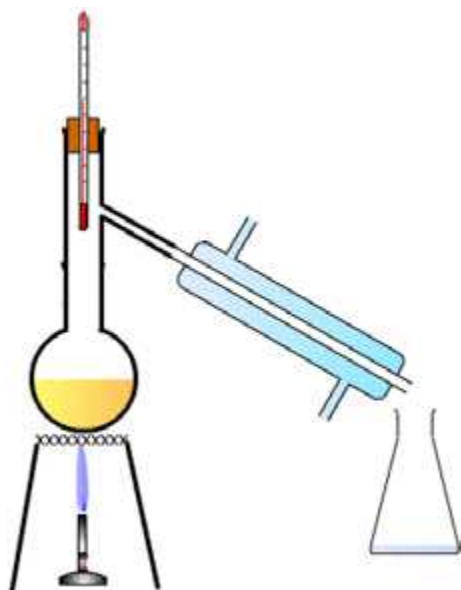
(1 mark) **KA4**

- (2) Draw and name the alcohol that reacts with palmitic acid to produce ethyl palmitate.

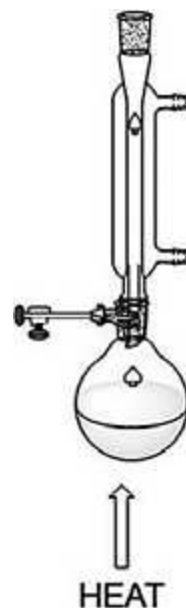
Name:

(3 marks) **KA4**

- (3) Circle which apparatus, 1 or 2, would be used to produce ethyl palmitate.



Apparatus 1



Apparatus 2

- (4) Label the water flow on Apparatus 2 above.
 (5) Explain why concentrated sulfuric acid is used in the condensation reaction to produce ethyl palmitate.

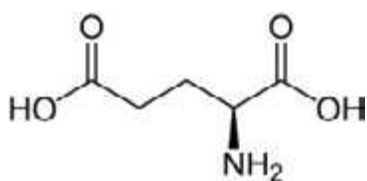
(3 marks) KA1

- (6) State **one other** condition required to produce ethyl palmitate.

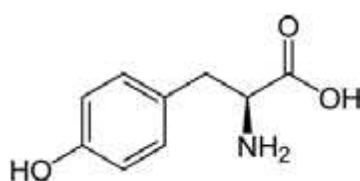
(1 mark) KA4

8. Milk is a primary source of nutrition for young mammals.

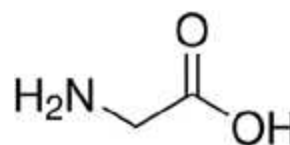
- (a) Three of the most abundant amino acids found in raw milk are glutamic acid, tyrosine, and glycine, whose structures are shown below:



Glutamic acid



Tyrosine

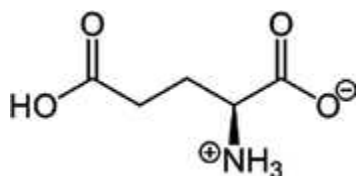


Glycine

- (i) Tyrosine reacts with glycine to form a dipeptide. Draw this dipeptide and circle the peptide link.

(3 marks) KA1

- (ii) Glutamic acid exists as a zwitterion at pH 3.2 with the following structure:



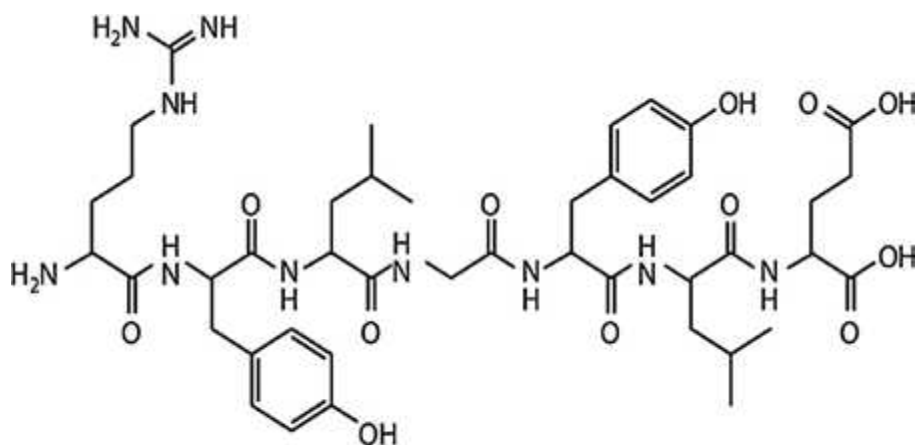
- (A) Explain why the zwitterion form of glutamic acid is more soluble than its neutral form.

(3 marks) **KA1**

- (B) Draw the structure of glutamic acid at pH 12.

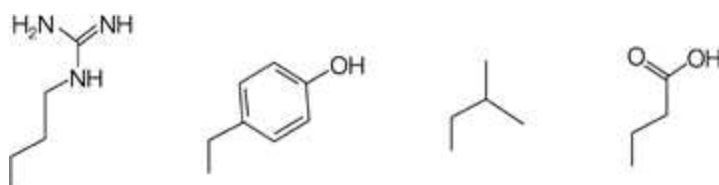
(2 marks) **KA4**

- (b) Milk contains proteins called casein. A fragment of the larger casein structure is shown below.



Structure of casein.

- (i) Circle one peptide link in the diagram above.
 (ii) Some side chains of casein are shown below.



Using the space provided, show how one or more of these side chains would be affected when lactic acid produced by bacteria react with casein.

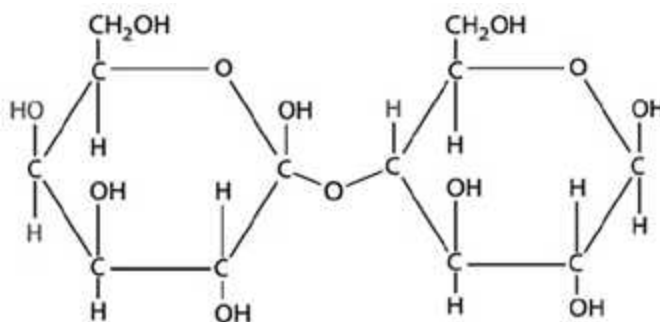
(2 marks) **KA4**

- (iii) Milk is converted to yoghurt by a process of fermentation with lactic acid bacteria. When lactic acid bacteria react with casein, the original proteins change from being spherical shape and soluble in water to strand-like proteins that are insoluble in water.

Explain why the reaction between the lactic acid produced by bacteria and casein results in the change in chemical properties of the protein.

(4 marks) **KA1**

- (c) Milk contains the disaccharide *lactose*, shown below.



Lactose

- (i) Lactose is classified as a carbohydrate. State the definition of “carbohydrate”.

(2 marks) **KA4**

- (ii) The *lactase enzyme* breaks down lactose. People with lactose intolerance do not produce enough of the enzyme, and undigested lactose continues along the intestinal tract and attracts water molecules.

Explain why lactose can attract water molecules.

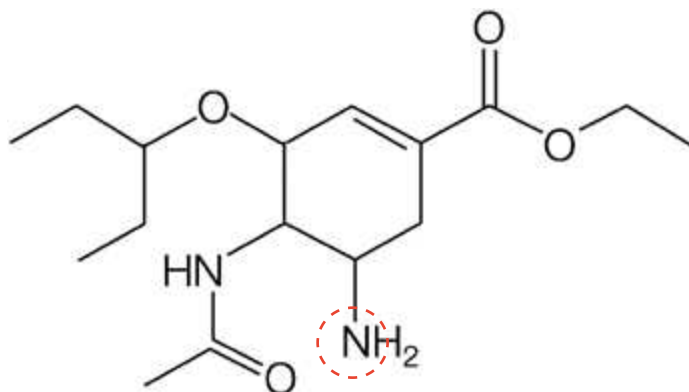
(2 marks) **KA4**

- (iii) Lactose is formed from the condensation reaction between galactose and glucose. Galactose and glucose both have the same molecular formula, $C_6H_{12}O_6$. State the name given to molecules with the same molecular formula but different structures.

(1 mark) **KA4**

9. Tamiflu is an antiviral drug that can help treat the symptoms of influenza.

(a) The structure of the organic compound contained in Tamiflu is shown below, "Compound OP".



Organic compound in Tamiflu, **Compound OP**

(i) State the names of the functional groups in **Compound OP** that contain nitrogen.

(1 mark) **KA4**

(ii) State whether the circled nitrogen is primary, secondary, or tertiary.

(1 mark) **KA4**

(iii) **Compound OP** can undergo ester hydrolysis to form a carboxylic acid and another compound.

State the name of the **other compound** that is formed from the ester hydrolysis of **Compound OP**.

(2 marks) **KA2**

(b) Scientists have discovered that Tamiflu may also offer treatment for hearing loss.

The following information is from New Scientist (1 June 2024, p 11).

Researchers from Creighton University in Nebraska discovered that Tamiflu seemed to ease noise-induced hearing loss in mice. Noise-related hearing loss affects approximately five per cent of people worldwide. Prevention focuses on just avoiding loud sounds where possible, and treatments are limited to hearing aids and implants. One researcher states, "While promising, it is a study in mice and so the drug effects in humans would need to be established before we can get excited about its potential to reduce or prevent hearing loss."

Using the SHE concept of *Application and Limitation*, explain how this discovery relates to Science as a Human Endeavour.

(3 marks) **KA3**

(c) So far, only one drug has ever been approved to prevent any type of hearing loss: sodium thiosulphate, $\text{Na}_2\text{S}_2\text{O}_3$.

(i) State the charge on the thiosulphate ion.

(1 mark) **KA4**

(ii) State the oxidation state of sulphur in sodium thiosulphate.

(1 mark) **KA4**

Topic 4: Managing resources

4.1 Energy

Science understanding

Photosynthesis and respiration are important processes in the cycling of carbon and oxygen on Earth.

In photosynthesis the light energy absorbed by chlorophyll is stored as chemical energy in carbohydrates such as glucose.

Describe and write the equation for photosynthesis.

The chemical energy present in carbohydrates can be accessed by respiration and combustion.

Describe and write the equation for the aerobic respiration of glucose.

© SACE 2025

The carbon cycle

The **carbon cycle** describes the movement of carbon, in its various forms, between the atmosphere, oceans, biosphere (parts of Earth where life exists), and geosphere (geology of the Earth's crust) as shown in Figure 4.1.1.

The carbon cycle identifies **carbon reservoirs** (the ocean, atmosphere, living things, rocks) and the processes by which carbon moves between these reservoirs. If more carbon enters a carbon reservoir than leaves it, it is referred to as a **net carbon sink** (oceans). Conversely, if more carbon leaves a reservoir than enters it, it is referred to as a **net carbon source** (combustion of fossil fuels).

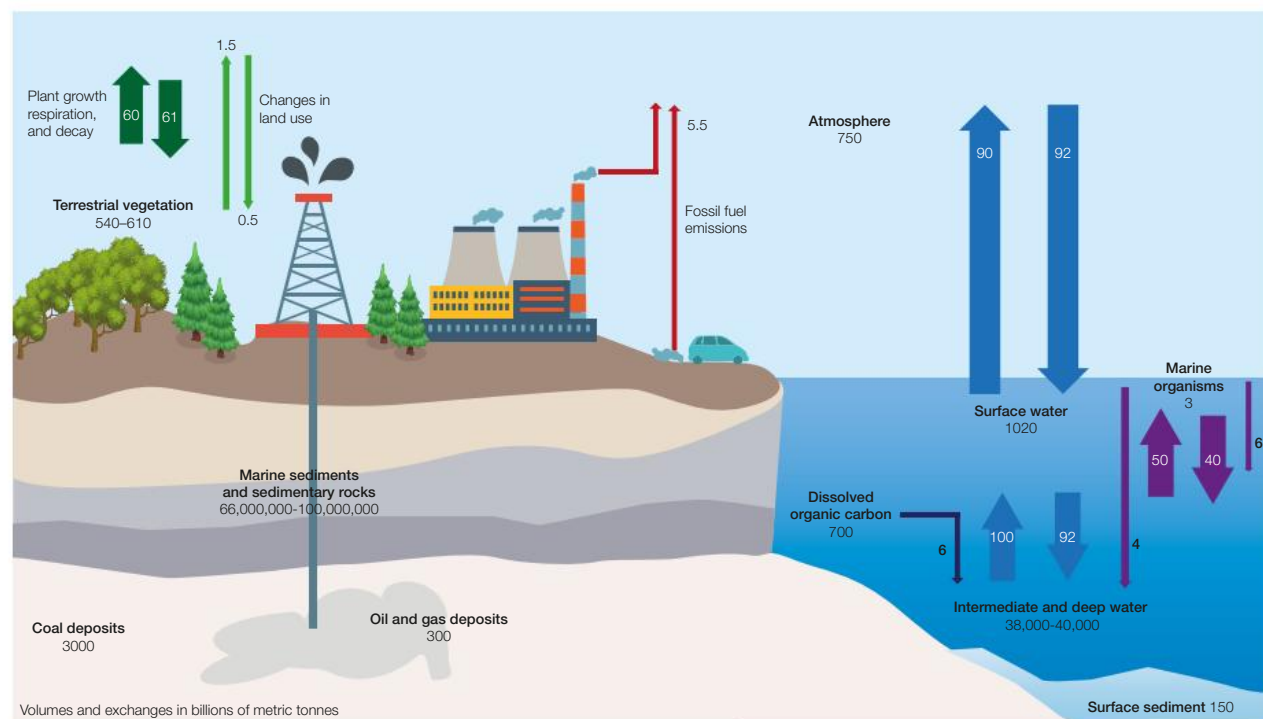
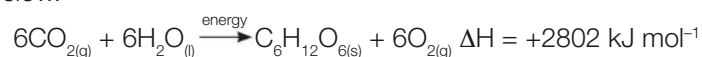


Figure 4.1.1: The carbon cycle.

Photosynthesis

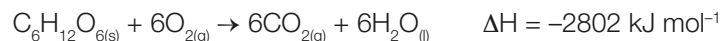
Photosynthesis is the chemical process by which plants and some microorganisms (algae, phytoplankton and cyanobacteria) use carbon dioxide, water and energy absorbed from sunlight to produce oxygen and glucose. Glucose (monomer) is stored as starch (polymer) in plants and glycogen (polymer) in animals for future use. The reaction is summarised below.



Photosynthesis is an **endothermic** process, as there is a net absorption of energy. The conversion of energy from sunlight into stored chemical energy, in the form of glucose, is associated with the green pigment **chlorophyll**.

Aerobic respiration

Respiration is the chemical process by which organic compounds release energy in the cells of living things. Aerobic respiration is a series of reactions that release the energy stored in carbohydrates (and in some cases lipids) formed during photosynthesis. Respiration is an **exothermic** process, as there is a net release of energy. Respiration occurs in the cells of living organisms, making this energy available for **metabolic activity** (processes such as the synthesis of larger molecules, contraction of muscles, and maintenance of body temperature). The reaction is summarised simply through the rearrangement of the photosynthesis reaction.



Science understanding

Fossil fuels (coal, petroleum, and natural gas) have been formed over geological timescales by anaerobic decomposition of dead organisms. They are considered to be non-renewable because reserves are depleted more quickly than they are formed.

Carbon-based fuels provide energy and are feedstock for the chemical industry.

Biofuels are produced by present-day biological processes.

Identify bioethanol and biodiesel as biofuels.

Discuss the advantages and disadvantages of using carbon-based fuels as sources of heat energy, compared with their use as feedstock.

© SACE 2025

Carbon-based fuels

Carbon-based fuels include **fossil fuels** and **biofuels**. Fuels undergo combustion with an oxidiser (oxygen) to release chemical energy stored in the covalent bonds. This energy is primarily used in electricity production and transport applications. Fuels are also used as a **feedstock** (raw material) in the manufacture of a range of consumer products or as an energy source in their production. Carbon-based fuels provide the raw materials required for the production of a vast range of products, including paints, textiles and pharmaceuticals.

Fossil fuels

Fossil fuels have been formed over hundreds of thousands of years through the decay of organic (plant and animal) matter under **metamorphic** (heat and pressure) geological conditions. Fossil fuels include coal, petroleum and natural gas. Combustible fossil fuels have been used extensively as a source of energy since the industrial revolution. Fossil fuels are a finite and **non-renewable** resource. The rate at which fuels are consumed greatly exceeds the rate of their geological formation.

Biofuels

Biomass fuels (biofuels) are derived from biomass (organic material) from plants and the waste matter from animals. Biofuels include bioethanol, biodiesel and biogas. Biofuels provide a **renewable** alternative to many fossil fuels. Bioethanol and biodiesel are being blended with petrol and diesel respectively.

In applications as an energy source and as feedstock, fossil fuels and biofuels offer a range of advantages and disadvantages.

Fossil fuel		Advantages
Reserves	Energy and feedstock	Coal, crude oil and natural gas are relatively abundant.
Extraction, processing & distribution	Energy and feedstock	Fossil fuels are easily extracted and distributed. Coal is mined and transported via train or truck. Drilling is used to extract oil, which is then transported via pipelines or oil tankers. Drilling is also used to extract natural gas, which is associated with deposits of petroleum. The gas is then processed and distributed via pipelines.
Infrastructure	Energy and feedstock	Proven technologies have been employed to generate electricity from the combustion of fossil fuels and run internal combustion engines in motor vehicles. Well-established industries exist for a multitude of products derived from crude oil and associated petrochemicals. A great deal of infrastructure has been developed and maintained worldwide for the distribution and continued use of fossil fuels.
Energy density	Energy	Combustion of fossil fuels releases large amounts of energy per gram or litre, making them highly effective fuels for energy production and transportation.

Fossil fuel		Disadvantages
Reserves	Energy and feedstock	Fossil fuel reserves are being depleted at a growing rate. Their rate of consumption is much faster than their rate of geological formation.
Production	Energy and feedstock	Fossil fuels are non-renewable.
Combustion products	Energy	Combustion of fossil fuels releases large quantities of carbon dioxide, contributing to global warming (refer to Page 1). Other products of combustion include carbon monoxide and soot (carbon). Both contribute to global air pollution, which is a leading cause of respiratory and cardiovascular illness. The high temperatures experienced during the combustion of fossil fuels leads to the formation of oxides of nitrogen, which may contribute to the formation of photochemical smog and acid rain (refer to Page 19). The composition of coal and petroleum products are variable, but both contain sulfur impurities. On combustion, oxides of sulfur are formed, which may contribute to the formation of acid rain.

Biofuels		Advantages
Reserves	Energy and feedstock	Biofuels are plentiful as they can be grown in relatively short periods of time to meet demands.
Production	Energy and feedstock	Biofuels are renewable. Biofuels can be derived from traditional crops such as corn, sugar cane and oil seeds. Second-generation biofuels utilise non-food biomass produced as waste products from cropping or grasses not grown for food. Third-generation biofuels include algae, which are highly efficient at undergoing photosynthesis and produce a range of biofuel products.
Energy density	Energy	Many biofuels provide energy densities comparable with traditional fossil fuels.
Products of combustion	Energy	Biofuels are often described as being carbon-neutral, as the emissions of carbon dioxide from combustion are offset by the absorption of carbon dioxide by biofuel crops and microbes during photosynthesis (plant growth).

Biofuels		Disadvantages
Production	Energy and feedstock	First-generation biofuel production competes directly with land used for agriculture, designated for food production. First and second-generation biofuels require vast areas of land.
Product of combustion	Energy	Production and combustion of biofuels produce carbon dioxide, which contributes to global warming. Some forms of biodiesel produce higher concentrations of the oxides of nitrogen compared to traditional diesel fuel, contributing further to photochemical smog and acid rain.
Infrastructure	Energy and feedstock	There is currently limited production, distribution and use of biofuels. Very few manufacturers have motor vehicles in production, designed to run on high-concentration blends of biofuels. Infrastructure is not widespread for the production, distribution and use of biofuels.



Science as a human endeavour

Sustainable oil from algae

Biofuels are divided into 'generations' according to whether they consume resources that could otherwise be used for food production. First-generation biofuels derive from food crops and, therefore, compete directly with food supply. Second-generation biofuels derive from non-edible materials such as crops grown specifically for biofuel or unwanted biomass from farms or forest clearing; second-generation biofuels still require large amounts of land. Third-generation biofuels derive from aquatic biomass, such as algae grown in tanks, and generally require much less land. Fourth-generation biofuels are derived from bio-engineered algae and other microorganisms. The key advantage of algae as a biofuel source is that it does not compete with food crops for arable land.

Biodiesel and useful by-products are harvested from large-scale algal farms in Australia. Microalgae are microscopic organisms that can directly convert carbon dioxide and sunlight into biochemical energy through photosynthesis. Microalgae grow extremely fast and can be grown throughout the year, as, unlike conventional crops, microalgae do not rely on the seasons. Microalgae have been found to provide up to ten times the yield of biofuels per area of land used when compared to traditional crops of plant species. Algae also offer the benefit of growing in saline environments where traditional crops will not.



Algae contain lipids (oils) that can be extracted as a raw material for biodiesel production. The remainder of the algae biomass can be used as feed for livestock. Biodiesel production and use as a biofuel contribute very little to global warming, as the carbon dioxide produced during production and combustion is offset by highly efficient photosynthesis during the algae's growth.

Biofuels may offer the best solution to decarbonising the aviation industry, particularly for long-haul flights where other options are limited. Electric aircraft face significant challenges due to the weight of batteries, making them promising for short distances but unsuitable for long-range air travel. By contrast, biofuels are compatible with existing aviation infrastructure and can immediately reduce carbon emissions. This is especially important in Australia, where per capita carbon emissions from aviation are among the highest in the world—five to ten times greater than the global average. Transitioning to sustainable biofuels for aviation could be a crucial step toward reducing these emissions.

Question

1. (a) **Describe** how the development of third- and fourth-generation biofuels relies on evidence from multiple scientific disciplines and **explain** why this multidisciplinary approach is necessary.

(3 marks) **KA3**

- (b) **Identify** and **explain** how social, economic, or cultural factors might influence the acceptance and use of biofuels to decarbonise the aviation industry.

(3 marks) **KA3**

- (c) **Explain** how the use of biofuels in aviation could have both beneficial and potentially unexpected consequences. **Suggest** how these outcomes could be monitored or evaluated.

(3 marks) **KA3**

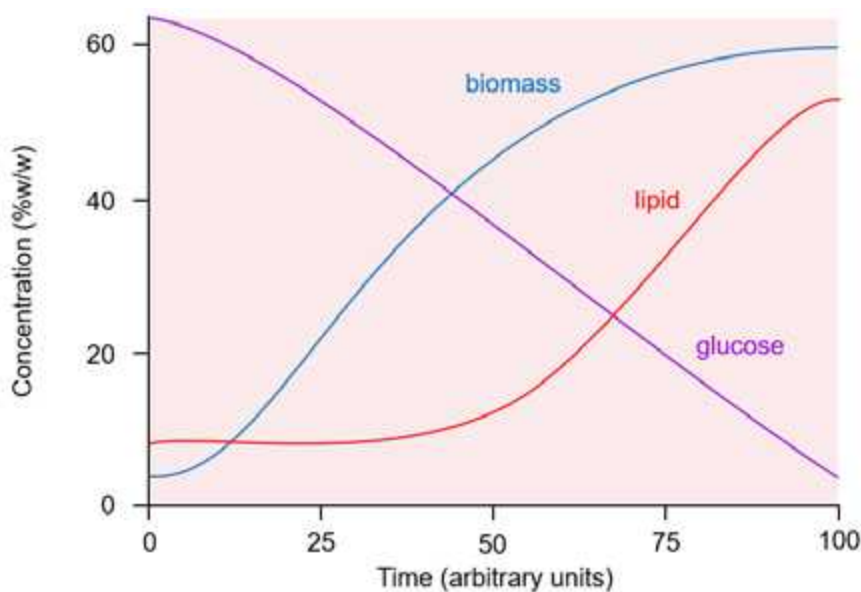
2. Algae can be farmed to provide a sustainable source of biodiesel.
- (a) Algae are microorganisms that undergo photosynthesis in a highly efficient manner.
- (i) **Write** an equation for photosynthesis, forming glucose as a product.

(2 marks) **KA4**

- (ii) **State** and **explain** whether photosynthesis represents an endothermic or exothermic reaction.

(2 marks) **KA1**

- (b) The following graph represents the relative changes in glucose, lipids (oils), and biomass for algae during their growth.



- (i) **Suggest** why the relative percentage of glucose decreases over time, as the relative percentage of biomass and lipid increases.

(2 marks) **KA2**

- (ii) Algae are grown and farmed for extended periods of time before harvesting.
- (1) **State** one advantage of extended growth periods in the production of biodiesel from algae.

(1 mark) **IAE3**

- (2) **State** and **explain** one environmental advantage of extended growth periods for the algae.

(2 marks) **KA2**

- (c) **Discuss**, with the aid of an equation, the advantages and disadvantages of the production and use of biodiesel compared to diesel derived from petroleum.

(6 marks) **KA2**

Science understanding

Renewable energy is generated over time scales of years to decades, from sources that are replenished much more quickly than fossil fuels.

Identify bioethanol, biodiesel, sunlight, and wind as renewable energy sources.

Compare the contributions of fossil fuels to global warming with those from renewable energy sources.

© SACE 2025

Renewable energy sources

Renewable energy is energy that has been generated from natural renewable sources. **Renewable sources** include hydropower (including tidal), wind power, solar energy, geothermal energy and biomass fuels.

The raw materials required for energy production from renewable energy sources are generated in timescales (ranging from minutes to years) that are considerably shorter than those required for the formation of fossil fuels (millions of years). Therefore, renewable energy sources can be naturally replenished. When renewable sources are used, the demand for fossil fuels is also reduced.

Direct emissions from the use of renewable sources (apart from biofuels) do not significantly contribute to the production of greenhouse gases. However, the establishment, production, distribution and ongoing maintenance of technologies related to these energy sources generate a significant contribution to the release of greenhouse gases, which affects global warming.

Energy source	Renewable / non-renewable	Contribution to global warming
Fossil fuels	Non-renewable	Significant quantities of greenhouse gases are produced during the extraction, processing and burning of fossil fuels. Large quantities of carbon dioxide are emitted during the combustion of fossil fuels in electricity production and in the internal combustion engines of motor vehicles.
Biofuels	Renewable	Intensive farming practices rely on burning fossil fuels during the production, processing and transportation of crops and livestock. Biofuel production uses electricity derived from the combustion of fossil fuels. Greenhouse gases are emitted in the production, processing and combustion of biofuels. Some production of carbon dioxide is offset by the carbon dioxide absorbed during photosynthesis.
Hydropower (including tidal)	Renewable	Hydropower does not directly generate greenhouse emissions. However, construction of the plant and the distribution and maintenance of equipment and associated power networks uses energy derived from fossil fuels, thus contributing to atmospheric emissions of greenhouse gases and pollutants.
Wind	Renewable	Wind power does not directly generate greenhouse emissions. However, the production and maintenance of wind turbines and infrastructure require the input of energy derived from fossil fuels, thus contributing to atmospheric emissions of greenhouse gases and pollutants.
Solar	Renewable	Photovoltaic cells do not directly generate greenhouse emissions. However, the production, distribution and maintenance of solar arrays and associated power networks uses energy derived from fossil fuels, thus contributing to atmospheric emissions of greenhouse gases and pollutants.
Geothermal	Renewable	Greenhouse gases – methane and carbon dioxide (released from steam in groundwater) – are emitted directly into the troposphere when energy is harnessed from the Earth's crust. Drilling, the construction of the plant and the distribution and maintenance of equipment and associated power networks uses energy derived from fossil fuels, thus further contributing to greenhouse emissions.

Science understanding

Describe the production, from biological materials, of ethanol and biodiesel, including the writing of chemical equations for the reactions involved.

Explain how fossil fuels contribute more than biofuels to global warming.

© SACE 2025

Bioethanol

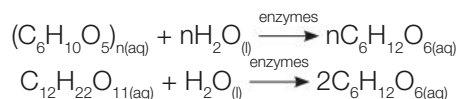
Bioethanol has been pursued as an alternative fuel source to reduce demands on dwindling supplies of petroleum, which is the raw material used to produce petroleum-based fuels. Ethanol is blended with petrol in varying ratios, or is used as a pure liquid in motor vehicles that have been designed to accommodate the fuel.

Bioethanol is produced from the action of microorganisms during **fermentation** of simple carbohydrates derived from natural vegetation. Ethanol is the product of enzyme-catalysed reactions occurring inside **yeast** (single-celled microorganism). Fermentation of the carbohydrate glucose is an anaerobic process and is represented by the equation below.



The production of carbon dioxide is observed as effervescence. Heat is generated as fermentation is an exothermic process.

Ethanol can be produced directly from plant sources containing simple carbohydrates (monosaccharides such as glucose or fructose) or indirectly from the hydrolysis of complex carbohydrates (polysaccharides such as starch and cellulose, or disaccharides such as sucrose). Polysaccharides and disaccharides undergo hydrolysis reactions to form monosaccharides prior to fermentation. This can be achieved through the action of enzymes (proteins) such as amylase and cellulase.



The ethanol content is limited by the types of yeast and enzymes present during fermentation. Higher concentrations of ethanol are obtained through fractional distillation (Figure 4.1.2).

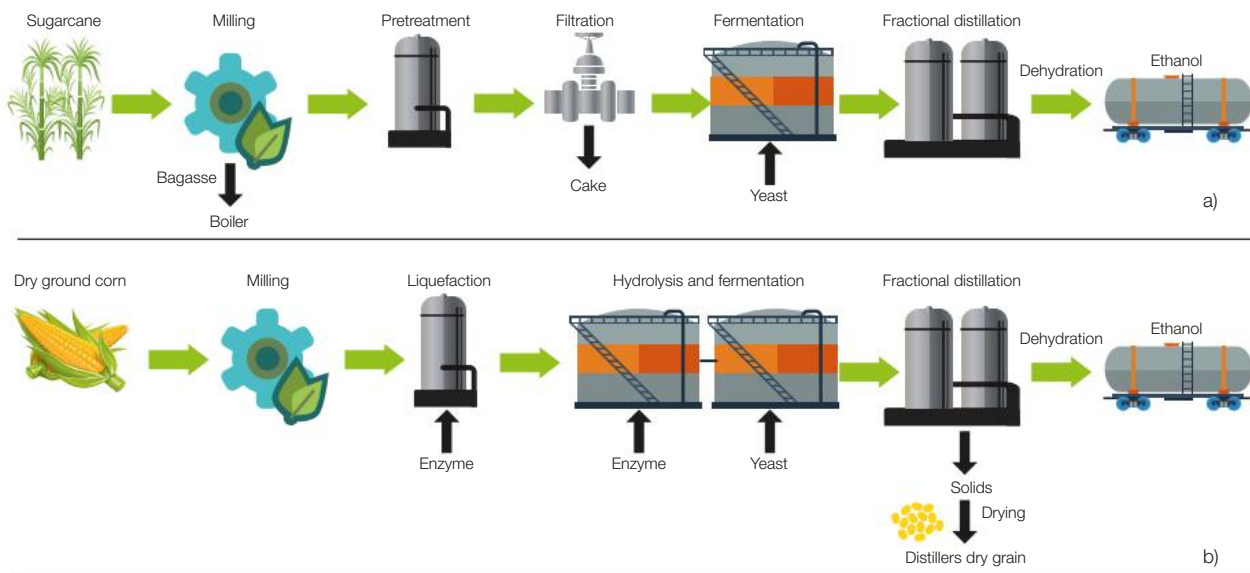


Figure 4.1.2: Stages in the production of bioethanol.

Biodiesel

Biodiesel has been pursued as an alternative to petroleum diesel derived from crude oil. As a renewable fuel source, biodiesel has the potential to reduce demands on traditional fossil fuels and is easily incorporated into diesel blends.

Biodiesel is a liquid biofuel derived from triglycerides including animal fats and oils from both plants and algae. Biodiesel is produced through the **transesterification** (conversion of the carboxylic acid present in one ester into another) of triglycerides (Figure 4.1.3). In the first stage of the process, methanol (CH_3OH) is mixed with a catalyst, typically a strong base such as sodium or potassium hydroxide ($NaOH$, KOH).

The resulting mixture is then reacted with a triglyceride. An esterification reaction occurs with the fatty acids (long-chain carboxylic acids) present in the triglyceride. The resulting products are the esters (fatty acid methyl esters) and glycerol (propane-1,2,3-triol).

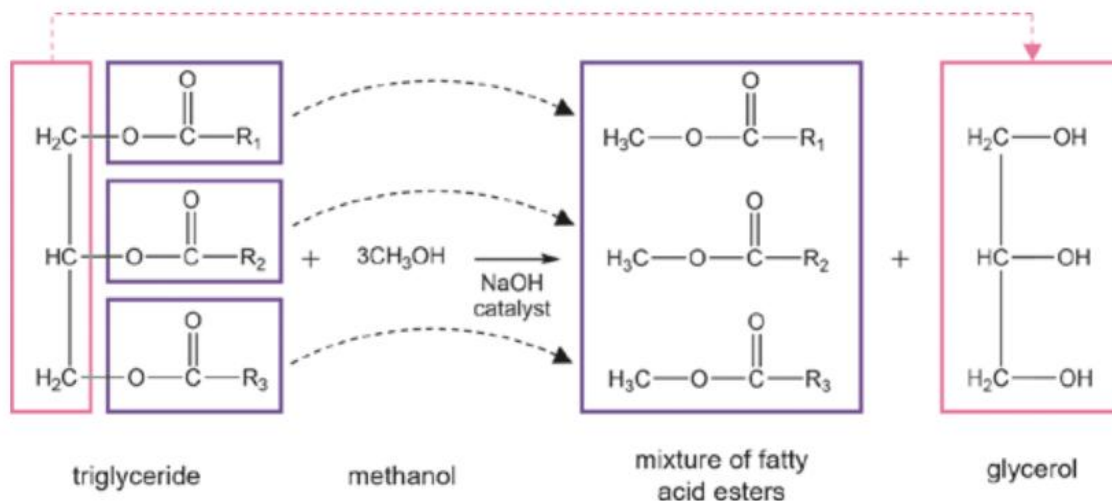
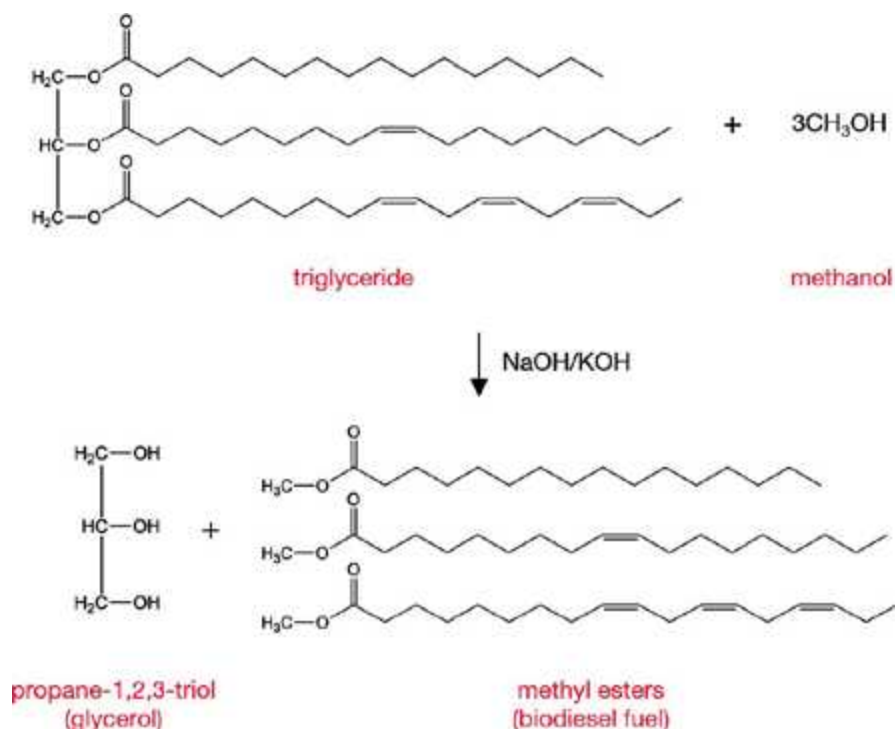


Figure 4.1.3: Production of biodiesel.

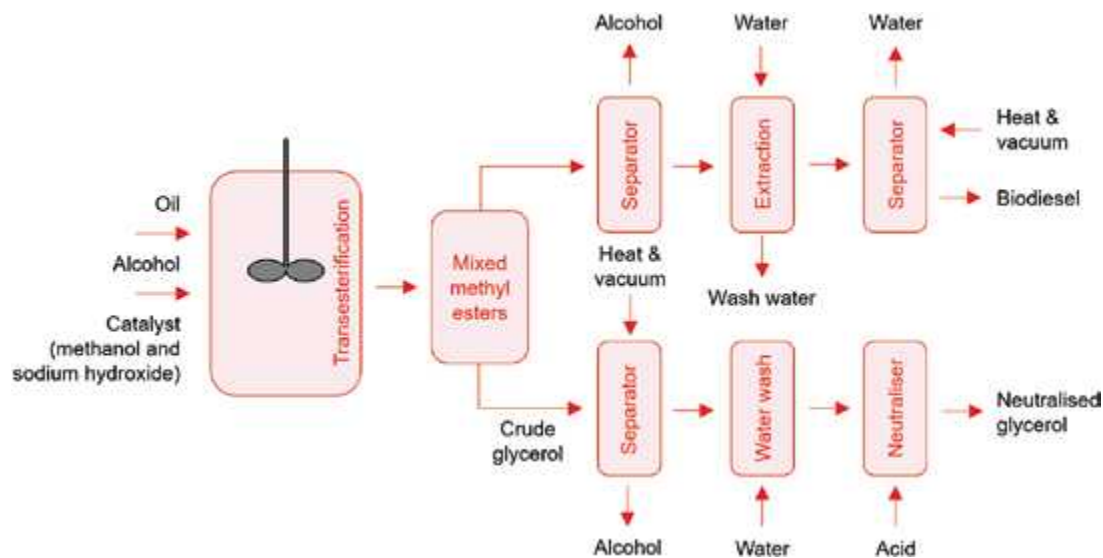
Example

The following triglyceride, found in canola oil as a waste vegetable oil, can be converted into biodiesel.



Question

3. Biodiesel can be produced according to the following industrial flowchart.



(a) A number of stages are undertaken during the production of biodiesel.

(i) **Identify** two raw materials used in the formation of biodiesel.

(2 marks) **IAE3**

(ii) Heat required for multiple stages may be supplied via the combustion of fossil fuels.

State one disadvantage of the addition of heat released from the combustion of fossil fuels.

(1 mark) **KA2**

- (iii) Methanol is combined with a sodium hydroxide catalyst.

State and **explain** the effect of the addition of a catalyst on the rate of reaction.

(3 marks) **KA1**

- (b) The alcohols methanol and glycerol are by-products of the process. The structural formula and boiling point of methanol are given below.

Molecule	Structure	Boiling point (°C)
methanol	$ \begin{array}{c} \text{H} \\ \\ \text{H}-\text{C}-\text{OH} \\ \\ \text{H} \end{array} $	64.7
glycerol	$ \begin{array}{ccccc} & \text{H} & & \text{H} & & \text{H} \\ & & & & & \\ \text{H} & -\text{C} & - & \text{C} & - & \text{C} & -\text{H} \\ & & & & & \\ & \text{OH} & & \text{OH} & & \text{OH} \end{array} $	290

- (i) **State** the systematic name of glycerol.

(2 marks) **KA4**

- (ii) During the washing phase, glycerol demonstrates a high degree of solubility.

Explain, with reference to the structure above, why glycerol is soluble in water.

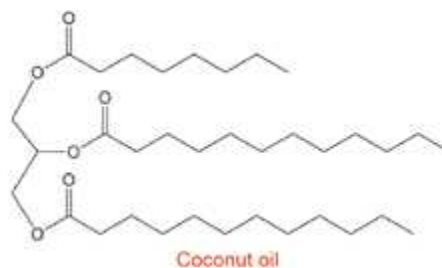
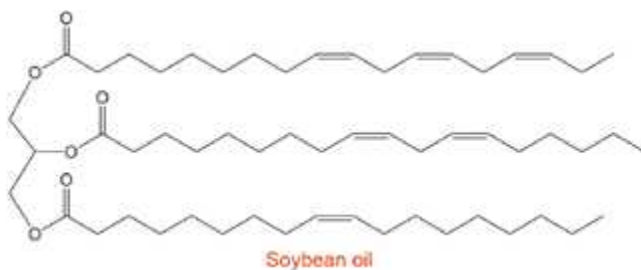
(3 marks) **KA2**

- (iii) Methanol and glycerol are able to be effectively separated using fractional distillation.

Explain how methanol and glycerol are able to be separated using fractional distillation.

(2 marks) **KA2**

- (c) Biodiesel produced from soybean oil and coconut oil can both be used as liquid fuels. The triglycerides present in both are shown in the diagram below.



- (i) **Circle** one ester functional group on the structure of soybean oil above. (1 mark) **KA1**
- (ii) **State** and **explain**, with reference to the structures above, which oil would be expected to have the higher melting point.

(3 marks) **KA2**

- (iii) **Draw** two of the methyl esters formed between the fatty acids in soybean oil and methanol.

(4 marks) **KA4**

- (iv) **State** one advantage of the production of biodiesel derived from soy beans.

(1 mark) **KA3**

- (v) Raw coconut oil is used directly as a diesel substitute in some developing countries.

Suggest one reason why it is used in this raw form and not processed into biodiesel.

(1 mark) **KA3**

Science understanding

The complete combustion of fuels containing carbon and hydrogen produces carbon dioxide and water and energy. Write thermochemical equations for the complete combustion of fuels in which the only products are carbon dioxide and water.

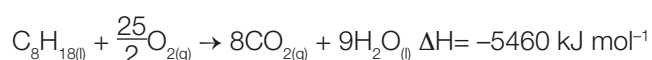
© SACE 2025

Complete combustion

Combustion is a reaction between a fuel and an oxidant (oxygen) that occurs at higher temperatures. Combustion is an exothermic process. The heat generated from combustion is harnessed in electricity production, industry, and transport applications.

Complete combustion occurs when there are enough moles of oxygen available to completely oxidise all carbon atoms (in the fuel) into carbon dioxide (CO₂).

For example, when fuels undergo combustion in an internal combustion engine, air and fuel are provided in a stoichiometric ratio that theoretically promotes complete combustion. 2,2,4-trimethylpentane (C₈H_{18(l)}) is one of the components of petrol that undergoes combustion. The complete combustion of the molecule is shown below.



Writing Combustion Equations

Combustion reactions are essential for energy production, powering everything from vehicles to power plants. However, the by-products of these reactions, such as carbon dioxide (CO₂) and other greenhouse gases, contribute significantly to global warming. Understanding and balancing combustion equations not only helps in calculating energy outputs but also allows us to predict and manage emissions, making it a critical skill in the pursuit of cleaner, more sustainable energy sources.

Use the following steps to balance an equation for the complete combustion of one mole of any compound containing only carbon, hydrogen, and (optionally) oxygen.

1. Write the unbalanced equation showing the fuel and oxygen reacting to produce carbon dioxide and water.
2. Write the coefficient for CO₂ based on the number of carbons in the fuel.
3. Write the coefficient for H₂O based on the number of hydrogens in the fuel, remembering that water has two hydrogens.
4. To find the coefficient for oxygen,
 - a. count the number of oxygens on the product side of the equation,
 - b. subtract the number of oxygens on the reactant side, if any, and
 - c. divide this number by two. (If the number is odd, use a fractional coefficient).

Note that, in general, fractional coefficients should not be used when balancing equations. However, an exception can be made when writing combustion equations in order to show the ratio for one mole of fuel.

Example

Write a balanced equation for the complete combustion of butanol.

Explanation	Step
Unbalanced equation	$\text{C}_4\text{H}_9\text{OH} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$
Balance carbon	$\text{C}_4\text{H}_9\text{OH} + \text{O}_2 \rightarrow 4\text{CO}_2 + \text{H}_2\text{O}$
Balance hydrogen	$\text{C}_4\text{H}_9\text{OH} + \text{O}_2 \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O}$
Balance oxygen	$\text{C}_4\text{H}_9\text{OH} + 6\text{O}_2 \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O}$

Example

Write a balanced equation for the complete combustion of hexane.

Explanation	Step
Unbalanced equation	$\text{C}_6\text{H}_{14} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$
Balance carbon	$\text{C}_6\text{H}_{14} + \text{O}_2 \rightarrow 6\text{CO}_2 + \text{H}_2\text{O}$
Balance hydrogen	$\text{C}_6\text{H}_{14} + \text{O}_2 \rightarrow 6\text{CO}_2 + 7\text{H}_2\text{O}$
Balance oxygen	$\text{C}_6\text{H}_{14} + \frac{19}{2}\text{O}_2 \rightarrow 6\text{CO}_2 + 7\text{H}_2\text{O}$

Question

4. Write a balanced equation for the complete combustion of:

(a) propane, C_3H_8

(1 mark) KA1

(b) methanol, CH_3OH

(1 mark) KA1

(c) methyl stearate, $\text{C}_{19}\text{H}_{38}\text{O}_2$ (a component of biodiesel)

(1 mark) KA1

4

Thermochemical equations

A thermochemical equation represents chemical change as well as the associated energy change for a chemical reaction. The four components of a thermochemical equation are identified below.

Component	Explanation
Correct species	The correct formulae for all reactants and products for the reaction must be included.
Fully balanced	A fully balanced chemical equation is required. (This may include non-integer values for balancing oxygen in combustion equations to represent the molar enthalpy for the combustion of one mole of the fuel.)
States of matter	Standard states of matter, (s) (l) (g) and (aq), are required for each species in the reaction.
Enthalpy change	The molar enthalpy change, ΔH , is included with a corresponding sign to express the energy change associated with the chemical reaction.

Example

1371 kJ of heat is released when one mole of bioethanol undergoes complete combustion.

Write a thermochemical equation for the complete combustion of ethanol.

Explanation	Step
Correct species	$\text{C}_2\text{H}_5\text{OH} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$
Fully balanced	$\text{C}_2\text{H}_5\text{OH} + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O}$
States of matter	$\text{C}_2\text{H}_5\text{OH}_{(l)} + 3\text{O}_{2(g)} \rightarrow 2\text{CO}_{2(g)} + 3\text{H}_2\text{O}_{(l)}$
Enthalpy change	$\text{C}_2\text{H}_5\text{OH}_{(l)} + 3\text{O}_{2(g)} \rightarrow 2\text{CO}_{2(g)} + 3\text{H}_2\text{O}_{(l)} \quad \Delta H = -1371 \text{ kJ mol}^{-1}$

Science understanding

Incomplete combustion, producing carbon (soot) and carbon monoxide, is more likely with longer-chain carbon-based fuels.

Explain why incomplete combustion is more likely with longer-chain carbon-based fuels than with shorter chains.

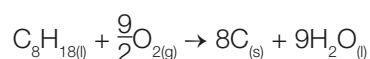
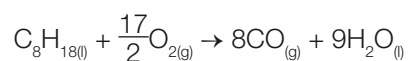
Discuss the undesirable consequences of incomplete combustion.

© SACE 2025

Incomplete combustion

Incomplete combustion occurs when there are insufficient moles of oxygen available to completely oxidise all carbon atoms in the fuel. This results in products in partial oxidation states, such as carbon (C) and carbon monoxide (CO). Carbon dioxide, represents the maximum oxidation state for carbon (+4). Carbon and carbon monoxide represent partial oxidation states (0 and +2 respectively).

Incomplete combustion occurs during the combustion of fuels in industrial furnaces and internal combustion engines. For example, under varying load on an internal combustion engine, it is difficult to maintain the required stoichiometric ratio of fuel and oxidant to ensure complete combustion. In reality, the products of combustion include those of both complete and incomplete combustion.



Fuels that contain larger hydrocarbon molecules are more likely to form products of incomplete combustion in air. Air contains approximately 21% oxygen by weight. As the length of the hydrocarbon chain increases or the degree of unsaturation increases, the ratio of carbon to oxygen increases, limiting the oxygen available to form carbon dioxide. Larger molecules also experience stronger dispersion forces, resulting in a less volatile fuel with limited ability to mix effectively with gaseous molecules during combustion.



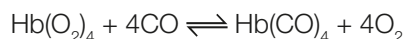
Figure 4.1.4: Bunsen flames produced during complete and incomplete combustion.

Products of incomplete combustion

The products of incomplete combustion are undesirable due to their impact on the built and natural environment.

Carbon monoxide

Carbon monoxide binds to haemoglobin (the molecule used to transport oxygen in the blood) and forms carboxyhaemoglobin. There is an equilibrium established in the body between oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (Hb) as shown in the equation below. Carbon monoxide binds much more strongly than oxygen to haemoglobin, shifting the position of equilibrium to the right in favour of the formation of carboxyhemoglobin.



The presence of carboxyhaemoglobin decreases the oxygen-carrying capacity of the blood, which limits the delivery and utilisation of oxygen in the body. Exposure to carbon monoxide at high concentrations can lead to significant toxicity in the human body. Exposure in low concentrations (100–200 ppm) can lead to fatigue and dizziness; exposure at high concentrations (2000–4000 ppm) can lead to loss of consciousness.

Soot

Soot is a complex aggregate of carbon nanoparticles and the bound products of incomplete combustion of fuels (Figure 4.1.5). Nanoparticles of soot (15–20 nanometres) released from these sources aggregate to form larger particles (80–100 nanometres). Soot primarily comes from the combustion of coal and biomass in power stations, coke in furnaces, and fossil fuels in internal combustions engines. Burning diesel fuel in motor vehicles is a major source of soot emissions.

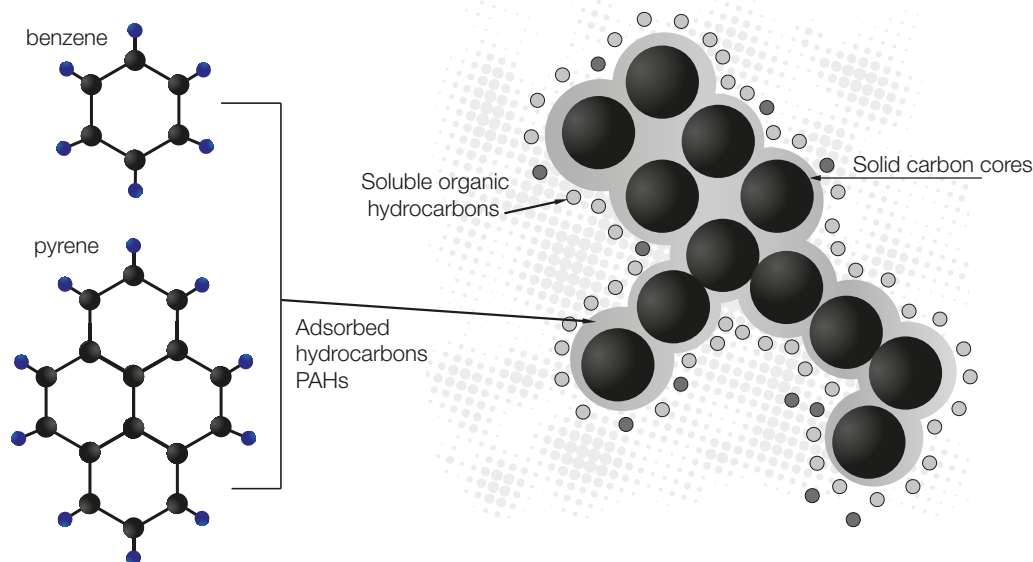


Figure 4.1.5: Soot aggregate.

Soot can limit visibility in urban areas and blackens surfaces causing **visual pollution**. Soot deposits on the surface of buildings and natural vegetation. When soot covers the leaves of plants it limits photosynthesis, leading to poor growth.

When inhaled as a fine airborne particulate, soot can lead to decreased respiratory function in humans and animals. Nanoparticles of soot can penetrate deep into the alveoli of the lungs (the lungs can only remove particles greater than approximately 200 nanometres in size), causing respiratory issues such as acute bronchitis and aggravated asthma. Long-term exposure to soot increases the risk of cardiovascular disease.

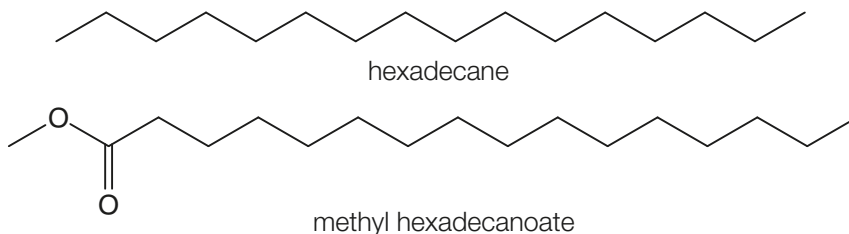
Concerns have also been expressed about the absorption of **carcinogens** (cancer-causing compounds) present on the surface of carbon such as **polycyclic aromatic hydrocarbons** (PAHs) and the toxicity of metal oxides containing arsenic, cadmium and chromium. Chemical pollutants accumulate on the surface of soot particles, which transport them to the lungs and eventually the bloodstream.

Soot particles are known to have considerable impact upon climate. Black carbon in soot is a major contributor to climate change through global warming (second only to carbon dioxide). Black carbon absorbs solar radiation at all wavelengths causing localised warming in the troposphere and on the surface of the Earth. This is of particular concern in the Arctic region where soot deposits increase the rate of melting and loss of Arctic ice and snow and the associated albedo (refer to Page 1).

Soot is also associated with the formation of high-altitude cirrus clouds in the troposphere. Soot particles provide sites for the formation of ice crystals. Increased cloud cover leads to greater reflectivity of solar radiation, cooling the Earth.

Question

5. Many modern motor vehicles use direct injection diesel engines (fuel is injected into the combustion chamber). Direct injection engines offer greater efficiency and power, and produce fewer pollutants in exhaust emissions.
- (a) Petroleum diesel contains hydrocarbons in the range of 8–21 carbon atoms. Hexadecane ($C_{16}H_{34}$), a component of petroleum diesel, and methyl hexadecanoate, a component of biodiesel, are shown below.



- (i) Hexadecane exists as a liquid at room temperature (25°C).

Explain, in terms of intermolecular forces, why hexadecane is a liquid at this temperature.

(2 marks) **KA1**

- (ii) **Determine** the molecular formula of methyl hexadecanoate.

(2 marks) **IAE3**

- (iii) The enthalpy of combustion of hexadecane is $-10701 \text{ kJ mol}^{-1}$.

Write a thermochemical equation for the complete combustion of hexadecane.

(4 marks) **KA4**

- (iv) **State** and **explain** whether each molecule of hexadecane would require more or fewer molecules of oxygen than methyl hexadecanoate to achieve complete combustion.

(2 marks) **IAE3**

- (v) Diesel is commonly recognised as containing hydrocarbons in the range of 8–21 carbons, while petrol is commonly recognised as containing 4–12 carbons.

Suggest why products of incomplete combustion are more common during the use of diesel as a fuel in motor vehicles when compared to the use of petrol.

(2 marks) **KA3**

- (b) It has been suggested that carbon monoxide sensors should be included in motor vehicles to warn occupants if carbon monoxide enters the cabin due to blocked or leaking exhausts.

Explain the dangers to occupants associated with exposure to elevated concentrations of carbon monoxide.

(3 marks) **KA2**

- (c) The atmospheric concentration of some pollutants has been found to decrease with the use of direct injection engines, while the emissions of soot have been shown to increase.

- (i) The introduction of a filter for exhaust products is being investigated.

Suggest one reason why a filter would be effective in the removal of soot.

(1 mark) **KA2**

- (ii) Soot particles have a short lifetime in the atmosphere when compared to greenhouse gases such as carbon dioxide, but their contribution to global warming is considerable. Soot is recognised as having a considerable impact on both climate change and human health.

Discuss the impact of soot on both climate change and human health.

(6 marks) **KA4**

Science understanding

The energy released in combustion of fuels can be determined experimentally.

Use experimental data to determine the enthalpy of combustion of a fuel.

Undertake thermochemical calculations involving enthalpy changes and temperature changes of a specified mass of water given the necessary data.

© SACE 2025

Enthalpy of combustion

The combustion of fuels results in a net release of energy (exothermic reaction). The energy released by a quantity of fuel can be determined experimentally.

Molar enthalpy of combustion

The **molar enthalpy of combustion** (ΔH_{comb}) represents the quantity of heat released per mole of fuel that undergoes complete combustion. The temperature change can be measured and recorded for the heat released from the combustion of a measured mass of fuel to a known volume of water.

Quantity	Description	Units
Q	Quantity of heat transferred	J
ΔH	Molar enthalpy of combustion	kJ mol^{-1}
m	Mass of water (or liquid) heated ($1\text{ g} = 1\text{ mL}$)	g
c	Specific heat capacity of the liquid	$\text{J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$
ΔT	Temperature change of the liquid	$^{\circ}\text{C}$
n	Moles of fuel that have undergone combustion	mol

The quantity of **heat** released in a combustion reaction is calculated using the expression:

$$Q = m \times c \times \Delta T \text{ (J)}$$

Example

Coal-fired power stations transform chemical energy (from combustion of coal) into electrical energy. 0.127 g of black coal was burnt and used to heat 100 mL of water. The temperature of the water increased from 18.3°C to 24.9°C . It is assumed that all heat from the reaction is transferred to the 100 mL volume of water. Calculate the heat released, in kJ, for the total mass of coal burnt and the heat energy released, per gram. (Specific heat capacity of water $c = 4.18 \text{ J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$.)

Explanation	Step
Calculate the change in temperature (ΔT). Substitute the quantities into the equation, where (m) is the mass of water equal to the volume and (c) is the heat capacity provided for the liquid heated.	$\Delta T = 24.9 - 18.3 = 6.6^{\circ}\text{C}$ $Q = m \times c \times \Delta T$ $Q = 100 \times 4.18 \times 6.6$
Apply units to the answer.	$= 2758.8 \text{ J}$ $= 2.76 \text{ kJ}$
Calculate per g by dividing by the mass of coal burnt.	$= \frac{2758.8}{0.127}$ $= 21.7 \text{ kJ g}^{-1}$

The **molar enthalpy of combustion** can be determined using:

$$\Delta H = \frac{m \times c \times \Delta T}{1000 \times n} \text{ (kJ mol}^{-1}\text{)}$$

Example

Brazil is a world leader in the production and use of biofuel, having generated a sustainable industry of bioethanol production from sugarcane for many years. Some cars in Brazil have been designed to run on E100, a fuel consisting of pure ethanol.

The molar enthalpy of combustion of ethanol was investigated through the use of a spirit burner containing ethanol. The burner was ignited under a 100 mL volume of water contained in an aluminium can and allowed to burn until the temperature increased by 20.0°C. The mass of the spirit burner decreased by 120.73 g to 120.21 g. (Specific heat capacity of water $c = 4.18 \text{ J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$.)

Calculate the experimental enthalpy of combustion for ethanol.

Explanation	Step
Calculate the change in mass for the fuel.	$\Delta m = m_{\text{initial}} - m_{\text{final}}$ $= 120.73 - 120.21$ $= 0.520 \text{ g}$
Calculate the moles of fuel combusted from the change in mass recorded.	$M(\text{C}_2\text{H}_5\text{OH}) = (2 \times 12.01) + (6 \times 1.008) + 16.00$ $M(\text{C}_2\text{H}_5\text{OH}) = 46.068$ $n = \frac{m}{M}$ $= \frac{0.52}{46.068} = 0.0113 \text{ mol}$
Substitute the quantities, mass of water heated, change in temperature and constant into the equation for molar enthalpy of combustion. Apply units for the molar enthalpy, including the sign of the enthalpy change.	$\Delta H = \frac{m \times c \times \Delta T}{1000 \times n}$ $\Delta H = \frac{100 \times 4.18 \times 20.0}{1000 \times 0.0113}$ $= -740 \text{ kJ mol}^{-1} \text{ (3 sig. fig)}$

Molar enthalpy and heat energy are associated through the following equations:

$$\Delta H = \frac{Q \text{ (kJ mol}^{-1}\text{)}}{n \text{ (mol)}}$$

$$\therefore Q = n \times \Delta H \text{ (kJ)}$$

A rearrangement of the equation for molar enthalpy may also be used to determine the temperature change:

$$\Delta T = \frac{\Delta H \times 1000 \times n}{m \times c} \text{ (}^{\circ}\text{C)}$$

Questions

6. Biodiesel and petrodiesel are two fuels that can be used for powering heavy-duty vehicles such as trucks.
- (a) Biodiesel can be represented by the formula $C_{17}H_{34}O_2$, methyl palmitate, which is one component of most biodiesel mixtures. The combustion reaction is given below:



- (i) **Calculate** the number of moles present in 50 kg of methyl palmitate.

(3 marks) **KA4**

- (ii) Using the enthalpy of combustion, **calculate** the energy released, in kJ, when 50 kg of methyl palmitate is completely combusted.

(4 marks) **KA4**

- (b) Conventional diesel fuel, often called petrodiesel, is also used for powering vehicles. Assume that petrodiesel releases 9% more energy per gram than biodiesel.

Calculate how much more energy, in kJ, would be released by 50 kg of petrodiesel.

(2 marks) **KA4**

- (c) Engines cannot convert all thermal energy into kinetic energy; the percentage that is converted is referred to as the "engine efficiency." This must also be considered when evaluating the effectiveness of a fuel.

If the engine efficiency of biodiesel is 35% and the engine efficiency of petrodiesel is 40%, **calculate** the usable energy (in kJ) from 50 kg of each fuel.

(3 marks) **KA4**

7. Coke is a fuel with a high carbon content, often derived from coal or crude oil. It is widely used in the production of iron from the mineral haematite, in a blast furnace.
- (a) Coke, predominantly carbon, is used as a fuel and to generate the reducing agent carbon monoxide. A range of reactions occur with carbon in the blast furnace, two of which are considered below.

The **complete** combustion of coke can be represented by the equation below.



Incomplete combustion also occurs during the combustion of coke.



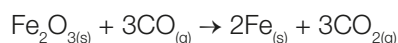
- (i) **Calculate** the energy, in kJ, released when 5.00 tonne (1 tonne = 10^6 g) of coke is reacted with oxygen if 100% of the coke is oxidised to carbon dioxide.

(4 marks) **KA4**

- (ii) **Calculate** the energy, in kJ, released when 5.00 tonne of coke is reacted with oxygen if 80% of the coke is oxidised to carbon dioxide and the remaining 20% is oxidised to carbon monoxide.

(5 marks) **KA4**

- (b) Haematite (Fe_2O_3) is reduced to molten iron in the blast furnace.



- (i) **Assign** oxidation numbers to carbon in the equation and hence **state** why carbon monoxide is the reducing agent.

(3 marks) **KA1**

- (ii) The annual production of iron is 959 Mt (megatonne) globally.

Calculate the mass, in kg, of carbon dioxide released during production.

(5 marks) **KA4**

- (c) Exposure to coke furnace emissions occurs for workers in the steel industry. Emissions from coke furnaces include soot and compounds containing benzene (polycyclic aromatic hydrocarbons, PAHs).

- (i) **Describe** the dangers associated with the inhalation of PAHs contained in soot.

(2 marks) **KA2**

- (ii) Regulations have been set by the EPA to limit the exposure to PAHs in the work environment to 0.150 ppm over an 8-hour shift. The average adult inhales and exhales 8 L of air per minute.

Calculate the mass, in mg, of PAHs inhaled into the lungs at this upper limit over an 8-hour period.

(2 marks) **KA4**

8. Bushwalkers used liquid fuel to heat a Trangia stove for cooking. The liquid fuel contained 95% ethanol and 5% methanol. A pot of water of 500 mL volume was heated from 21.0 °C using the liquid fuel. Molar enthalpy of combustion for the fuels is shown below.

Fuel	%	Molar mass (g mol ⁻¹)	Molar enthalpy (kJ mol ⁻¹)
methanol	5%	32.04	-715.0
ethanol	95%	46.07	-1371

- (a) Only 5.00 g of fuel remained in the Trangia.

- (i) **Calculate** the total number of moles of liquid fuel combusted according to the ratio indicated.

(6 marks) **KA2**

- (ii) **Calculate** the maximum temperature that can be obtained from the combustion of 5.00 grams of the liquid fuel. (Specific heat capacity of water $c = 4.18 \text{ J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$.)

(6 marks) KA2

- (b) **Suggest** two reasons why the temperature of the water was much lower than the calculated value.

(2 marks) IAE4

4

Experimental determination of the enthalpy of combustion

Energy changes associated with combustion reactions can be measured experimentally. **Calorimetry** is the measurement of the energy changes associated with a chemical reaction. It is a measure of the heat transfer during a chemical reaction or change of state.

Simple calorimeter

A simple calorimeter is typically an insulated reaction vessel with a thermometer used to measure associated energy changes. However, during the combustion of a fuel, a thermometer (or temperature probe) is used to measure the temperature change associated with the heat energy imparted to a volume of water. Due to the nature of combustion, limited thermal insulation can be applied to the apparatus (Figure 4.1.6).

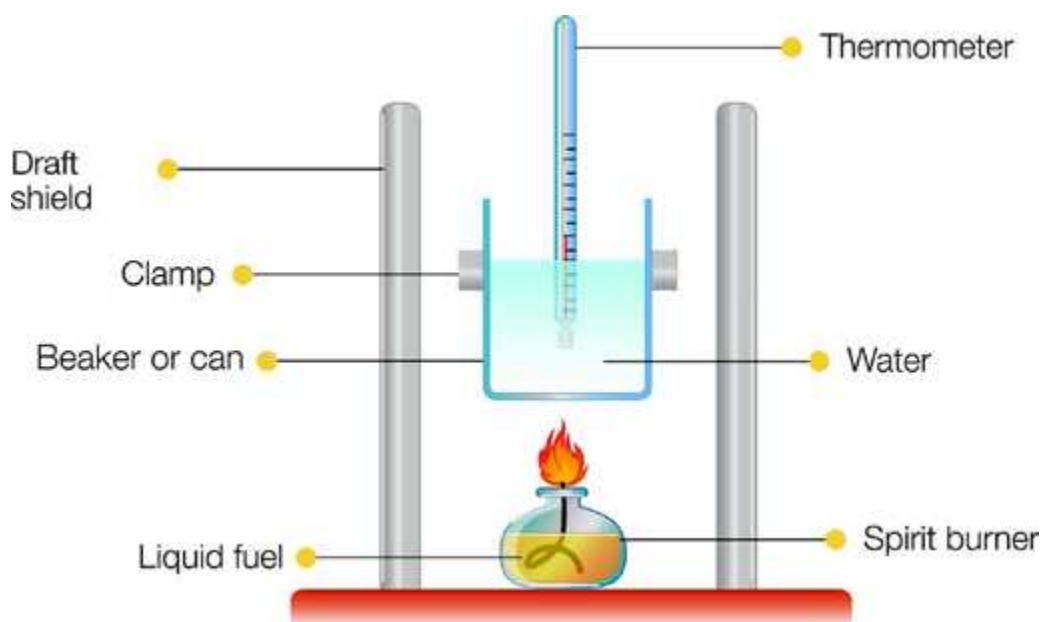


Figure 4.1.6: Simple calorimeter for measuring the enthalpy of combustion.

Determination of the enthalpy of combustion using a simple calorimeter

- A spirit burner containing a liquid fuel is weighed initially and the mass (m_{initial}) recorded.
- A known mass (hence volume) of distilled water is transferred to a metal can (or beaker). (The density of pure water is 1 g mL^{-1} therefore, 1 mL of water has a mass of 1 g .)
- A thermometer is introduced to the can and the initial temperature (T_{initial}) of the water is recorded.
- The spirit burner is placed under the mass of water. The wick of the burner is ignited. Heat flows from the burner to the mass of water, thus increasing the water temperature. The final temperature obtained is recorded (T_{final}) and the flame extinguished.
- The spirit burner is reweighed and the final mass (m_{final}) recorded. The associated loss in mass represents the change in mass (Δm) and is used to calculate the number of moles (n) of fuel combusted.
- Using the specific heat capacity of water (c) as a given constant, the heat energy or molar enthalpy is calculated.

? Science inquiry skills

Skills in context

Limitations in the experimental design

There are several limitations in the experimental design (many linked directly to assumptions that have been applied) that lead to obtaining values which are considerably lower than literature values.

Random errors

Slight variation occurs in human measurements of volume, mass and temperature. Small quantities of the volatile liquid fuel evaporate from the wick prior to lighting or after extinguishing the flame, when initial and final measurements of mass are taken. Slight variations in the positioning of the wick and burner may lead to inconsistent heat transfer.

Systematic errors

The first assumption made is that all heat released from the fuel is transferred to the water (Conservation of energy), with no external transfer of heat.

The can or beaker offers very little thermal insulation; therefore a great deal of heat is lost from the system to the external surroundings or absorbed by the apparatus, lowering the maximum temperature achieved.

The second assumption is that combustion is complete. (The molar enthalpy of combustion obtained through experiment is compared with an accepted literature value for the complete combustion of fuel.)

The liquid fuel is burnt in air and, depending on the size of the hydrocarbon molecules, combustion is unlikely to be complete, with insufficient oxygen leading to incomplete combustion and lower energy values being obtained. Less energy is released during incomplete combustion and energy is absorbed by the large component of nitrogen molecules present in the air.

The third assumption is that the thermometer and water have had sufficient time to reach thermal equilibrium before a measurement is taken and before the system begins to return to its original temperature.

To obtain a suitable temperature rise, the fuel typically undergoes combustion for a period of minutes. During this time, heat energy is lost to the surroundings outside of the calorimeter, allowing the water to begin to return to its original temperature. A lower final temperature results.

Bomb calorimeter

A bomb calorimeter (Figure 4.1.7) is a carefully engineered closed system that is used to efficiently and accurately obtain enthalpy values for the combustion of liquid and solid fuels. The values obtained from a bomb calorimeter offer high levels of accuracy when compared to literature values for the enthalpy of combustion. Bomb calorimetry is used to determine the enthalpy of combustion of fuels. Bomb calorimetry is also commonly used to determine the energy values quoted for many foods.

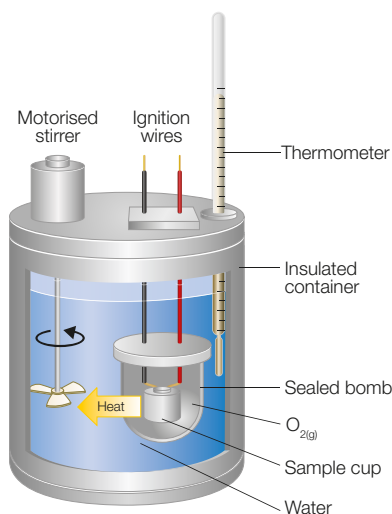


Figure 4.1.7: Bomb calorimeter.

Determination of the enthalpy of combustion using a bomb calorimeter

- A liquid or solid (crushed in a mortar and pestle) sample of the fuel of a predetermined mass is weighed and added to the sample cup that sits in the hanger.
- A fuse is set and the apparatus is lowered into the steel body and sealed.
- Air is displaced from the bomb through the introduction of pure oxygen.
- The bomb is lowered into a volume of water in an insulated vessel, with a stirrer and temperature probe.
- The bomb is ignited, and combustion of the fuel occurs instantly.
- Heat energy from the bomb slowly enters the surrounding water and the maximum temperature achieved is recorded.
- The molar enthalpy can be calculated using the calibration from a compound with a known molar enthalpy of combustion.

? Science inquiry skills

Skills in context

Improvements

The bomb calorimeter offers several improvements over a simple calorimeter.

The fuel undergoes combustion in pure oxygen, which generates complete combustion of all the available fuel.

As water surrounds the bomb, heat exiting the bomb moves directly into the water, with very little being retained by the stainless-steel bomb. The sealed container is close to achieving a closed system. The energy from the ignition wire is even accounted for.

The stirrer and adequate insulation ensure that a reliable measurement of the increase in water temperature can be obtained with a calibrated temperature probe.

Question

9. Octane ratings, often expressed as RON (research octane number), are provided for common fuels sold at petrol stations as a standard measure of the performance of a fuel. High-performance engines require the use of fuels with higher octane ratings (typically 95 and above).
- (a) The octane rating is a number that is determined by comparing the combustion of the fuel against mixtures of 2,2,4-trimethylpentane and heptane in differing ratios.
- (i) **Draw** the structural formula of 2,2,4-trimethylpentane.

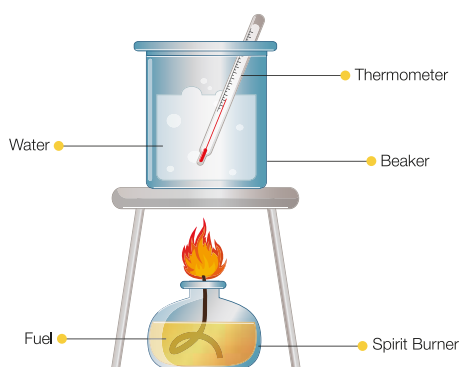
(2 marks) **KA4**

- (ii) The molar enthalpy of combustion of pure hexane is $-4163 \text{ kJ mol}^{-1}$.

Write a thermochemical equation for the complete combustion of hexane.

(4 marks) **KA4**

- (b) The molar enthalpy of combustion of 2,2,4-trimethylpentane (C_8H_{18}) and heptane (C_7H_{16}), both found in fuels, can be determined experimentally.
- (i) A simple calorimeter can be used to gain an approximation of the values. The apparatus below was used for the approximation.



The following data was collated during the investigation.

Fuel	C_8H_{18}	C_7H_{16}
Mass of water (g)	100	100
Initial mass of spirit burner (g)	136.20	134.70
Final mass of spirit burner (g)	135.76	134.27
Initial temperature ($^{\circ}\text{C}$)	21.0	21.0
Final temperature ($^{\circ}\text{C}$)	41.0	41.0
Specific heat capacity ($\text{J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$)	4.18	4.18

(1) **Calculate** the moles of each fuel that underwent combustion.

(6 marks) **KA4**

(2) **Calculate** the molar enthalpy of combustion for each fuel using the data provided in the table.

4

(6 marks) **KA4**

- (ii) The determination of the molar enthalpy of combustion for the two fuels was repeated using a bomb calorimeter. The values obtained are displayed in the table below.

Fuel	C_8H_{18}	C_7H_{16}
ΔH (kJ mol ⁻¹)	-5463	-4825

Discuss two reasons why the values obtained with the bomb calorimeter are substantially higher than those obtained with the simple calorimeter.

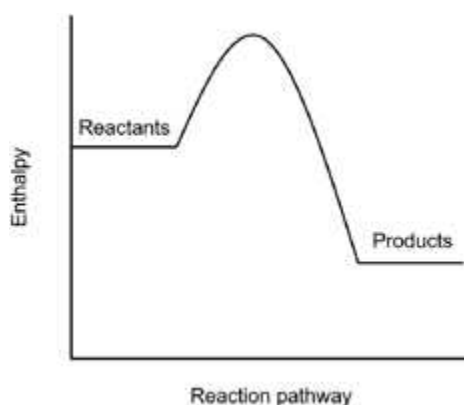
(4 marks) **IAE4**

- (c) The octane rating of a fuel is commonly mistaken for the energy released by the fuel. Instead, octane ratings are more closely linked to the activation energy of the fuel mixture. Higher octane ratings are associated with higher activation energy.

(i) **State** whether the combustion of a fuel represents an endothermic or exothermic reaction.

(1 mark) **KA1**

(ii) **Complete** the energy profile diagram, clearly labelling the activation energy and enthalpy change.



(2 marks) **KA1**

(iii) The energy profile diagram represents a 91-octane fuel.

On the energy profile diagram above, **draw** a reaction to represent the activation energy expected for a 98-octane fuel.

(1 mark) **KA2**

Science understanding

Fuels, including fossil fuels and biofuels, can be compared in terms of their energy output and the nature of products of combustion.

Calculate the quantities of heat evolved per mole, per gram, and per litre (for liquids) for the complete combustion of fuels.

Compare fuels given appropriate data.

© SACE 2025

Specific energy and energy density of fuels

When selecting and evaluating the effectiveness of fossil fuels and biofuels, many factors are considered, including viscosity, melting and boiling points, the products of combustion, specific energy and energy density.

Specific energy ($\frac{\Delta H}{M}$) represents the heat released per gram of fuel, whereas **energy density** ($\frac{\Delta H}{M} \times \rho$) represents energy released per litre of fuel undergoing combustion.

Both quantities are of interest in transport applications, where liquid fuels have to be stored in the vehicle. It is more economical to generate larger quantities of energy per gram or litre of fuel stored and combusted in the internal combustion engine of a motor vehicle. A vehicle is able to travel further on each litre of fuel consumed, which leads to greater efficiency.

The molar enthalpy of combustion and energy density are considered for a range of fuels below.

Fuel	Source	Molar mass (g mol ⁻¹)	Density (g L ⁻¹)	Heat energy released		
				Molar enthalpy	Specific energy	Energy density
				kJ mol ⁻¹	kJ g ⁻¹	kJ L ⁻¹
methane CH ₄	natural gas	16.04		891	55.55	
propane C ₃ H ₈	liquid petroleum gas (LPG)	44.10		2220	50.34	
ethanol C ₂ H ₅ OH	bioethanol	46.07	789	1371	29.75	23475
octane C ₈ H ₁₈	petrol	114.2	703	5530	48.42	34042
hexadecane C ₁₆ H ₃₄	diesel	226.5	775	10701	47.25	36615
methyl linoleate C ₁₇ H ₃₁ COOCH ₃	biodiesel	294.5	889	11690	36.69	35288

Energy conversions

Conversions are undertaken between molar enthalpy, specific energy and energy density to allow comparisons between fuels.

$$\frac{\text{kJ}}{\text{mol}} \div M \frac{\text{kJ}}{\text{g}} \times \rho \frac{\text{kJ}}{\text{L}}$$

$$\frac{\text{kJ}}{\text{L}} \div \rho \frac{\text{kJ}}{\text{g}} \times M \frac{\text{kJ}}{\text{mol}}$$

Where ρ = the density of the fuel in g L⁻¹.

Question

10. Methanol, ethanol, E85 (a blend of 85% ethanol), and petrol were compared in terms of energy density, specific energy and molar enthalpy. Selected data is shown below.

Fuel	Molar mass (g mol ⁻¹)	Density (g L ⁻¹)	Energy density	Specific energy	Molar enthalpy
			(kJ L ⁻¹)	(kJ g ⁻¹)	(kJ mol ⁻¹)
methanol	32.04	792			-715.0
ethanol	46.07	789	23475		
E85	mixture	770–790	25650	33.20 (determined experimentally)	
petrol	mixture	720–760	34800	47.30 (determined experimentally)	

(a) Some forms of motorsport burn pure liquid methanol or blends of ethanol as a fuel.

(i) **Write** a thermochemical equation for the complete combustion of methanol.

(4 marks) **KA4**

(ii) **Calculate** the energy density, in kJ L^{-1} , and specific energy, in kJ g^{-1} , for methanol and input these values into the table.

(4 marks) **KA4**

(iii) One of the problems associated with fuels containing alcohols is the miscibility of water in the fuel which can lead to corrosion in the engine.

Explain, with the aid of a labelled diagram, the solubility of water and methanol.

(3 marks) **KA1**

(b) Ethanol blends are being introduced to petrol stations and sold alongside traditional fuels.

(i) **Calculate** the specific energy in kJ g^{-1} and molar enthalpy in kJ mol^{-1} for ethanol to complete the table for this fuel.

(4 marks) **KA4**

(ii) Compare the energy densities of ethanol and petrol.

Discuss one implication of the energy density of these fuels for the use of blended fuels with a high concentration of ethanol in transport applications.

(2 marks) **IAE3**

- (iii) **State** and **explain** one environmental advantage of using fuels blended with bioethanol.

(2 marks) **KA2**

Science understanding

Although most electricity is generated using fuels to drive steam turbines, electrical energy can be also generated using photovoltaic cells (known as solar cells) and directly from oxidation of fuels using galvanic cells.

State the advantages and disadvantages of direct electricity generation (photovoltaic and fuel cells) compared to using steam turbines.

© SACE 2025

Electricity generation from steam turbines

Steam **turbines** are used to generate electricity. In a steam turbine power plant, a heat source is used to boil water into steam and generate high pressures. The steam is allowed to flow through a turbine, causing it to spin. The turbine is attached to a loop of wire in a strong magnetic field; as it spins, an electric current ("electricity") is generated and distributed to users via a network of cables and transformers ("the grid").

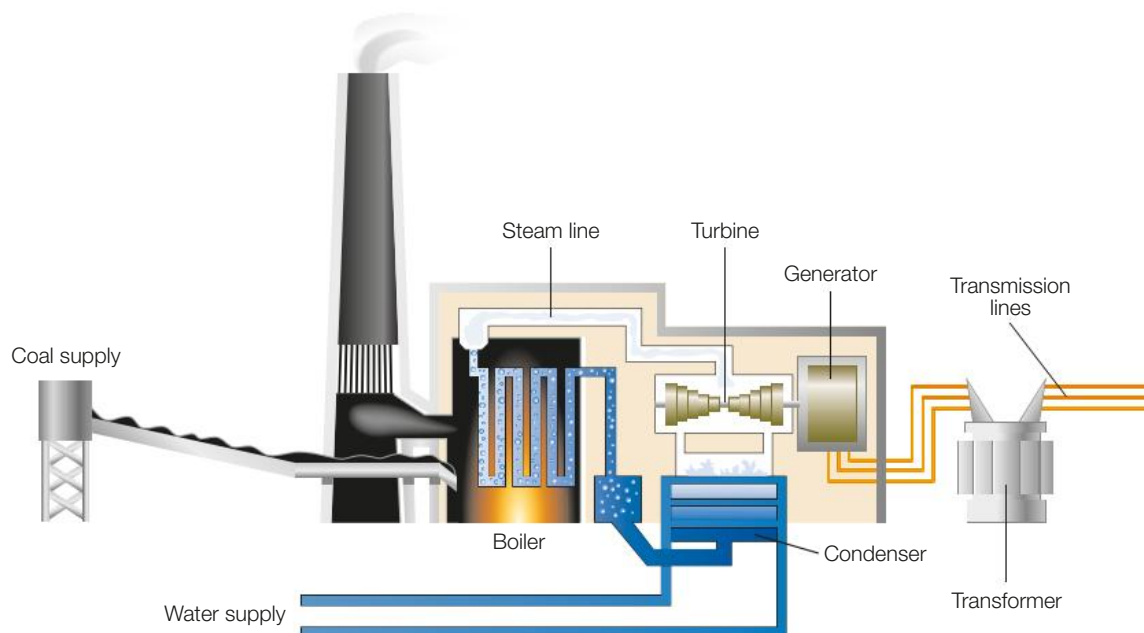


Figure 4.1.8: Conversion of coal to electricity.

The heat required to boil water into steam often comes from burning fossil fuels but can also come from other heat sources like a controlled fission reaction (nuclear energy) or deep within the Earth (geothermal energy). Other technologies use the flow of water (hydropower) or air (wind power) to spin the turbine.



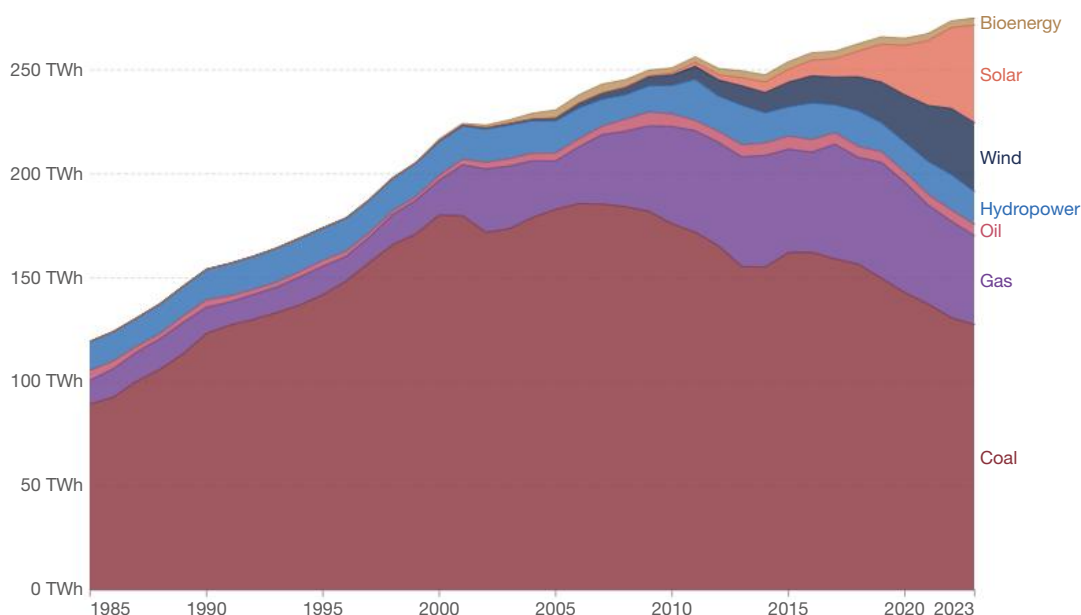
In 2023, 62% of Australia's electricity was generated by burning coal and gas to run steam turbines.

Most of the rest, 35% of the total, was generated using solar, wind, and hydropower.

Electricity production by source, Australia

Measured in terawatt-hours.

Our World
in Data



Data source: Ember (2024); Energy Institute - Statistical Review of World Energy (2024)

OurWorldinData.org/energy | CC BY

Note: "Other renewables" include waste, geothermal, wave, and tidal.

Figure 4.1.9: Electricity production in Australia by source

Burning coal and natural gas in power stations releases vast quantities of carbon dioxide into the atmosphere and oceans. Atmospheric pollutants are also formed from the release of oxides of sulfur and nitrogen. Heated water from power stations can also be released to local marine environments, thus affecting surrounding ecosystems.

Electricity generation from photovoltaic cells

Photovoltaic cells convert sunlight directly into electricity. Photovoltaics use semiconductor materials to allow electrons to absorb photons of light and shift them from the semiconductor to generate a current (Figure 4.1.10). Photovoltaic cells produce no pollution during operation. There are, however, considerable carbon emissions associated with the production of photovoltaic cells.

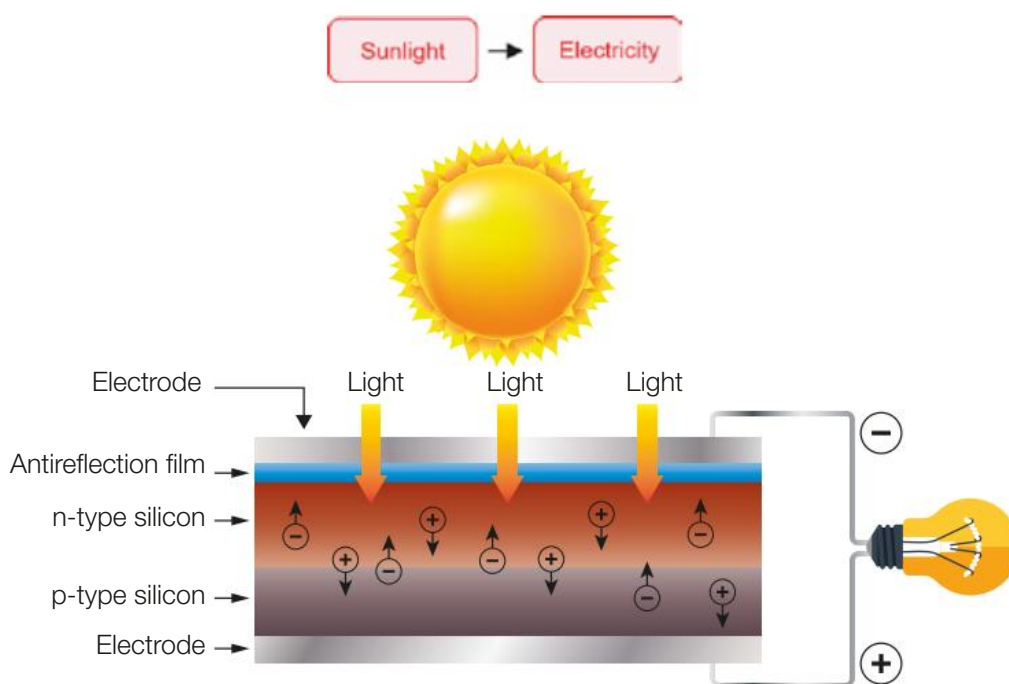


Figure 4.1.10: Conversion of sunlight to electricity.

Science understanding

Fuel cells, including flow cells, are galvanic cells in which the electrode reactants are available in continuous supply.

State the advantages and disadvantages of fuel cells compared with other galvanic cells.

Identify the anode and cathode and their charges, as well as the direction of ion and electron flow, in a fuel cell, given sufficient information.

Write electrode half-equations for a fuel cell given sufficient information.

Discuss the advantages of flow cells compared with other fuel cells.

© SACE 2025

Electricity production and storage in electrochemical cells

Galvanic cells

Galvanic cells (also known as **voltaic cells**) are electrochemical cells that rely on spontaneous redox reactions to generate a flow of current. Chemical energy is converted into electrical energy during the redox reaction when an electrical circuit is connected (Figure 4.1.11).

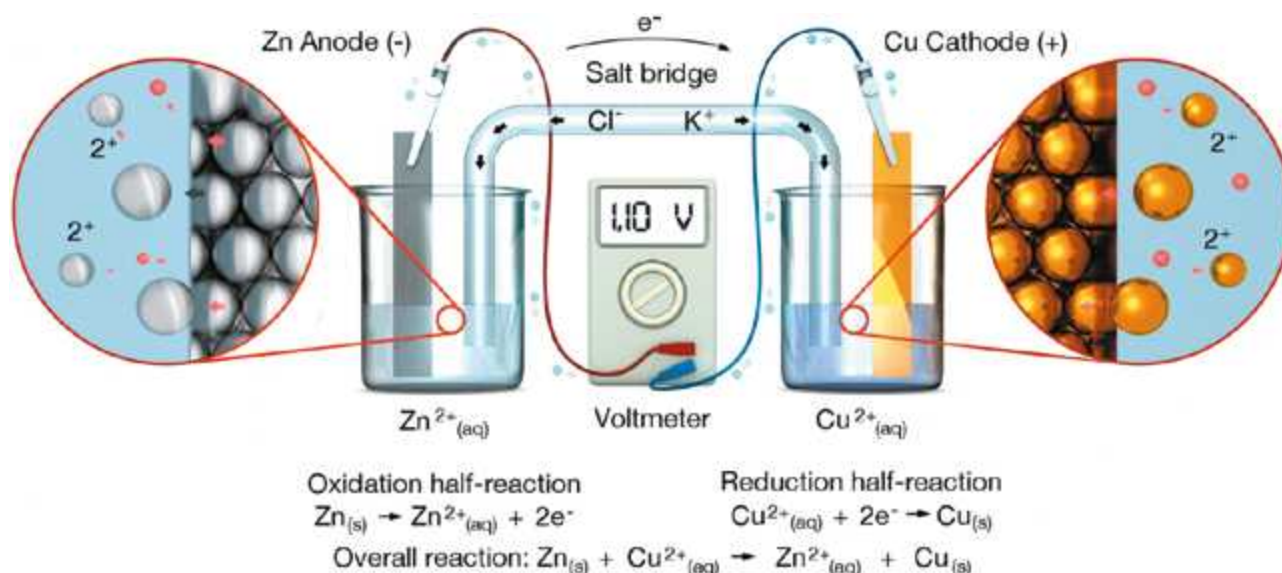


Figure 4.1.11: Simple zinc-copper galvanic cell

The operation of a galvanic cell can be summarised as follows.

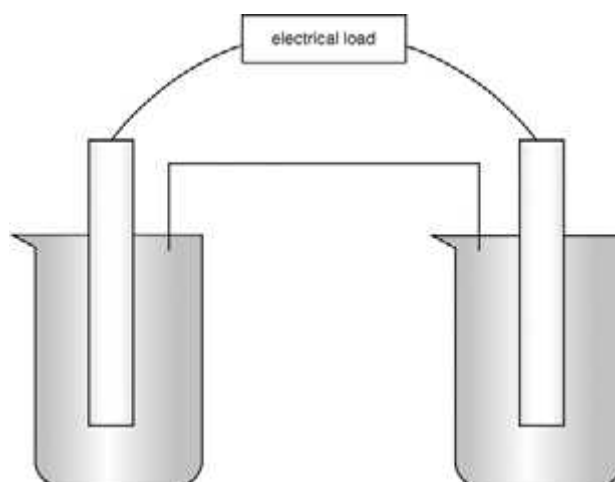
Galvanic cell	
Energy conversion	Chemical energy to electrical
Anode reaction	Oxidation
Cathode reaction	Reduction
Electron flow	Anode to cathode
Sign of anode	Negative (-)
Sign of cathode	Positive (+)
Anion movement	Anode
Cation movement	Cathode

Question

11. A galvanic cell was constructed using iron (Fe) and lead (Pb) electrodes, iron(II) nitrate and lead(II) nitrate electrolytes, and a salt bridge containing KNO_3 . Iron has a higher reactivity than lead.

(a) **Label** the following diagram of the cell with:

- (i) the anode and its charge
- (ii) the cathode and its charge
- (iii) the salt bridge
- (iv) the direction of electron flow in the wire
- (v) the direction that ions flow in the salt bridge



(b) **State** the metal that is oxidised in the cell.

(1 mark) **KA1**

(c) **Write a half-equation** to show the reaction at the anode in the cell.

(2 marks) **KA2**

(d) **Write a half-equation** to show the reaction at the cathode in the cell.

(2 marks) **KA2**

(e) Combine the half-equations to **write** the overall cell reaction.

(3 marks) **KA4**

Fuel cells

A **fuel cell** is also a galvanic cell. A fuel cell differs from galvanic cells in that typically a fuel and oxidant are in continuous supply.

In a conventional galvanic cell or **battery** (group of cells), the oxidiser and reducer are stored in the cell and are consumed during operation until it is discharged. In a **primary cell**, one or more reactants become depleted and the cell or battery is disposed of. **Secondary (rechargeable) cells** and batteries have the ability for the redox reactions to be reversed, effectively reforming the reactants. Secondary cells can be recharged for many cycles; however, the regeneration of reactants is less effective over time.

A fuel cell does not require the **oxidiser** and **reducer** to be stored or regenerated. Fuels such as hydrogen and methanol are fed directly into the cell. The oxidant, often simply oxygen from the air, is also drawn into the cell. Oxidation of the fuel at the anode and reduction of the oxidant at the cathode generates a flow of electrons through an external circuit. Electrode reactions are promoted by a metal catalyst. A solid electrolyte or selective membrane separates the electrodes and associated oxidiser and reducer.

There are many types of fuel cells, often defined by the material used as the fuel or electrolyte.

Type of fuel cell	Operating temperature (°C)	Electrolyte	Fuel
Proton exchange membrane fuel cell – PEMFC	40–90	polymer	hydrogen
Alkaline fuel cell – AFC	40–200	potassium hydroxide	hydrogen
Direct methanol fuel cell – DMFC	60–130	polymer	methanol
Phosphoric acid fuel cell – PAFC	200	phosphoric acid	hydrogen
Molten carbonate fuel cell – MCFC	650	molten carbonate	methane, hydrogen, carbon monoxide
Solid oxide fuel cell – SOFC	600–950	solid oxide	methane, hydrogen, carbon monoxide

4

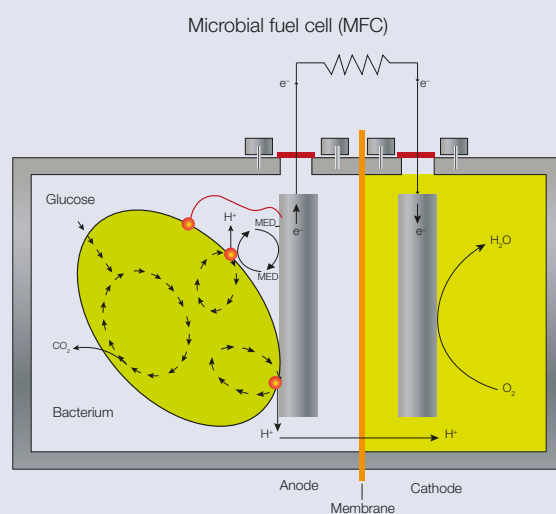


Science as a human endeavour

Microbial fuel cells (MFCs) represent a breakthrough in sustainable technology, converting organic waste into electricity using bacteria. This process not only generates energy but also helps in wastewater treatment, as the bacteria in MFCs consume pollutants present in wastewater. By using MFCs, industries can simultaneously address waste management and energy needs, reducing pollution and creating a new source of renewable energy. This innovation reflects the potential for biotechnology to solve multiple environmental challenges through a single, integrated process.

The implementation of microbial fuel cells in wastewater treatment plants could significantly reduce the environmental impact of waste disposal. Traditional treatment methods consume large amounts of energy, whereas MFCs generate energy from the waste itself, making the process both self-sustaining and eco-friendly. However, challenges remain in scaling up MFCs for widespread use, such as optimizing bacterial performance and reducing costs. As research advances, MFCs could play a pivotal role in achieving sustainable waste management and energy production, aligning with global efforts to reduce carbon emissions and protect natural resources.

MFCs provide low power and current, so they have limitations in their current proposed applications. However, they offer the advantage of having components inside the cell that are entirely biodegradable. For this reason, they are being considered for powering biosensors and generating electricity from wastewater disposal.



Science as a human endeavour

A recent meta-analysis (Bird et al., 2022) focused on advancing MFC technology by analysing pilot-scale systems to inform future designs; the study revealed important correlations between operational parameters and treatment performance across diverse conditions. By standardising data from these different studies, the researchers aim to streamline the transition from pilot demonstrations to more effective, full-scale applications, enhancing both the efficiency and scalability of MFCs. Such systematic insights are expected to provide a consistent basis for future research, potentially accelerating the commercial viability of MFCs as an eco-friendly wastewater treatment technology.

Bird, H., Heidrich, E.S., Leicester, D.D. and Theodosiou, P. (2022). Pilot-scale Microbial Fuel Cells (MFCs): A meta- analysis study to inform full-scale design principles for optimum wastewater treatment. Journal of Cleaner Production, 346, p.131227. <https://doi.org/10.1016/j.jclepro.2022.131227>.

Question

12. (a) **Identify** and **explain** two social, cultural, economic, or environmental considerations that could affect the acceptance and use of MFCs.

(4 marks) **KA3**

- (b) **Explain** how the current limitations of MFC technology might influence future applications.

(2 marks) **KA3**

- (c) **Explain** how the research by Bird et al. (2022) illustrates the role of communication and collaboration in advancing MFC technology.

(2 marks) **KA3**

Example

A **proton exchange membrane (PEM) fuel cell** uses the supply of hydrogen gas as a fuel and oxygen from the air as an oxidant. Each cell generates a low voltage that is dependent on the identity of both the fuel and the oxidiser. When combined in stacks as batteries, the cells are able to power devices in wide and varied applications. They have been used in electronics during space missions and have shown promising potential to drive electric motors to propel vehicles.

Hydrogen is fed into the anode half-cell as the fuel. Hydrogen undergoes oxidation on the surface of the porous anode, assisted by the presence of a metal catalyst (typically platinum). Protons (hydrogen ions) are able to migrate from the anode half-cell to the cathode half-cell through a selective proton exchange membrane. Electrons that are unable to pass through the membrane can flow through the external circuit; this generates a current. The electrons combine with hydrogen ions and oxygen molecules at the cathode, reducing the oxygen to water. As a waste product of the reduction reaction, water can be released from the cell (Figure 4.1.12).

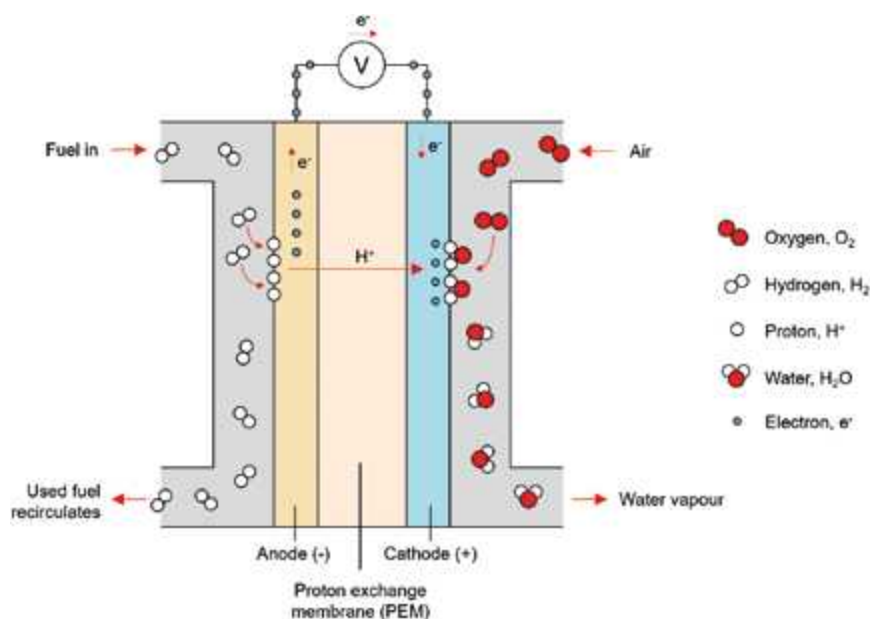


Figure 4.1.12: PEM fuel cell.

Cell reactions**Discharging (galvanic)**

Anode (-)	$\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$
Cathode (+)	$\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$
Overall	$2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$

Fuels cells, as an emerging technology, offer a range of advantages and disadvantages when competing against established technologies.

Advantages

In comparison to conventional galvanic cells

- Hydrogen is abundant as a fuel source, obtained easily from water and hydrocarbons. Other fuels, such as methanol, are commonly available and renewable.
- Components in the cell do not need to be regenerated if high-quality fuels are used. The cell can operate almost indefinitely, thus offering reliability.
- Cells offer high energy density and can be used in large-scale applications.
- Waste products are removed from the cell during operation.
- Cell power output is consistent and does not decrease over the duration of use.

Advantages

In comparison to internal combustion engines and electricity generation from fossil fuels

- Cells are silent during operation, with no moving mechanical parts that wear or require lubrication.
- Very few, if any, atmospheric pollutants are formed during operation.
- Waste products from fuel cells in most applications include water and carbon dioxide. Oxides of nitrogen and sulfur are not released as atmospheric pollutants.

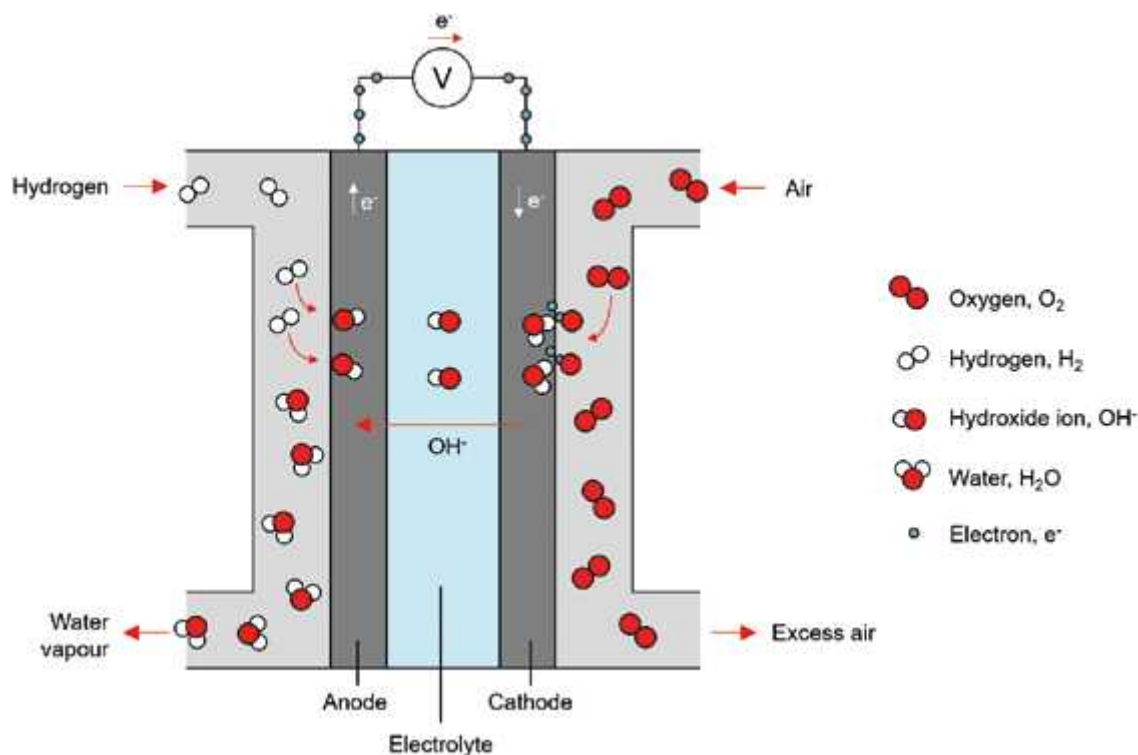
Disadvantages

In comparison to traditional galvanic cells

- Hydrogen may be obtained from non-renewable fossil fuels such as coal and natural gas.
- Hydrogen must be supplied in high purity, and challenges are associated with its safe storage.
- Electrodes are easily contaminated if impurities are present in the fuel.
- Metal catalysts (such as platinum) used on the surface of the electrodes are often expensive and in limited abundance.
- Limited infrastructure currently exists for hydrogen transport and refilling.
- The technologies are relatively new and expensive.

Question

13. Electrochemical cells including fuel cells and sensors are used in space missions. Alkaline fuel cells have been used in space missions by NASA since the 1960s due to their reliability, efficiency and safety.



- (a) A diagram of an alkaline fuel cell is shown above.

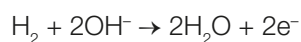
(i) **Identify** the energy change that occurs in the cell.

(2 marks) **KA1**

(ii) **Label** the positive and negative electrode on the diagram of the cell.

(2 marks) **KA1**

- (b) The cell is able to generate potable water. The reaction at one of the electrodes is shown below.



(i) **State** and **explain** whether this electrode equation represents oxidation or reduction.

(2 marks) **KA2**

(ii) **Hence**, state whether this reaction is occurring at the anode or cathode.

(1 mark) **KA1**

(iii) **Suggest** one advantage of the generation of water as a product from the cell during a mission to space.

(1 mark) **KA3**

- (c) Alkaline fuel cells offer several advantages over conventional galvanic cells when used during space flight.

Discuss two of the advantages offered by fuel cells compared to traditional galvanic cells.

(4 marks) **KA2**

- (d) The two electrodes are separated by potassium hydroxide as an electrolyte contained in a porous material. The electrolyte is susceptible to absorption of carbon dioxide, reducing the efficiency of the cell.
- (i) Carbon dioxide reacts with potassium hydroxide to form potassium carbonate and water as products.

Write a fully balanced chemical equation for this reaction.

(2 marks) **KA4**

- (ii) In the infamous Apollo 13 mission, exploding oxygen tanks on the spacecraft left astronauts with limited oxygen and rising carbon dioxide concentrations beyond the capacity of the lithium hydroxide carbon dioxide absorbers.

Suggest how an understanding of the chemistry of oxides and alkaline fuel cells could have been used to assist in these circumstances.

(2 marks) **KA2**

- (e) Carbon dioxide and carbon monoxide concentrations are monitored during missions using electrochemical cells. Carbon monoxide sensors rely on the oxidation of carbon monoxide to carbon dioxide at the negative electrode, generating an electrical current.

- (i) **State** the type of cell that produces electrical energy from redox reactions.

(1 mark) **KA1**

- (ii) **State** whether the negative electrode represents the anode or cathode.

(1 mark) **KA1**

- (iii) **Write** a balanced half-equation for the cell reaction in acidic conditions.

(2 marks) **KA4**

Science understanding

Hydrogen is a fuel that is produced from fossil fuels, biomass, or water.

- Compare the benefits of producing hydrogen from each of these three sources.
- Describe the benefits of using hydrogen, rather than fossil fuels, as a fuel..

© SACE 2025

Hydrogen as a Fuel

Hydrogen fuel is a promising alternative for a low-emission future, but the method of hydrogen production significantly affects its environmental impact. Grey hydrogen, produced from natural gas, releases large amounts of carbon dioxide, while blue hydrogen captures these emissions to mitigate environmental harm. The most sustainable option is green hydrogen, produced through electrolysis powered by renewable energy sources like wind or solar. However, green hydrogen production is currently more costly, presenting a challenge for widespread adoption.

Hydrogen can be used either by burning to create heat or in fuel cells to generate electricity. When hydrogen combusts with oxygen, it produces water as the only byproduct:



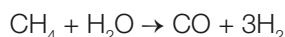
Additionally, hydrogen can be used in hydrogen fuel cells to produce electricity directly while emitting only water vapour, as explained earlier in this chapter.

Hydrogen has the highest specific energy of any fuel, 120 MJ/kgH₂. However, it has a much lower energy density than other common fuels: approx. 5–6 MJ/L for compressed hydrogen gas, or 8 MJ/L for liquid hydrogen, compared to 32 MJ/L for standard petrol.

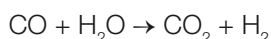
Production Methods of Hydrogen

Steam Methane Reforming (Grey Hydrogen)

The most common method for producing hydrogen is **steam methane reforming (SMR)**. In this process, methane reacts with steam under high temperatures, resulting in hydrogen and carbon monoxide:



The carbon monoxide then reacts with steam in the water-gas shift reaction, producing additional hydrogen and carbon dioxide:



The hydrogen produced by this method is called **grey hydrogen** because it involves fossil fuels without carbon capture. Steam methane reforming is currently the most cost-effective method for producing hydrogen on a large scale. The technology is well-established and widely used, offering a relatively high hydrogen yield. However, it comes with significant environmental impacts, as the process emits large quantities of carbon dioxide, contributing to global warming. It also relies on non-renewable natural gas resources, which will eventually be consumed.

Biomass Gasification

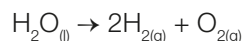
Hydrogen can also be produced through **biomass gasification**, where organic materials such as wood chips or agricultural waste are converted into hydrogen-rich gas through high-temperature reactions.

This method is carbon neutral since the carbon dioxide released was recently absorbed from the atmosphere through photosynthesis, resulting in no net increase in atmospheric CO₂. Biomass gasification also allows waste materials to be converted into fuel, reducing landfill use and utilising renewable resources that can be replenished.

However, biomass gasification tends to be more expensive compared to grey hydrogen due to the smaller scale and less mature technology. It is also resource-intensive, as it requires significant amounts of biomass, which could impact land use and food supply. Existing infrastructure is limited, and scaling up production would require substantial investments.

Electrolysis of Water (Green Hydrogen)

Another method for producing hydrogen is **electrolysis**, where electricity is used to split water into hydrogen and oxygen:



When powered by renewable energy sources, this method produces what is known as **green hydrogen** as there is no emission of greenhouse gases either in forming or using the hydrogen. Electrolysis can be conducted anywhere with access to water and electricity, making it especially useful for small-scale or niche applications, e.g., producing hydrogen fuel (and oxygen) in space.

Additionally, surplus renewable energy can be stored as hydrogen fuel, which can be transported as either a gas or liquid. However, the relatively high cost of electricity and electrolyser technology currently makes it more expensive compared to other methods. Like biomass gasification, electrolysis requires investment in new technologies and distribution systems to become more widely adopted.

Advantages of Hydrogen over Fossil Fuels

Environmental	Hydrogen combustion or use in fuel cells produces only water vapour, resulting in zero emissions at the point of use. This eliminates pollutants like nitrogen oxides and particulates, improving air quality and reducing health risks.
Energy Security	Hydrogen enables diversification of energy sources. Countries that lack fossil fuel resources can produce their own hydrogen fuel domestically, enhancing energy independence.
Economic	Hydrogen has the potential to create new trade opportunities by enabling the export of renewable energy. Unlike electricity, which cannot be easily transported over long distances, hydrogen can be compressed and transported like any other liquid fuel. This characteristic allows renewable energy generated in regions rich in solar or wind resources to be converted into hydrogen and shipped globally, driving economic growth and opening new markets.

4



Science as a human endeavour

The Diverging Paths of Lithium Battery EVs and Hydrogen FCVs

The development of lithium battery electric vehicles (EVs) and hydrogen fuel cell vehicles (FCVs) both began as responses to the need for cleaner transportation, but they have followed different paths. Lithium battery EVs gained an early foothold due to their relatively simpler technology and the rapid decline in battery costs. Government incentives and the expansion of charging infrastructure further supported their adoption, while their visibility and association with innovation helped position them as environmentally friendly, tech-savvy choices.

In contrast, hydrogen FCVs have faced more challenges and slower adoption. Despite being developed around the same time, hydrogen vehicles remained niche due to the high cost of fuel cell technology and the lack of a widespread hydrogen refuelling network. Although companies like Toyota and Honda have released hydrogen vehicles, the infrastructure needed to support these cars—particularly hydrogen production and refuelling stations—has not kept pace with the growth of EV charging networks. Additionally, the production of green hydrogen remains expensive and energy-intensive, which limits the immediate environmental benefits of FCVs compared to the increasing reliance on renewable electricity for lithium battery EVs.

Lithium battery EVs have benefited from strong branding and a cultural association with innovation, mainly through high-profile companies like Tesla. In contrast, hydrogen cars remain less visible and have struggled to capture the same public attention. The combination of superior infrastructure and consumer perception has led lithium battery EVs to dominate the personal transportation market. At the same time, hydrogen vehicles are still seen as promising for the future, particularly in industries like heavy-duty transport, where batteries may not be as practical.



Question

14. (a) **Identify** and **explain** one economic factor that has influenced the greater adoption of lithium battery EVs over hydrogen FCVs.

(2 marks) **KA3**

- (b) **Identify** and **explain** one social and cultural factor that has influenced the greater adoption of lithium battery EVs over hydrogen FCVs.

(2 marks) **KA3**

- (c) **Identify** and **explain** one environmental factor that has influenced the greater adoption of lithium battery EVs over hydrogen FCVs.

(2 marks) **KA3**

Flow cells

A **flow cell** is a rechargeable fuel cell. Two **electrolytes** (anolyte and catholyte) are separated by an ion-selective membrane (Figure 4.1.12). Both half-cells are also joined to external tanks of the electrolyte linked with pumps to circulate the electrolytes. When the cells are depleted, the electrolytes are pumped from the cell and regenerated.

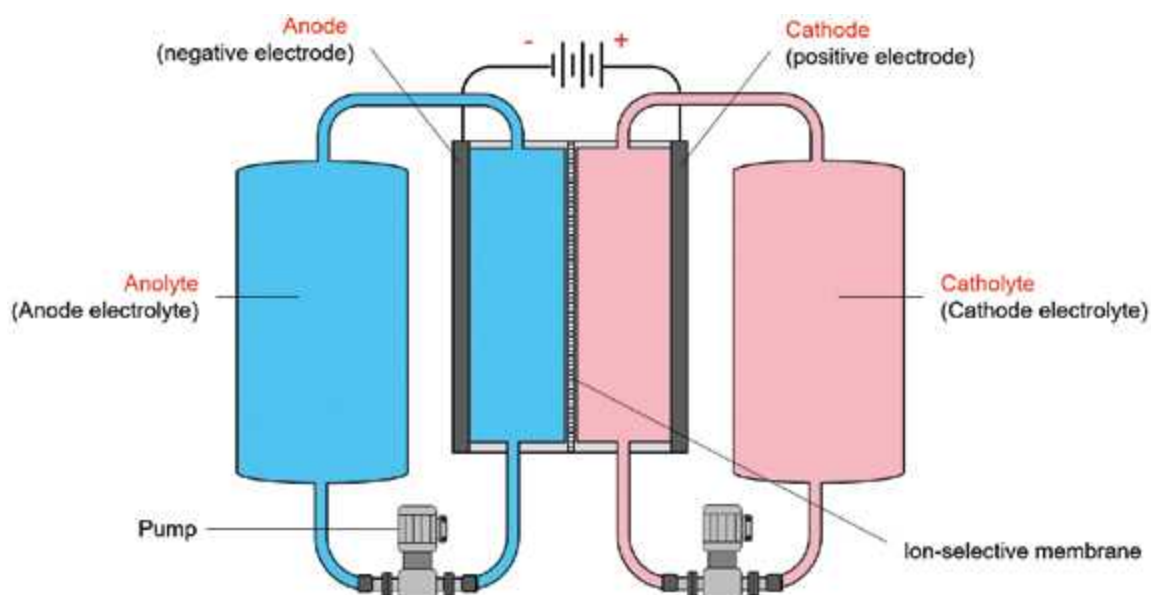


Figure 4.1.12: Flow cell.

Flow cells offer a number of significant advantages over fuel cells as another type of galvanic cell.

Advantages	
In comparison to fuel cells	Virtually unlimited capacity, as electrolytes are stored externally; therefore flow cells are effective for large stationary applications.
	Cells are rechargeable, which means that electrolytes can be used indefinitely. They are quickly charged through the addition of electrolyte.
	Can be left discharged for extended periods and recharged indefinitely without loss of output.
	No emissions of atmospheric pollutants during operation.
	Components of the cell can be laid out in varying configurations, which can include burying the electrolyte tanks underground.

Example

A **vanadium flow battery** (or vanadium redox battery, VRB) uses the many oxidation states of vanadium to generate a flow of electrons in redox reactions. Vanadium flow batteries are implemented due to their ability to be recharged and their capacity for energy storage. Vanadium flow batteries only require one electrolyte. The electrolyte can be prepared by dissolving the vanadium pentoxide V_2O_5 in sulfuric acid.

- In the **anolyte** (anode electrolyte), vanadium(II) ions are oxidised to vanadium(III) ions with the loss of an electron.
- In the **catholyte** (cathode electrolyte), vanadium(V) is reduced to vanadium(IV) through the gain of an electron.

When discharging (galvanic cell), the electrolytes are pumped into the half cells, which are separated by a proton exchange membrane. The membrane selectively allows hydrogen ions to pass to the cathode while not allowing other ions through that are present in the electrolytes. A transfer of electrons occurs in the external circuit to balance the overall cell charge, thus generating a current.

Recharging the cell (electrolytic cell) reverses the anode and cathode reactions by forcing current to flow in the opposite direction via an external power source.

Cell reactions

Discharging (galvanic)	
Anode (-)	$V^{2+} \rightarrow V^{3+} + e^{-}$
Cathode (+)	$VO_2^{+} + 2H^{+} + e^{-} \rightarrow VO^{2+} + H_2O$
Overall	$V^{2+} + VO_2^{+} + 2H^{+} \rightarrow V^{3+} + VO^{2+} + H_2O$
Recharging (electrolytic)	
Anode (+)	$VO^{2+} + H_2O \rightarrow VO_2^{+} + 2H^{+} + e^{-}$
Cathode (-)	$V^{3+} + e^{-} \rightarrow V^{2+}$
Overall	$V^{3+} + VO^{2+} + H_2O \rightarrow V^{2+} + VO_2^{+} + 2H^{+}$

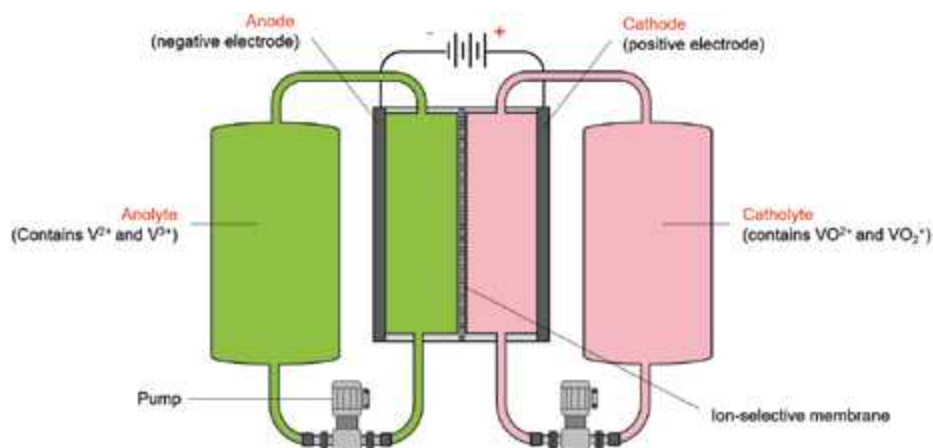


Figure 4.1.13: Vanadium flow cell.

The energy capacity of a vanadium flow cell is only limited by the size of the storage tanks for the electrolyte. The power achieved is determined by the surface area of the electrodes.

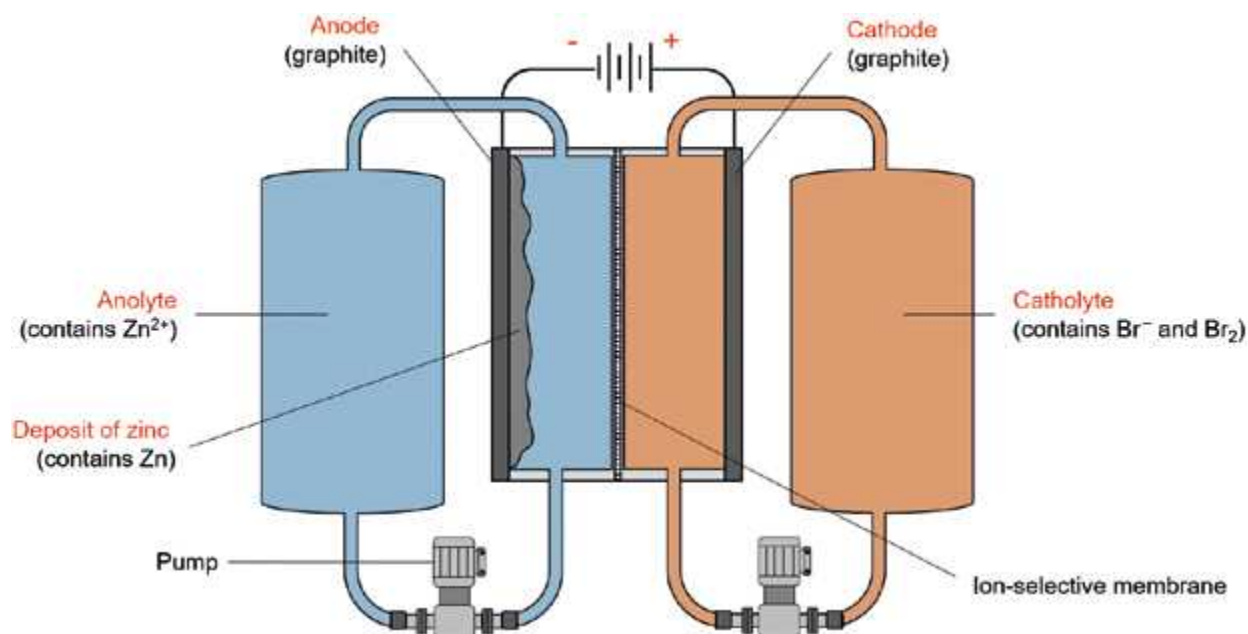
Question

15. The ZCell™ home battery is a flow battery designed to compete with current lithium-ion batteries for home energy storage and supply from solar arrays of photovoltaic cells.

- (a) **Discuss** two advantages of generating electricity from photovoltaic cells compared to coal-fired steam turbines in power stations.

(4 marks) KA1

- (b) The ZCell™ used for electricity storage is an example of a zinc-bromine hybrid flow cell.



- (i) On the diagram above, **show** the direction of electron flow during discharge.
- (ii) During discharge deposited zinc is lost from the anode moving into solution.

(1 mark) KA1

Write a balanced half-equation for this reaction.

(2 marks) KA4

- (iii) **Suggest** why the cell is considered a hybrid flow cell.

(1 mark) KA2

- (iv) **Discuss** two advantages of the zinc-bromine cell in domestic applications for the storage and supply of electrical energy.

(4 marks) **KA2**

- (v) Bromine is formed at the other electrode during charging from photovoltaic cells.

(1) **State** the energy transformation during charging.

(2 marks) **KA2**

(2) **Construct a half-equation** for the formation of bromine from bromide ions.

(2 marks) **KA4**

- (3) In domestic applications, the batteries are contained in a double-walled casing.

Suggest one reason why this level of containment is required.

(1 mark) **KA3**

4.2 Water

Science understanding

Water from different sources is treated with different methods depending on its origin and intended use.

Suspended matter is commonly removed from water by flocculation, followed by sedimentation and filtration.

The surface of fine silicate and aluminosilicate particles in clays is negatively charged and can be flocculated into larger particles by the addition of salts containing highly charged cations such as aluminium ions or polymers.

Explain the use of aluminium ions and polymers in flocculating clay particles suspended in water.

© SACE 2025

Water treatment

Techniques used for the treatment of water are dependent upon a number of factors including the source of the water and the range of organic and inorganic impurities present. Sources of freshwater are typically treated through the removal of suspended solids and disinfection to make the water **potable** (safe for human consumption). The treatment of sources of saltwater requires **desalination** (the removal of dissolved salts).

Treatment of freshwater

The following stages are typically applied in the treatment of freshwater for domestic use in Australia (Figure 4.2.1).

- **Coagulation and flocculation:** coagulation neutralises charge on suspended impurities and flocculation aggregate the impurities.
- **Sedimentation:** the floc (aggregated impurities) settle out as sediment and are removed.
- **Filtration:** remaining solid impurities are trapped and filtered out as they move through layers of sand and charcoal.
- **Disinfection:** chlorine, chloramines (derivatives of ammonia and chlorine), ozone, and ultraviolet radiation are used to kill potentially harmful microorganisms present in the water.
- **Fluoridation:** fluoride is added to the water in low concentrations to reduce tooth decay.

The treatment of water begins with understanding colloidal chemistry. Colloidal particles, typically ranging from 1 nanometer to 1 micrometer in diameter, remain suspended in water due to their surface electrical properties. These particles, particularly clay minerals, possess a negative surface charge due to isomorphous substitution within their crystalline structure. This negative charge creates an electrical double layer, where positive ions from the solution are attracted to the particle surface while still maintaining a net negative charge. This electrostatic repulsion between particles prevents natural aggregation and settling, contributing to water turbidity.

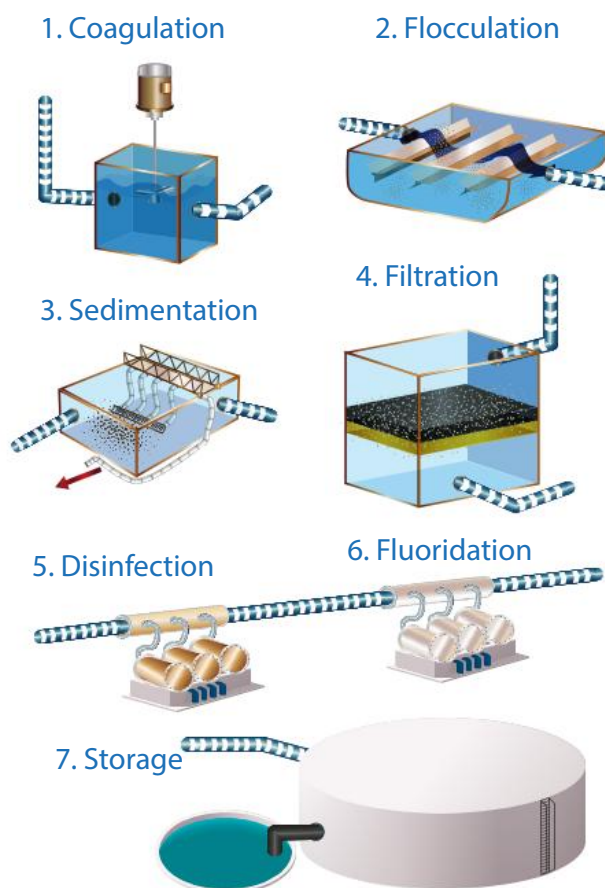


Figure 4.2.1: Stages of water treatment.

Coagulation

Dissolved and suspended particles are present in freshwater. The suspended particles originate from organic and inorganic sources. Suspended organic impurities include viruses, bacteria, algae, and decaying organic matter. Suspended inorganic impurities are formed during the weathering and erosion of rocks and include a range of aluminosilicate minerals, collectively referred to as **clays**.

After larger solid particles settle in the water, fine **colloids** (particles approximately within the nanometre (nm) to micrometre (µm) range) remain on the surface and in suspension due to the small size and the repulsion of regions of like charge. Colloidal suspensions account for the **turbidity** (cloudiness) of unprocessed water.

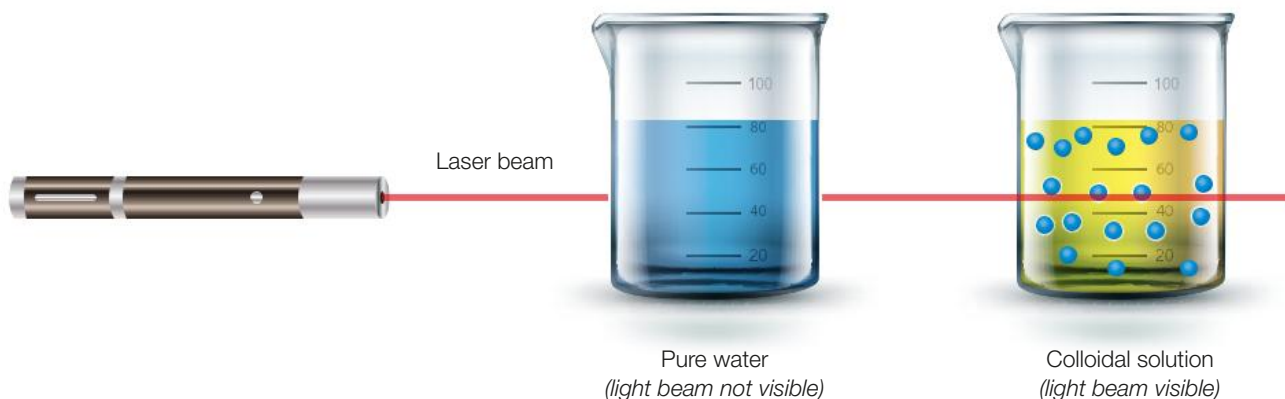
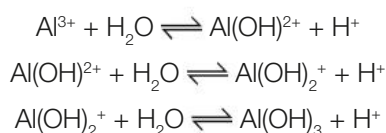


Figure 4.2.2: Colloidal suspension.

The coagulation process is more complex than simple charge neutralisation. When aluminum sulfate ($\text{Al}(\text{SO}_4)_3$) is added to water, it undergoes hydrolysis to form various aluminum hydroxide species:



These hydrolysis products form polynuclear complexes that are more effective at destabilising colloids than simple Al^{3+} ions. The process involves both charge neutralization and sweep flocculation, where particles become enmeshed.

Clays are composed of minerals in the micrometre (µm) range and form colloidal suspensions in water. Clays have negatively charged regions on the surface of the **aluminosilicates** (covalently bonded networks of Si, Al and O).

Clay particles form stabilised (dispersed) colloidal suspensions due to the repulsion of negatively charged sites. During water treatment, salts and polymers are used to destabilise the suspension and aggregate clay minerals, allowing them to settle out. These stages are referred to as **coagulation** and **flocculation** respectively. Coagulation is a chemical process neutralising charge on the surface of colloids, whereas flocculation is a physical process aggregating particles.

Commonly used metal coagulants are based on salts of aluminium, such as aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$). When added to water, the metal ions hydrolyse to form charged metal complexes (Figure 4.2.3).

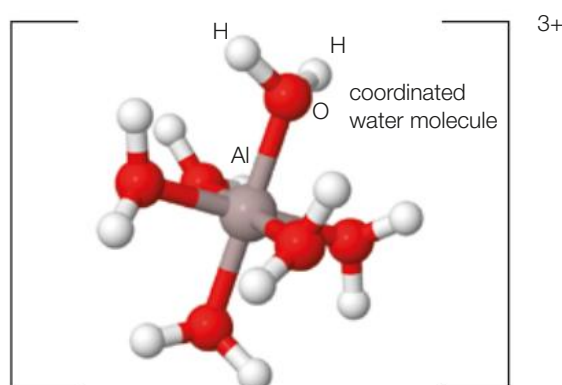


Figure 4.2.3: Hydrated complex of aluminium.

Positively charged metal complexes neutralise negative charge on the surface of clay particles. Once repulsive negative charges have been neutralised and the suspension is destabilised, dispersion forces allow the particles to aggregate to form **microfloc** (Figure 4.2.4).

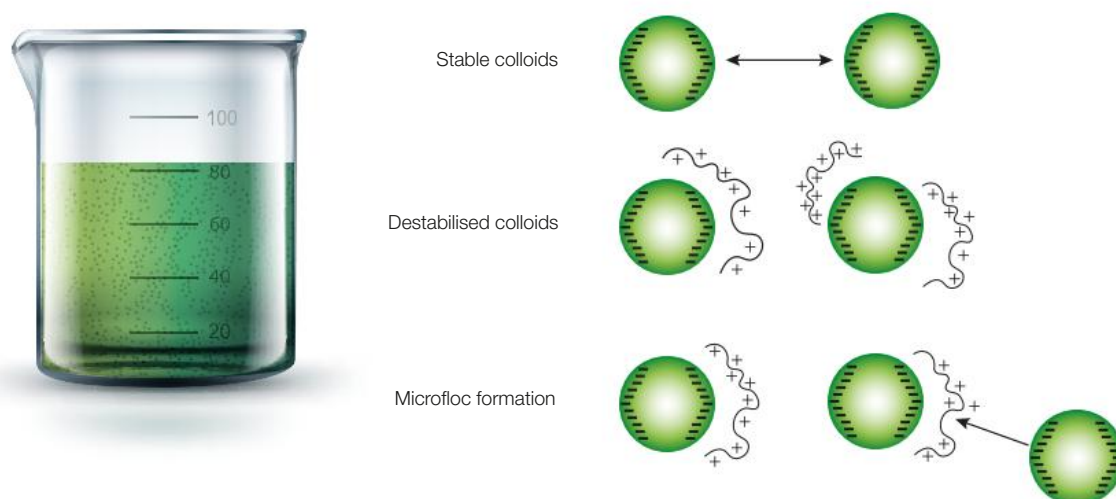


Figure 4.2.4: Coagulation of colloids.

Flocculation

Flocculation is the further aggregation of destabilised particles into larger particles. With gentle agitation, coagulated microfloc will combine to form larger **floc**. The floc settles due to their size and mass. Floc is then removed as sediment.

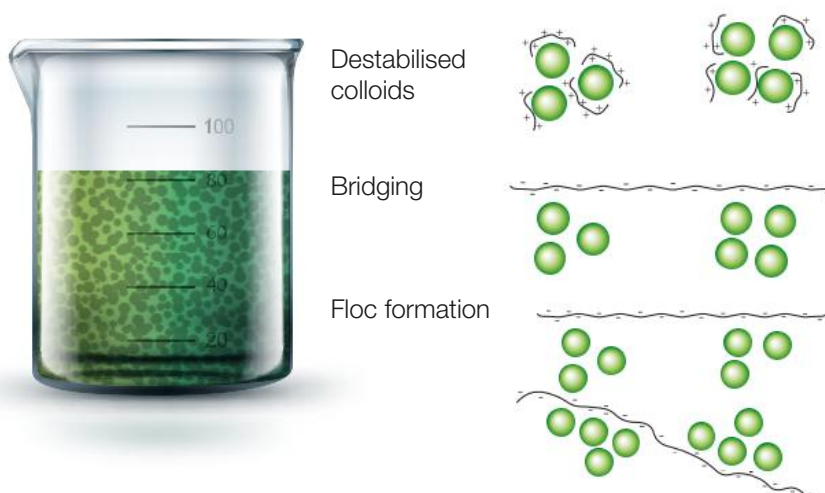


Figure 4.2.5: Flocculation of coagulated colloids.

Coagulation and flocculation can also be achieved or assisted through the addition of large molecular mass polymers (anionic and cationic) which not only neutralise the surface charge, but also physically entrap particles.

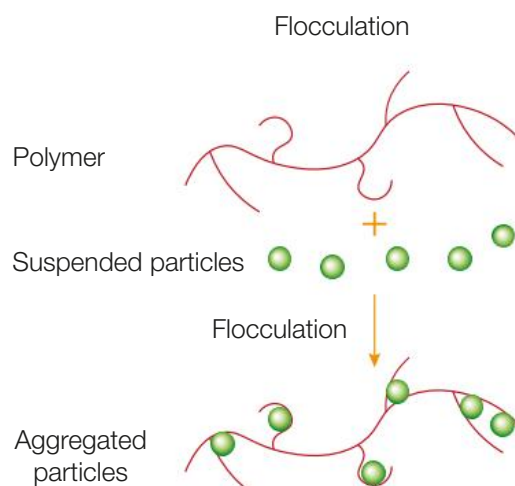
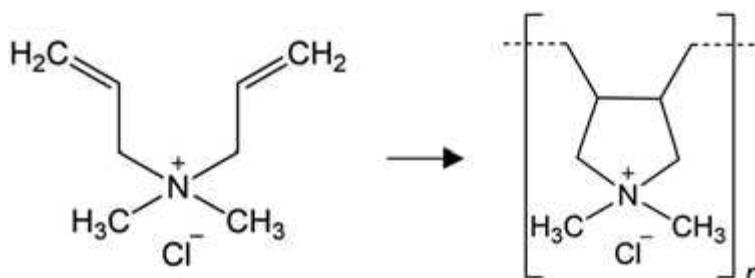


Figure 4.2.6: Coagulation and flocculation with polymers.

Question

16. Metal salts and natural and synthetic polymers are commonly used in water treatment to aid in coagulation and flocculation of colloidal particles.

- (a) PolyDADMAC is an example of a synthetic polymer used as a coagulant and flocculation aid. The conversion of the monomer to the polymer, polyDADMAC, is shown below.



- (i) **State** the feature of the monomer that allows for the formation of a polymer

(1 mark) IAE3

- (ii) **State** whether the surface of the polymer formed is anionic or cationic.

(1 mark) KA1

- (iii) PolyDADMAC is commonly used in conjunction with hydrated salts of aluminium such as aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$).

- (1) **Write an equation** for the dissociation of aluminium sulfate in water.

(2 marks) KA4

- (2) **State** one advantage of the use of aluminium sulfate compared to polyDADMAC during coagulation.

(1 mark) KA2

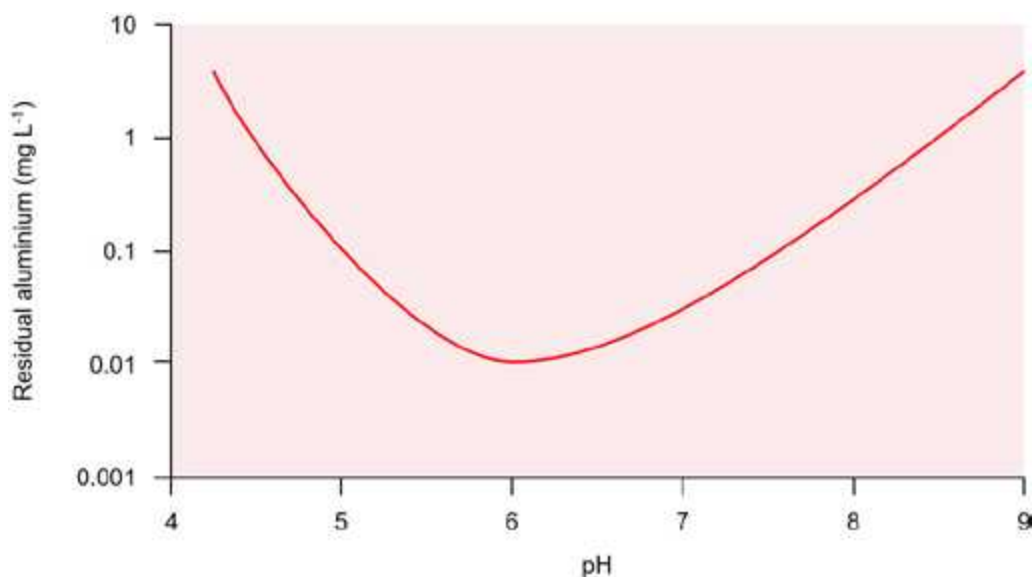
- (3) **State** one advantage of the use of polyDADMAC compared to aluminium sulfate during flocculation.

(1 mark) KA2

- (iv) **Explain** how polyDADMAC generates coagulation and flocculation of clays during water treatment.

(3 marks) KA1

- (b) Aluminium residuals in drinking water from the use of aluminium during treatment are highly regulated.
- (i) The pH during treatment is controlled in terms of the effectiveness of the coagulant and flocculant but also to control the concentration of residual aluminium.



Describe the trend in the graph above.

(2 marks) **IAE3**

- (ii) **Calculate** the mass, in g, of aluminium consumed in a 300 mL glass of water containing aluminium ions at a residual obtained at a pH of 6.

(3 marks) **KA2**

- (iii) Guidelines for aluminium consumption are derived from the amount of aluminium that would be absorbed by a 60 kg adult drinking 2 L of water per day at the maximum aluminium concentration of 1.5 mg L⁻¹.

Calculate the concentration, in ppm, present in a 60 kg adult consuming 2 L of water containing this aluminium concentration. Assume that the human body has the same density as water, 1 kg/L.

(3 marks) **KA2**

- (c) The seeds from the Nirmali (clearing nut) tree have been used for clarifying water in India since 2000 BC. When crushed and added to water the natural polymers present assist in coagulation and flocculation to clarify water.

Discuss two advantages of using polymers derived from the seed of a plant for water treatment in remote communities in developing nations.

(4 marks) KA3

Science understanding

Hard water contains high concentrations of Ca^{2+} and Mg^{2+} ions. Hard water renders soaps less effective and causes build-up of precipitates.

Natural and modified zeolites can be used in the purification and softening of water, through the exchange of cations. Explain the use of zeolites in water softeners.

© SACE 2025

4

Hard water

Hard water is water that contains a high mineral (naturally occurring chemical compound) content.

Rainwater and freshwater from rivers and lakes contains dissolved carbon dioxide, which lowers the pH of water. The acidic water dissolves calcium and magnesium carbonates, releasing calcium and magnesium ions into the water.

Dissolved calcium and magnesium ions are two ions most widely recognised as causing hard water. The degree of hardness increases with the concentrations of these ions. Water hardness can be classified according to the following concentrations of dissolved cations.

Classification	mg L ⁻¹ (ppm)
Soft	0 – 17.1
Slightly hard	17.2 – 60
Moderately hard	61 – 120
Hard	121 – 180
Very hard	Above 180

Hard water inhibits the cleaning ability of soaps as surfactants and forms precipitate deposits (scum), (Figure 4.2.7) in plumbing, associated tapware and surfaces.

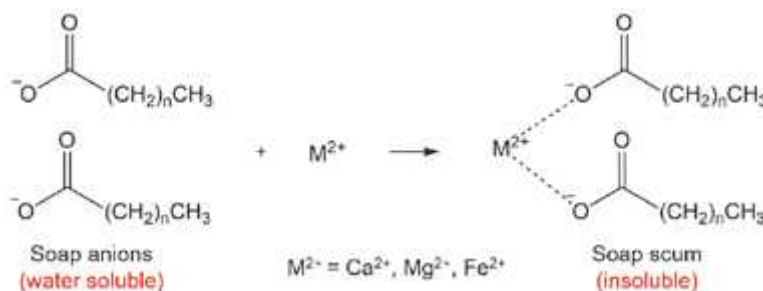


Figure 4.2.7: Formation of soap scum.

Hard water contributes to the inefficiency and expense associated with hot water systems, dishwashers and washing machines. A precipitate of calcium carbonate (scale) is formed when hard water is heated. The resulting precipitate blocks pipes and drains and restricts water flow.



Zeolites

Zeolites can be mined naturally or formed synthetically. Zeolites are **hydrated aluminosilicate** minerals composed of linked alumina (AlO_4) and silica (SiO_4) tetrahedra. Excess negative charge on the surface of the aluminosilicate can accommodate metal cations such as sodium, magnesium and potassium. Natrolite ($\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$) is an example.

Tetrahedra combine to form a wide range of structures, with cavities present in the three-dimensional structure of the material. The microporous (pores in the micrometre range) nature of these extended structures provides vast surface area for interactions between the solvent and the surface of the zeolite material (Figure 4.2.8).

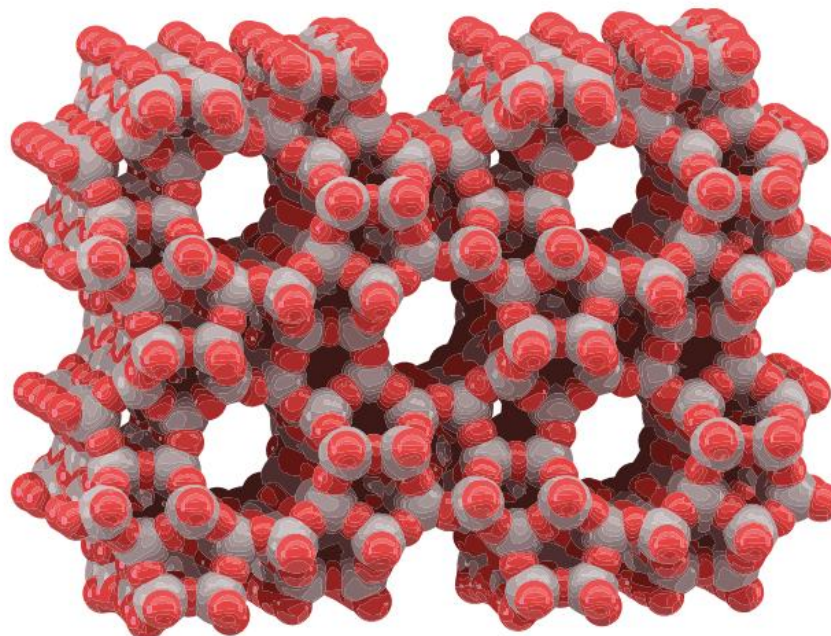
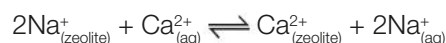


Figure 4.2.8: Porous zeolite structure.

Zeolites are used as an exchangeable adsorbent surface in analysis (refer to ion chromatography on page 88), as a catalyst in the petrochemical industry, and to remove excess ions during water treatment and cleaning with detergent formulations.

Zeolites as water softeners

Cations held on the surface of the zeolite can readily be exchanged. Cations present in water undergo cation exchange with the cations on the surface of the zeolite. In domestic use, water softeners containing zeolites are paired with a source of sodium chloride solution. Sodium chloride solution is passed over the surface of the zeolite, which causes sodium ions to absorb to the charged surface. As hard water passes over the zeolite, excess calcium and magnesium ions present in the water ($\text{Ca}^{2+}/\text{Mg}^{2+}_{(\text{aq})}$) exchange with sodium ions present on the negative surface of the pores ($\text{Na}^+_{(\text{zeolite})}$). The following equilibrium equation can be used to represent the process.



Eventually all the negative sites on the surface of the zeolite are occupied with cations from hard water and the zeolite loses effectiveness. At this point the zeolite can be regenerated by shifting the equilibrium to favour the backward reaction. This is achieved by the addition of concentrated sodium chloride solution.

Science understanding

Desalination is a process used to remove minerals from saline water to produce fresh potable water. Reverse osmosis and thermal distillation are two widely used methods for desalination.

Describe the disadvantages of using desalination for the production of potable water.

© SACE 2025

Treatment of saltwater (desalination)

Desalination refers to processes that are undertaken to remove dissolved salts and minerals from water. Lowering the salinity of seawater and brackish water can make it suitable for human consumption or industrial use.

Advantage	Description
Production of potable water	Water of a quality that exceeds World Health Organization standards can be generated.
Reduction in demands on fresh water	Seawater, which is more abundant in comparison to fresh water, can be used to generate potable water. This reduces the demands on sources of fresh water and the associated ecology.
Availability is not reliant on climate	Potable water can be generated that is not reliant on rainfall or climate. For example, droughts do not affect supply. Potable water can be generated in regions of the world where fresh water is not available.
Reliable production	The processes rely on well-established, proven technologies. More efficient uses of waste heat and advanced materials have led to more effective and efficient processes.
Disadvantage	Description
Energy-intensive processes	Large amounts of energy are required to be input as electricity and heat.
Expense	Processes are expensive due to energy inputs and the requirement for specialised equipment and its ongoing maintenance.
Waste products	Disposal of the waste products, which contain high concentrations of salts (in the brine) and other chemicals used in treatment, can be problematic in some environments.
Waste heat	Waste heat, released locally in the oceans, can affect marine ecology.
Death of organisms	Inlets can drag in aquatic organisms which are subsequently killed during processing in the plant.

4



Science as a human endeavour

Digital Revolution in Water Treatment

Smart Systems Transform Water Treatment Plants

Australian water utilities are revolutionising water treatment through the integration of artificial intelligence and real-time monitoring systems. This technological transformation, initially piloted at Melbourne's Eastern Treatment Plant in 2020, represents a significant shift from traditional manual testing to automated, predictive management of water quality.

The SA Water Corporation has implemented AI-powered systems that continuously monitor water quality parameters using a network of sensors throughout treatment plants. These sophisticated sensors provide comprehensive monitoring of critical parameters including turbidity levels, chlorine concentrations, pH variations, dissolved oxygen content, and organic matter levels across the treatment process.

The system analyses this data in real-time and automatically adjusts treatment parameters. When storm events cause sudden increases in turbidity, the AI system responds within seconds, adjusting coagulant dosing rates and modifying filtration parameters while simultaneously alerting operators to potential issues. This rapid response capability has proven invaluable during extreme weather events.

Early results from implementing these smart systems have been remarkable. Treatment plants have reported a 15% reduction in chemical usage and a 20% decrease in energy consumption. Water quality incidents have decreased by 40%, leading to significant cost savings for utilities while improving water quality consistency.

Two methods of desalination commonly employed are **thermal distillation** and **reverse osmosis**.

Thermal distillation

Thermal distillation is a process whereby saline water is boiled and the vapour formed is condensed and collected as pure water. This is an energy-intensive process requiring large inputs of electricity and heat. Thermal distillation is often linked to processes that generate heat as a by-product.

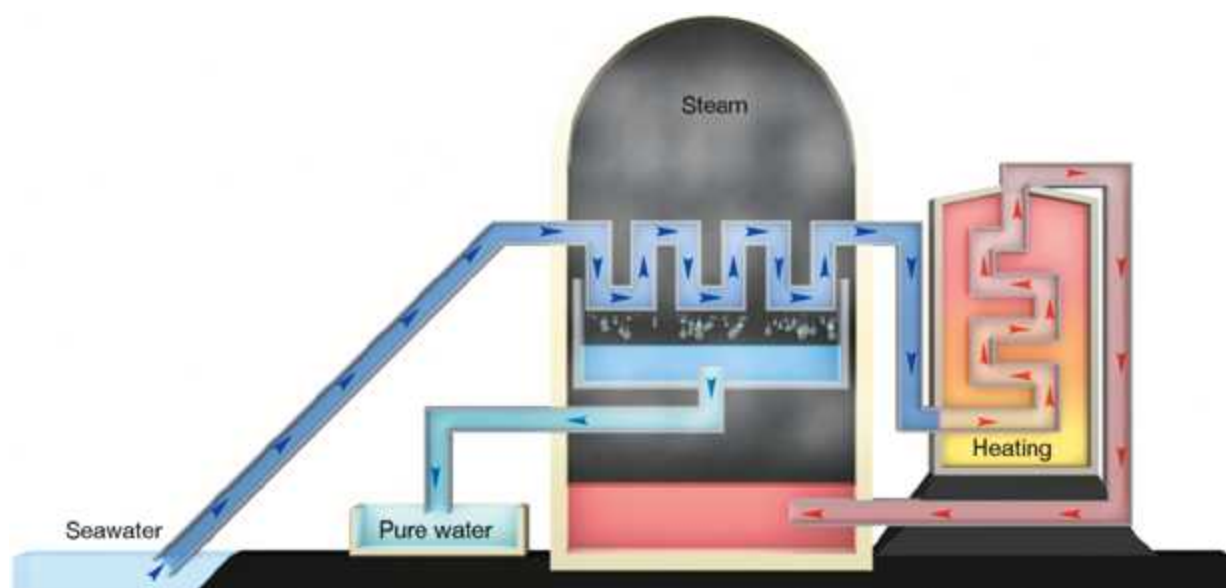


Figure 4.2.9: Thermal distillation.

Thermal distillation is used extensively in the Middle East, where rainfall is low and fuel sources from petroleum are plentiful and relatively cost-effective.

Science understanding

Reverse osmosis is a filtration technique whereby water is forced, under pressure, through a semi-permeable membrane.

Explain how reverse osmosis produces potable water from saline water.

© SACE 2025

Reverse osmosis

Osmosis is the spontaneous movement of water molecules through a semipermeable membrane to equalise solute concentrations. The semipermeable membrane allows for the transfer of water, but not the solute.

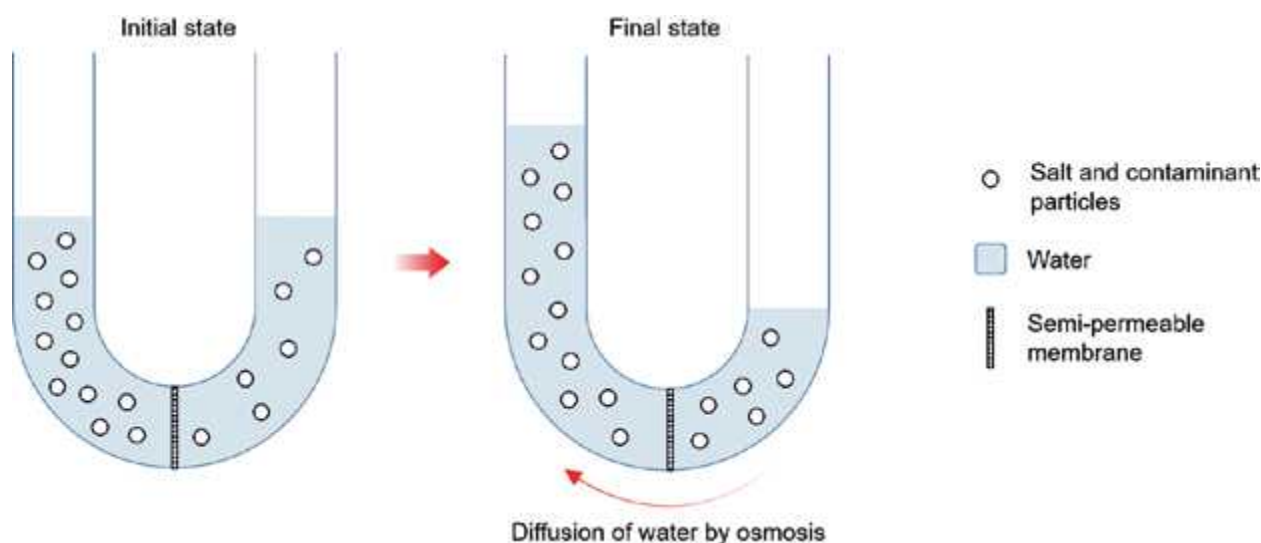


Figure 4.2.10: Osmosis.

Reverse osmosis (RO) is a process which employs a semipermeable membrane to remove dissolved ions, molecules and suspended particles (depending upon size) from water. Pressure is applied to overcome the **osmotic pressure** (the pressure required to stop the natural osmotic flow), forcing the solute to remain on the pressured side of the membrane and water to shift to the other side of the membrane (Figure 4.2.11).

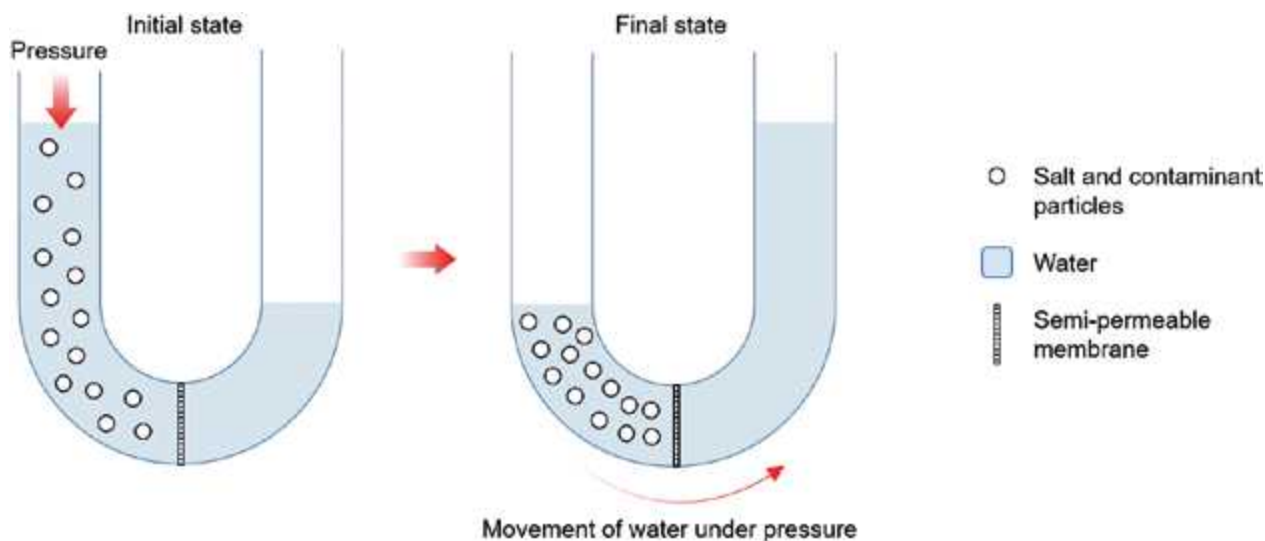


Figure 4.2.11: Reverse osmosis.



Science as a human endeavour

Adelaide Desalination Plant (ADP)

The desalination plant at Lonsdale, South Australia, has the capacity to supply up to 50% of Adelaide's supply of household water (100 GL per year). The desalination plant utilises the reverse osmosis of seawater. The plant was funded by the government as a response to the "millennium droughts" in 2006/7 and diminishing water flow from the primary water source, the Murray River.

A saline concentrate is produced from the reverse osmosis process. The concentrate is returned to the ocean offshore through a series of diffusers. The diffusers are designed to rapidly mix the saline waste with sea water to ensure homogeneity and dilution. The marine environment is monitored with real-time data for water temperature, salinity, and currents to determine impact on the marine environment.



Question

17. Cafés often use reverse osmosis and zeolites to remove dissolved calcium and magnesium ions from water supplied to coffee machines. The ions damage boilers and affect the taste of coffee.

(a) **State** the term used to describe water containing an elevated concentration of calcium and magnesium ions.

(1 mark) **KA1**

(b) **Explain** how reverse osmosis can remove ions present in domestic water supplies before that water is used in coffee machines.

(2 marks) **KA1**

- (c) Calcium ions present in the water lead to the build-up and precipitation of calcium carbonate (CaCO_3) as scale in the boilers of coffee machines.

- (i) As cold water is heated in the boiler of a coffee machine, carbon dioxide is lost.



Explain, with the aid of the equation above, how this leads to an increased concentration of calcium carbonate.

(4 marks) **IAE3**

- (ii) Sulfamic acid, $\text{NH}_2\text{SO}_3\text{H}$, is used in commercial coffee machines to remove scale. It undergoes an acid–base reaction with calcium carbonate to form calcium sulfamate, $\text{Ca}(\text{NH}_2\text{SO}_3)_2$.

Write a balanced equation for the reaction described above.

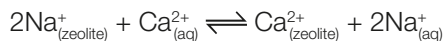
(2 marks) **KA4**

- (d) Domestic coffee machines often use zeolite resins to remove calcium and magnesium ions from water.

- (i) **State** two important features of zeolites that make them effective as water softeners.

(2 marks) **KA1**

- (ii) The equation below represents the equilibrium.



- (1) **Explain**, using equilibrium principles, the effect on the zeolite when water with a high concentration of calcium ions is passed by the zeolite surface.

(4 marks) **IAE3**

- (2) **State** how the zeolite resin can be regenerated, removing calcium ions.

(1 mark) **KA2**

- (e) Filter coffee is a mixture of dissolved and undissolved solids. Undissolved solids form a colloid suspension. Very fine paper or stainless-steel filters are used to filter the coffee.

Suggest why a colloidal suspension is still formed.

(1 mark) **KA2**

Science understanding

Hypochlorous acid, chlorine, and hypochlorites are oxidisers used for water disinfection.

Explain the effect of pH on the equilibrium between chlorine and water, and hydrochloric acid and hypochlorous acid

© SACE 2025

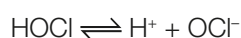
Disinfection using chlorine and compounds of chlorine

Chlorine and a range of associated compounds containing chlorine are used in the large-scale and domestic **chlorination** of water for domestic use (water for households) and recreation (pools and spas).

Chlorine

Chlorine gas (Cl_2) is added to water supplies as a disinfectant. Chlorine reacts with water to establish an equilibrium with the formation of hypochlorous acid (HClO) and the products of the complete ionisation of hydrochloric acid (HCl).

The effectiveness of chlorine disinfection depends on complex equilibrium reactions. The distribution of chlorine species follows the equation:



The relative concentrations of HOCl and OCl^- critically affect disinfection efficiency because HOCl is approximately 80 times more effective as a disinfectant.



The resulting equilibrium is pH dependent. The position of equilibrium is shifted by altering pH concentration of hydronium ions (H_3O^+). The equilibrium is manipulated to maintain a high concentration of hypochlorous acid and a low concentration of gaseous chlorine (Figure 4.2.12).

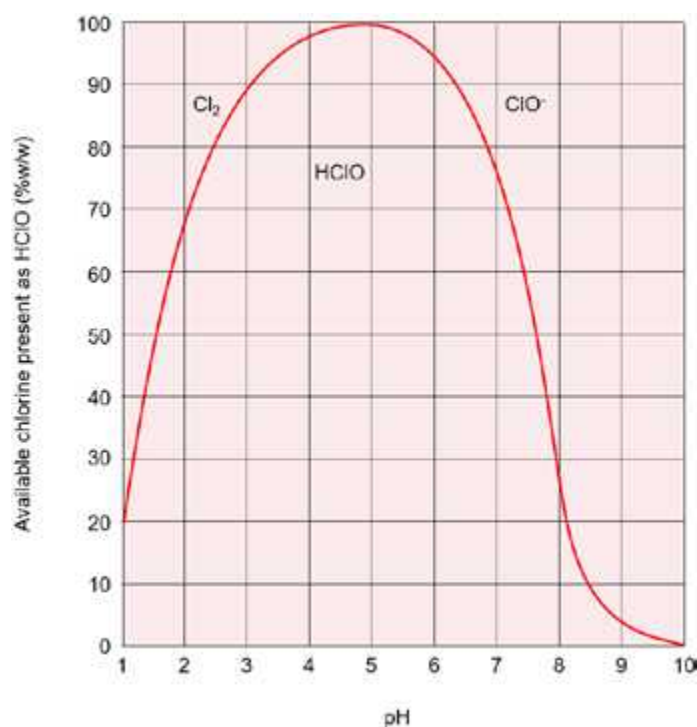
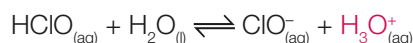


Figure 4.2.12: Effect of pH and available chlorine, hypochlorous acid and hypochlorite ions.

According to Le Châtelier's principle, the addition of a base such as sodium hydroxide (NaOH) will effectively reduce the concentration of hydronium ions through neutralisation. To counteract the change, the position of equilibrium will favour the forward reaction in response. While re-establishing the hydronium ion concentration, the concentration of hypochlorous acid will increase.

An equilibrium is also established between hypochlorous acid as a weak acid and hypochlorite ions.



Hypochlorites

Hypochlorite salts of calcium, lithium and sodium are commonly used for the disinfection of domestic water supplies and swimming pools. Hypochlorites are chlorine-containing compounds that react with water to form hypochlorous acid. They are chosen for some applications due to their ease of storage, transportation and handling as solid compounds or in alkaline solution, when compared to chlorine gas.



The equilibrium is once again sensitive to changes in pH. The pH is monitored and adjusted accordingly to maintain a high concentration of hypochlorous acid as the stronger oxidant.

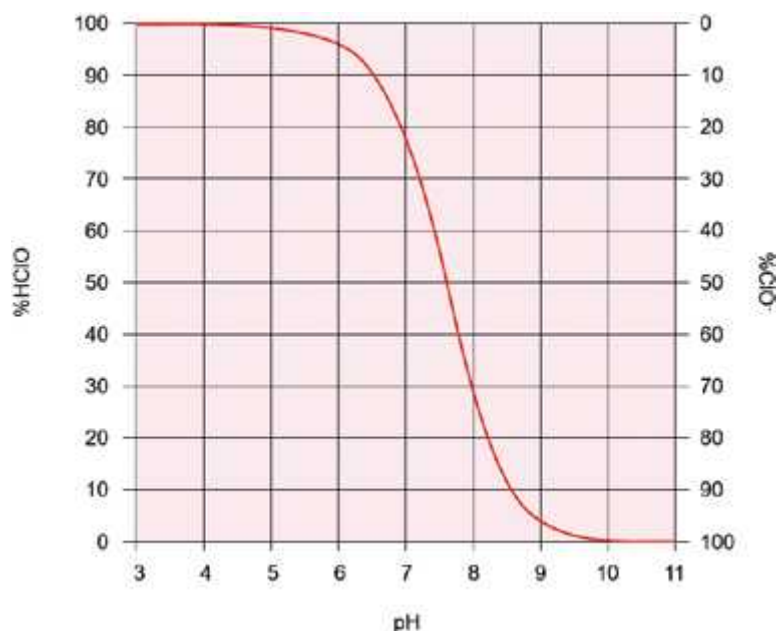
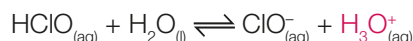


Figure 4.2.13: Effect of pH on hypochlorous acid and hypochlorite ions.

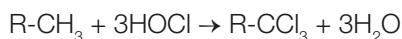
According to Le Châtelier's principle, the addition of a strong acid such as hydrochloric acid (HCl) will effectively reduce the concentration of hydroxide ions through neutralisation. To counteract the change, the position of equilibrium will favour the forward reaction in response. While re-establishing the hydroxide ion concentration, the concentration of hypochlorous acid will increase.

Once again, an equilibrium is established between hypochlorous acid and hypochlorite ions.



Chlorine, hypochlorous acid and hypochlorite ions are all oxidants. As oxidants, they have varied ability to kill **pathogens** (bacteria and other microbes) found in domestic water supplies. Hypochlorous acid and hypochlorite ions are able to enter the cell wall of bacteria and oxidise the cell contents. The oxidants break down lipids in the cell wall and oxidise enzymes and proteins inside the cell, denaturing them. This inhibits cellular reactions and the ability of the pathogen to reproduce. Hypochlorous acid is much more effective in this capacity, as, unlike hypochlorite ions, it does not carry a charge and is a stronger oxidant.

Modern water treatment must balance effective disinfection against the formation of potentially harmful by-products. When chlorine reacts with natural organic matter (NOM), it can form trihalomethanes (THMs) and haloacetic acids (HAAs):



These reactions are pH-dependent and increase with contact time, temperature, and precursor concentration.

Question

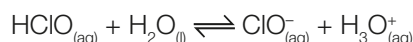
18. Chlorine and hypochlorite salts are added to outdoor swimming pools to make the water safe for use.

(a) Chlorine reacts with water to form hypochlorous acid.

(i) **Write** an equation for the reaction.

(2 marks) **KA4**

(ii) Hypochlorous acid is a weak acid, partially ionising in water according to the following equation.



The combined concentration of hypochlorous acid and hypochlorite ions is referred to as the free chlorine level.

(1) **State** the action of hypochlorous acid and hypochlorite ions during disinfection of water.

(1 mark) **KA1**

(2) **State** whether the concentration of hypochlorous acid would be increased at a high or low pH.

(1 mark) **KA1**

(iii) During disinfection, hypochlorous acid and hypochlorite ions enter the cell wall of bacteria degrading proteins.

(1) **Suggest** why hypochlorous acid is more effective than hypochlorite ions at killing pathogens.

(1 mark) **KA2**

(2) **State** and **explain** the effect of degrading the protein structure on the action of enzymes in the cell.

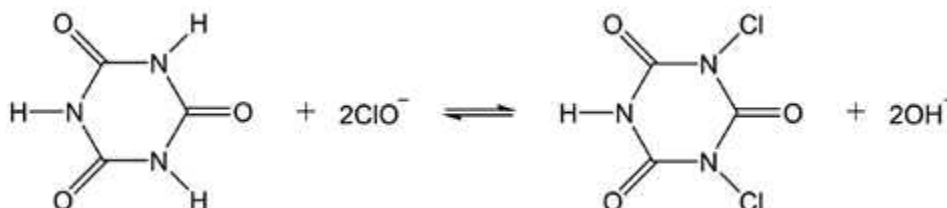
(3 marks) **KA2**

(b) Hypochlorite ions (ClO^{-}) undergo rapid decomposition by the absorption of ultraviolet light from solar radiation in photochemical reactions. In outdoor pools this poses a problem, leading to a loss of nearly 90% of the available chlorine.

(i) **State** the name given to reactions that absorb energy.

(1 mark) **KA1**

(ii) To stabilise levels of hypochlorite ions, cyanuric acid is added to swimming pools, thus establishing the equilibrium shown below.



- (1) **Explain** how the reaction above maintains the levels of hypochlorite ions in outdoor pools exposed to sunlight.

(4 marks) **IAE3**

- (2) Cyanuric acid molecules are also able to absorb ultraviolet radiation.

Suggest how this assists in the maintenance of the hypochlorite ion concentration in outdoor pools.

(2 marks) **KA2**

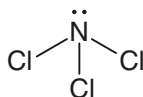
- (c) Studies have shown that nitrogen-containing compounds in urine and sweat introduced to swimming pools react with chlorine compounds to form a range of by-products including cyanogen chloride (CNCl) and trichloramine (NCl₃).
- (i) Studies have determined that public pools contain up to 3.0×10^4 ng of cyanogen in every litre of water. World Health Organization limits are 70 ppb. **Determine** whether this amount exceeds these limits.

(2 marks) **KA2**

- (ii) **Draw** the structure of a cyanogen chloride molecule.

(2 marks) **KA4**

- (iii) The trichloramine molecule is shown below:



- (1) **State** the shape of the trichloramine molecule.

(1 mark) **KA1**

- (2) Trichloramine is released from pools as a gas that gives a distinct “chlorine smell”.

Explain why trichloramine exists as a gas at room temperature.

(3 marks) **KA2**

- (iv) **State** the effect of the formation of these by-products on the availability of chlorine compounds for disinfection.

(1 mark) **IAE3**

- (d) Flocculants can be used to remove the cloudiness in pools. Aluminium sulfate ($\text{Al}_2(\text{SO}_4)_3$) is added as a granular flocculant.

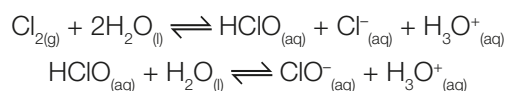
- (i) **Explain** how aluminium ions are able to coagulate and flocculate colloidal particles in a pool.

(3 marks) **KA1**

- (ii) **State** the effect of adding flocculant on the appearance of the pool water.

(1 mark) **KA2**

19. Swimming pool water is treated with chlorine gas which establishes the following equilibria:



- (a) The pH is maintained between 7.2-7.8 to optimise disinfection.

Using Le Châtelier’s principle, **explain** the effect of adding hydrochloric acid on the second equilibrium.

(3 marks) **KA1**

- (b) Cyanuric acid is added to outdoor pools to stabilise chlorine levels.

State what type of reaction occurs when hypochlorite ions decompose in sunlight.

(1 mark) **KA1**

4.3 Soil

Science understanding

Plants require nutrients, which they obtain from the soil.

Explain why plants need soil nutrients in soluble form.

© SACE 2025

Soil

Soil is a complex mixture of various components that work together to support plant growth and sustain ecosystems. Soil is composed of mineral particles, organic matter, water, and air.

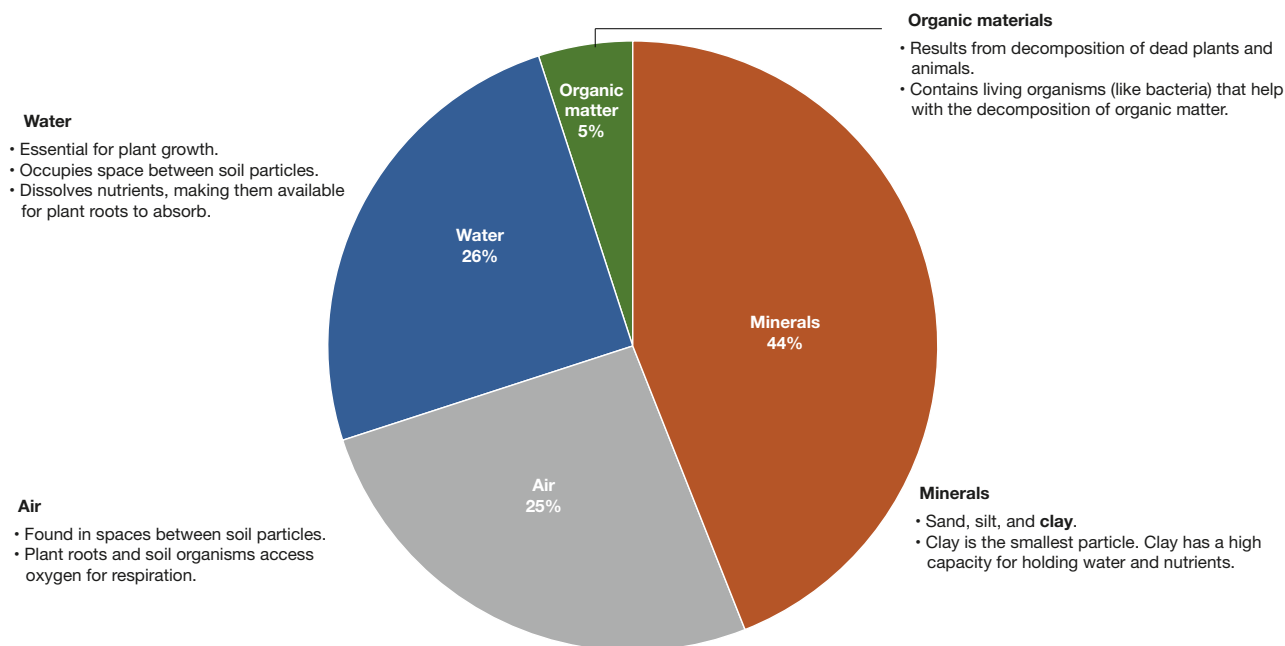


Figure 4.3.1: The composition of soils.

Plants require nutrients from soil to support their growth, development, reproduction, and overall health. These nutrients play essential roles in various physiological processes that are crucial for the plant's survival.

The major nutrients that plants require from the soil are **nitrogen, phosphorus, and potassium (NPK)**.

Nitrogen	- Promotes root development and leaf growth. - Found in amino acids. - Required for the formation of proteins, nucleic acids (DNA & RNA), and chlorophyll.
Phosphorus	- Helps transfer energy from sunlight to plants. - Helps stimulate early root and plant growth; hastens the maturity of plants. - Required for the formation of nucleic acids and energy-producing compounds (ATP & ADP).
Potassium	- Helps to increase disease resistance. - Helps to maintain and regulate water balance.

Soluble nutrients

Soluble nutrients, also known as 'available' nutrients, are in a form that plants can easily absorb through their roots. These nutrients are dissolved in water and move with soil moisture to reach root surfaces. In contrast, 'fixed' nutrients are bound within mineral or organic compounds, making them less accessible to plants until they undergo chemical changes that render them soluble. Understanding the balance between soluble and fixed nutrients allows farmers to optimise fertilisation practices, ensuring plants have consistent nutrient access without excessive runoff, which could harm nearby water bodies.

If a nutrient **is soluble**, it is called “**available**”.

If a nutrient **is not soluble**, it is called “**fixed**”.

For example, *available* phosphorus is in the form H_2PO_4^- , while *fixed* phosphorus is in the forms PO_4^{3-} and HPO_4^{2-} . Roots will only be able to absorb phosphorus in the form of the H_2PO_4^- ion. Similarly, *available* nitrogen is in the form of the nitrate ion, NO_3^- , so roots will only absorb nitrogen in this form.

Once the soluble nutrients are absorbed by roots, they are transported around the plant to the cells that need them. Without a balanced supply of essential nutrients, plants may experience stunted growth, poor yields, and increased susceptibility to diseases and other challenges.

Nutrients can be replenished naturally, or by the addition of fertilisers.

Science understanding

Nitrogen, phosphorus, and potassium are the major nutrients that plants require from the soil.

Explain how natural processes (including lightning, nitrogen-fixing bacteria, and decay) replenish soil nitrogen.

© SACE 2025

4

Nitrogen

Atmospheric nitrogen (N_2) is abundant but chemically inert, requiring conversion into reactive forms through **nitrogen fixation**. This process occurs naturally via nitrogen-fixing bacteria in legume roots, or through abiotic means like lightning, which provides the energy needed to break the strong triple covalent bond in N_2 molecules.



Industrially, nitrogen is fixed through the Haber process, producing ammonia-based fertilizers. While these fertilisers enhance crop yield, overuse can lead to nutrient runoff, causing eutrophication in aquatic systems. Sustainable nitrogen management, including crop rotation with legumes, is crucial to maintain soil health and prevent environmental degradation.

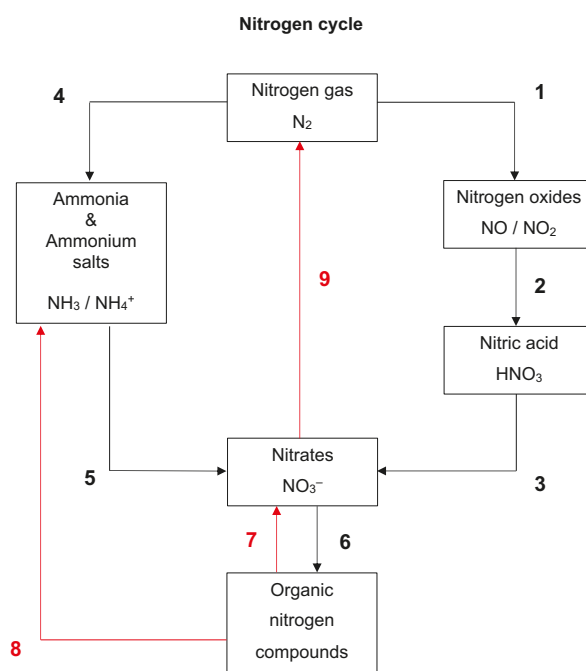
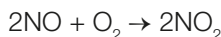
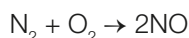


Figure 4.3.2: The nitrogen cycle

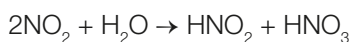
1: Nitrogen gas to nitrogen oxides ($N_2 \rightarrow NO / NO_2$)

High temperatures from natural and artificial sources break the strong covalent bonds in N_2 molecules. Natural sources include lightning, volcanoes, and forest fires. Artificial sources include industrial furnaces and internal combustion engines.

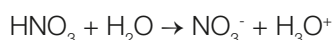
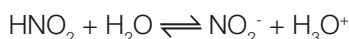
Nitrogen combines with oxygen to form nitric oxide, and this further reacts to form nitrogen dioxide.

**2: Nitrogen dioxide to nitric acid ($NO_2 \rightarrow HNO_3$)**

Nitrogen dioxide reacts with water in the atmosphere to form nitrous acid and nitric acid (acid rain).

**3: Nitric acid to nitrates ($HNO_3 \rightarrow NO_3^-$)**

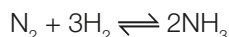
Nitrous acid partially ionises and nitric acid completely ionises, releasing soluble NO_2^- and NO_3^- . These nitrite and nitrate ions deposit into the soil when it rains.

**4: Nitrogen gas to ammonia / ammonium salts**Biological fixation

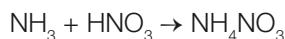
Over 90% of nitrogen fixation is due to nitrogen-fixing bacteria, which convert atmospheric nitrogen into ammonia and/or ammonium compounds. These bacteria are found in the nodules on the roots of legume plants.

Artificial fixation

Ammonia is synthesised from atmospheric nitrogen and hydrogen gas (derived from natural gas and other sources) under high pressure and temperature.



Ammonia can then be converted into ammonium salts, which are used in the production of fertilisers. These fertilisers provide plants with essential nitrogen.

**5: Ammonia / ammonium ions to nitrate ions**

Nitrifying bacteria in the soil convert ammonia (NH_3) and ammonium ions (NH_4^+) into nitrate ions (NO_3^-) in a process called *nitrification*.

6: Nitrates to organic nitrogen compounds

Plants are now able to absorb NO_3^- from the soil. These absorbed nitrates are used to make amino acids and other plant proteins. The uptake and incorporation of nitrogen into plant tissues is called *assimilation*. This nitrogen is now available to the rest of the food chain.

7: Organic nitrogen compounds to nitrates

Aerobic decomposition of plants and animals, and their waste products, puts nitrates back into the soil. Proteins are broken down by microorganisms in the presence of oxygen.

8: Organic nitrogen compounds to ammonia

Anaerobic decomposition of plants and animals, and their waste products, puts ammonia back into the soil. Proteins are broken down by microorganisms in the absence of oxygen.

9: Nitrates to nitrogen gas

Denitrifying bacteria in the soil convert nitrate ions into nitrogen gas in anaerobic conditions.

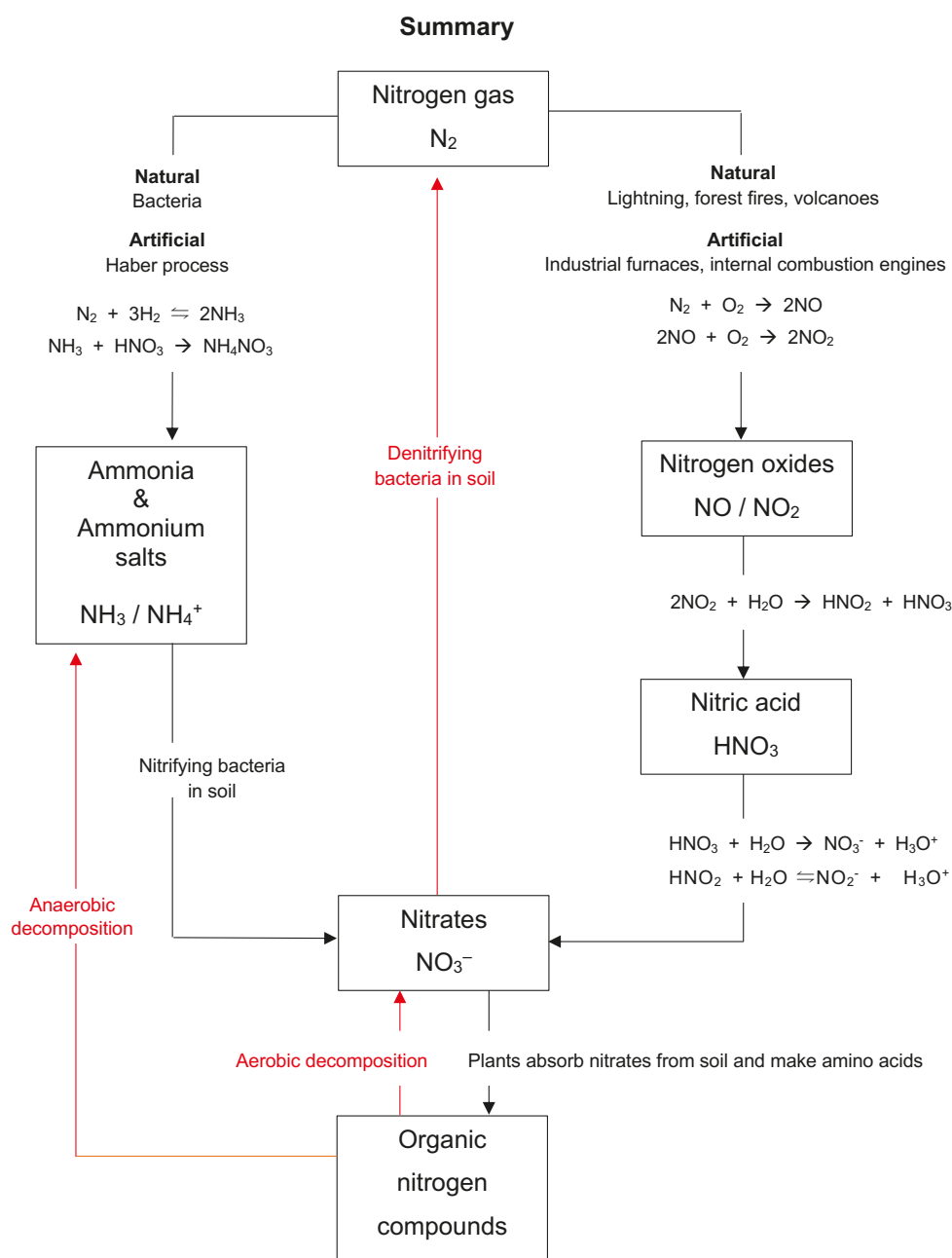


Figure 4.3.3: Summary of the nitrogen cycle

Question

20. Fixed nutrients in soil need to be converted to available nutrients so they can be absorbed by plants.

(a) **State** what is meant by the terms:

(i) “Fixed” nutrient

(1 mark) **KA4**

(ii) “Available” nutrient

(1 mark) **KA4**

(b) **State** the form in which plants are able to absorb the following:

(i) Nitrogen

(1 mark) **KA4**

(ii) Phosphorus

(1 mark) **KA4**

21. Nitrifying bacteria thrive in areas with high ammonia content, such as lakes and rivers with high inputs and outputs of sewage.

- (a) Two reactions that occur in the complex process of nitrification by bacteria are shown below. **Balance** these redox half-equations.



(2 marks) **KA4**

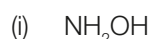


(2 marks) **KA4**

- (b) **State** and **explain** whether the half-equations in (i) and (ii) above are oxidation or reduction.

(4 marks) **KA1**

- (c) **Calculate** the oxidation states of nitrogen in the following species.



(1 mark) **KA4**



(1 mark) **KA4**



(1 mark) **KA4**



(1 mark) **KA4**

Science understanding

Soil productivity is related to the availability of plant nutrients, which need to be replenished naturally or by the addition of fertilisers.

- Explain why fertilisers are required to improve the productivity of some soils.

© SACE 2025

Fertilisers

Fertilisers are essential for maintaining and enhancing soil fertility, especially in cases where natural soil nutrient levels are insufficient for sustaining optimal plant growth and productivity.

Some key reasons why fertilisers are necessary:

- Continuous farming and harvesting can deplete essential nutrients like nitrogen (N), phosphorus (P), and potassium (K).
- Some soils are naturally deficient in essential nutrients (e.g. sandy soils).
- Increased crop demand means plants need more nutrients than the soil can provide.
- Soil pH may need correcting, so the addition of lime can improve the availability of other nutrients.
- A need to meet global food demands.

To achieve optimal plant growth, plants require both macronutrients and micronutrients. **Macronutrients** are required in larger quantities, while **micronutrients** are required in trace amounts.

Nitrogen, phosphorus, and potassium are primary macronutrients – they are required in the largest amounts by plants. Synthetic fertilisers need to contain water-soluble compounds of nitrogen and phosphorus to allow them to be absorbed by the plant roots along with water.

Nitrogen fertilisers

Nitrogen is taken up by plants in the form of the nitrate ion (NO_3^-). However, some nitrogen-containing fertilisers do not contain the nitrate ion. Fertilisers containing nitrogen include:

- Ammonia NH_3
- Urea NH_2CONH_2
- Ammonium nitrate NH_4NO_3
- Ammonium sulfate $(\text{NH}_4)_2\text{SO}_4$

If nitrogen is applied to the soil as ammonia, ammonium salts, or urea, they must be converted by soil bacteria into nitrate ions before absorption can occur.

Phosphate fertilisers

Phosphate is taken up by plants in the form of the H_2PO_4^- ion; hence, phosphate fertilisers contain the water-soluble dihydrogen phosphate ion. Fertilisers containing H_2PO_4^- include:

Triple superphosphate $\text{Ca}(\text{H}_2\text{PO}_4)_2$

Monoammonium dihydrogen phosphate $\text{NH}_4\text{H}_2\text{PO}_4$

Calcium, magnesium, and sulfur are also important nutrients for plants. These are considered secondary macronutrients – while they are still essential for plant growth, they are required in smaller amounts than primary macronutrients. Calcium is essential for root health and the development of leaves; magnesium is vital for photosynthesis as it is the central component of chlorophyll; and sulfur is a key element in amino acids found in plant proteins and plays a role in energy-producing processes within plants. Iron, boron, and zinc are examples of some micronutrients, and fertilisers will contain trace amounts of these elements.

Fertilisers play a crucial role in modern agriculture by replenishing essential nutrients in the soil, thereby supporting healthy plant growth and maximising crop yields. Synthetic fertilisers, in particular, are formulated to deliver specific nutrients – such as nitrogen, phosphorus, and potassium – that may be depleted from the soil due to continuous cultivation. In many agricultural systems, natural soil fertility is insufficient to meet the nutrient demands of high-yield crops, making fertilisers essential for sustaining productivity. By addressing nutrient deficiencies and imbalances, fertilizers contribute to more efficient land use and are instrumental in meeting the food requirements of a growing global population. However, the use of fertilisers must be carefully managed to prevent environmental issues such as nutrient runoff and soil degradation, underscoring the importance of sustainable fertilisation practices.

Science understanding

Excess nitrogen and phosphorus can be leached from soils and can cause eutrophication in water bodies.

Explain the process and consequences of eutrophication.

© SACE 2025

Eutrophication is the process where a freshwater ecosystem, such as a lake or a river, becomes enriched with excess nutrients, primarily **nitrates** and **phosphates**. These excess nutrients are leached from soils due to natural processes or human activities.

Natural contributions to eutrophication include:

Weathering	The weathering of rocks and the erosion of topsoil into water has dissolved nutrients that accumulate over time.

Human activities that contribute to eutrophication include:

Fertilisers	Fertilisers used in farming wash off from fields into nearby water bodies during rainfall, causing nutrient build up.
Detergents	Many detergents contain phosphates , which are highly soluble and can easily make their way into water systems.
Wastewater	Untreated or poorly treated sewage can release high levels of nutrients.
Urban runoff	Cities contribute through stormwater runoff that carries pollutants and nutrients into rivers and lakes.

Consequences of eutrophication

Excess nitrogen and phosphorus from agricultural runoff can lead to nutrient-rich environments in water bodies, causing rapid algal blooms. These blooms form dense layers that block sunlight, reducing photosynthesis for submerged aquatic plants and leading to oxygen depletion as these plants die and decompose.

The oxygen that was in the waterway is now being consumed by aerobic bacteria during the decay of plants, and less oxygen is being produced by photosynthesis; hence, the oxygen concentration reduces in the waterway. Due to the depletion of oxygen, other organisms in the waterway die. They decay under anaerobic conditions. Anaerobic bacterial decay produces toxic products, including hydrogen sulfide (H_2S), methane (CH_4), ammonia (NH_3), and phosphine (PH_3).

The depletion of oxygen can create "dead zones", and these dead zones can no longer support fish and other aquatic life, impacting biodiversity and local economies. Scientists and environmentalists advocate for buffer zones around water bodies and controlled fertiliser use to minimise nutrient pollution and its ecological impact.

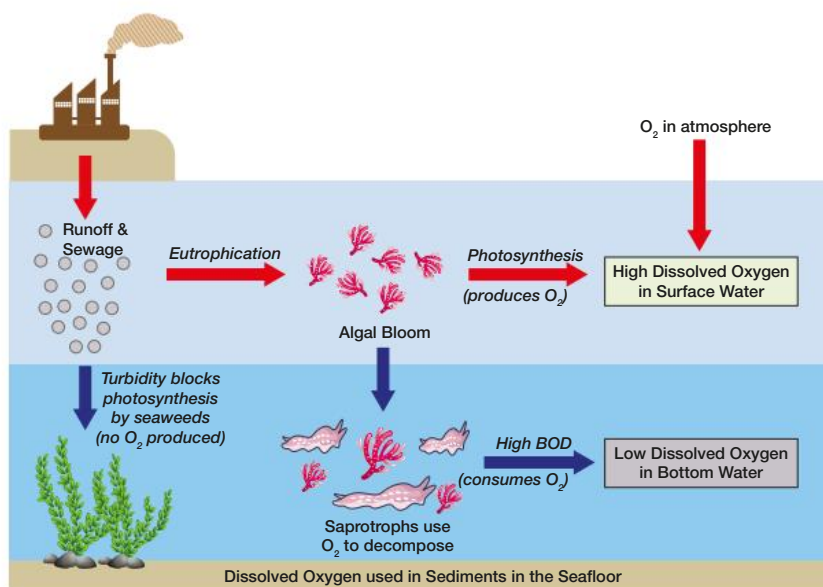


Figure 4.3.4: Eutrophication in a body of water



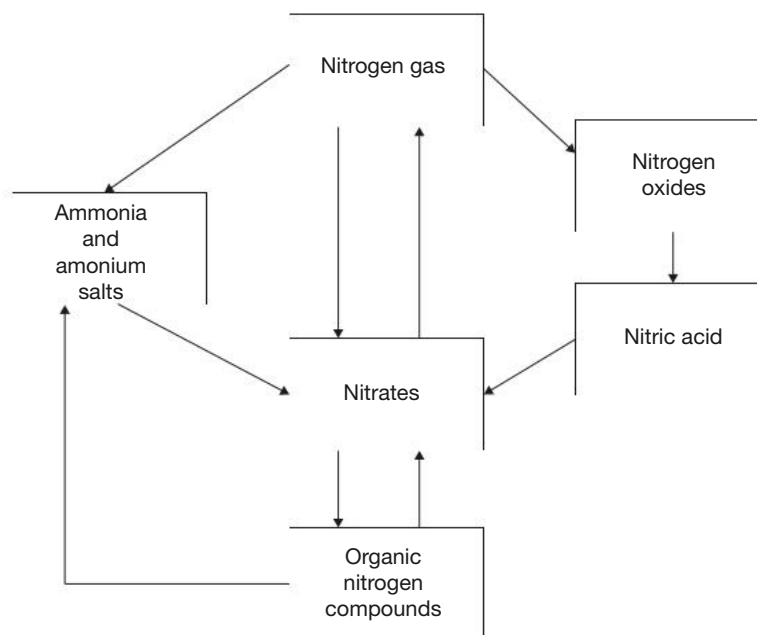
Science as a human endeavour

Innovations in Soil Fertility and Environmental Sustainability

As the demand for higher agricultural yields increases, scientists are developing innovative fertilisation methods that reduce environmental impacts. Technologies like controlled-release fertilisers and soil sensors allow farmers to provide precise nutrient levels, minimizing runoff and enhancing plant absorption. These advances reflect society's need for sustainable food production and showcase the ethical responsibility of science to protect natural resources.

Question

22. Nitrogen constitutes approximately 80% of the Earth's atmosphere. The diagram below shows how the nitrogen cycle operates in nature:



- (a) Under certain conditions, organic nitrogen compounds in decaying matter may be converted into ammonia, NH_3 .
- (i) **Name** one organic nitrogen compound that is found in living organisms.

(1 mark) **KA4**

- (ii) **State** the condition required for the conversion into ammonia of the organic nitrogen compounds in decaying matter.

(1 mark) **KA4**

- (iii) **Name** the carbon-containing compound that is produced under the same conditions as ammonia.

(1 mark) **KA4**

- (b) With the aid of *at least one* equation, **describe** how lightning is responsible for the formation of nitric acid in the atmosphere.

(4 marks) **(KA1, KA2, KA4)**

- (c) Some fertilisers contain nitrogen compounds. An excessive use of fertilisers leads to increased algal growth in rivers and lakes.

Explain why increased algal growth leads to a decreased amount of animal life in rivers and lakes.

4

(3 marks) **(KA1, KA4)**

23. The Murray–Darling basin is an interconnected system of waterways in Australia that is heavily relied upon for farming irrigation and domestic water supply.

- (a) Legume crops, such as beans, are often grown in annual rotation with cereal crops to increase the concentration of available nitrate ions in the soil.

- (i) **Explain** why continual cropping and harvesting of cereals would lead to decreased concentrations of available nutrients in the soil.

(2 marks) **KA1**

- (ii) **Explain** how legume crops lead to an increase in the concentration of available nitrate ions in soils.

(2 marks) **KA2**

- (iii) Some farmers will till (dig) the green legume plants into the soil at the end of their growth period, rather than harvesting the crop.

Explain how this practice will further increase the concentration of available nitrate ions in the soil.

(3 marks) **KA2**

- (b) Farming practices adjacent to creeks and rivers can lead to increased nutrient levels in waterways due to fertiliser run-off.

- (i) Ammonium nitrate is one commonly used fertiliser spread on the soil surface as solid granules.

1. **Write the formula** of ammonium nitrate.

(2 marks) **KA4**

2. **State** why ammonium nitrate fertiliser provides an available form of nitrogen to plants, even when added to the soil as a solid.

(1 marks) **KA1**

- (ii) Fertiliser run-off can lead to increased nutrient levels in waterways resulting in blooms of blue-green algae.

1. **State** the term used to describe increased nutrient levels in waterways.

(1 mark) **KA4**

2. Blue-green algae undergo photosynthesis. **Write an equation** for photosynthesis.

(2 marks) **KA4**

Science understanding

Silicon dioxide, silicates, and aluminosilicates are important components of rocks and soils.

- Write the formula of the anion given the formula of a silicate or aluminosilicate.

© SACE 2025

Silicon

Silicon is the second most abundant element in the Earth's crust. It is classified as a metalloid as it displays both metal and non-metal properties. A silicon atom is tetravalent; it is a Group IV element that can form four covalent bonds. Silicon never occurs as a free element in nature and is almost always combined with the most abundant element in the Earth's crust: oxygen.

Silicon-oxygen structures include **silicon dioxide**, **silicates**, and **aluminosilicates**, which make up 95% of the Earth's crustal rocks, soils, clays, and sands.

Silicon dioxide (silica)

Silicon dioxide, commonly known as silica, has the chemical formula SiO_2 and exists as a giant covalent network structure. In this structure, each silicon atom is covalently bonded to four oxygen atoms in a tetrahedral arrangement, creating a highly stable 3D crystal lattice. This bonding arrangement gives silica its characteristic properties, including a high melting point and hardness. Silica is the primary component of sand, where it exists as tiny crystals often mixed with various impurities. The strength and durability of silica make it a valuable material in construction, glassmaking, and various industrial applications.

Silicates

Silicate minerals are ionic compounds. Their anions contain only Si and O, and their cations include common elements in the Earth's crust such as Al^{3+} , Ca^{2+} , Mg^{2+} , Na^+ , and K^+ .

The basic geometric unit for all silicates is the SiO_4 tetrahedron – one silicon atom in the centre joined to four oxygen atoms.

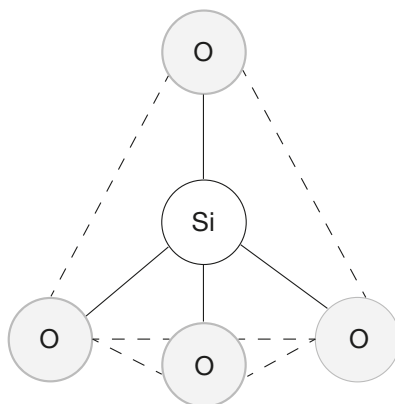


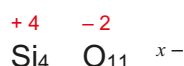
Figure 4.3.5: Diagram of the SiO_4 unit

It is important to note that the **oxidation state of silicon in all silicates is +4**.

Because the oxidation state of silicon in silicates is +4, it is possible to calculate the charge of mineral anions.

Worked example

Find the charge of $\text{Si}_4\text{O}_{11}^{x-}$.



$$\begin{aligned} 4(+4) + 11(-2) &= x \\ 16 - 22 &= x \\ -6 &= x \end{aligned}$$

$\therefore$ The charge is 6 – .

Silicate anions exhibit remarkable structural diversity, existing either as discrete units or as part of extensive arrays in complex mineral lattices. In discrete forms, silicate anions, such as SiO_4^{4-} , consist of isolated tetrahedra with each silicon atom bonded to four oxygen atoms. However, these tetrahedra can link together to form various structures, including chains, rings, sheets, and three-dimensional networks. Each structure type has distinct physical properties, making silicates versatile materials used in ceramics, electronics, and construction. The arrangement of silicate tetrahedra directly influences the mineral's characteristics, such as its hardness, flexibility, and melting point.

In discrete forms:

- The formula of the silicate anion is **given by the number of Si and O atoms in the structure**.
- The structure could be a single tetrahedron, two tetrahedra sharing a corner, three tetrahedra in a ring, or six tetrahedra in a ring.

In infinite arrays:

- The formula of the silicate anion is **derived from the repeating unit within the structure**.
- The structure could be a single chain, a double chain, a sheet, or a 3-D covalent network.

Single tetrahedron

The simplest silicates contain the SiO_4^{4-} anion, called the **silicate anion**. The Si:O ratio is 1:4, and there is no sharing of oxygen atoms.

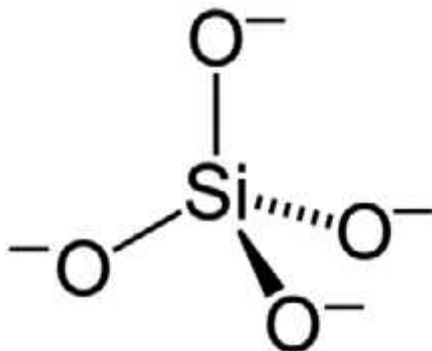


Figure 4.3.6: Diagram of the SiO_4^{4-} anion

Forsterite is a common mineral with the formula Mg_2SiO_4 , while rare mineral monticellite has the formula CaMgSiO_4 . Note how, as with all ionic compounds, the total positive charge of the metal cations in the mineral must balance the total negative charge of the silicate anions.

Worked example 1

Kirschsteinite, a silicate mineral, contains the anion SiO_4^{4-} and the cations Ca^{2+} and Fe^{2+} . The ratio of calcium to iron (II) is 1:1. Write the formula of the mineral kirschsteinite.

Cations	Anions
Ca^{2+} and Fe^{2+}	SiO_4^{4-}
Ratio 1:1	Overall charge: 4 –
Overall charge: 4 +	
Mineral formula: CaFeSiO_4	

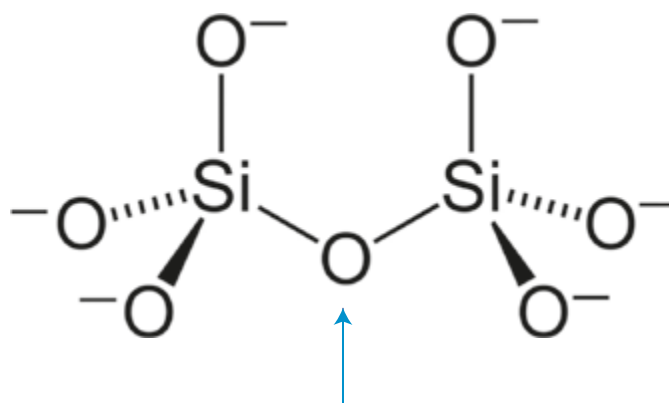
Question

24. The oldest recorded zircon mineral is 4.4 billion years old and was found in Australia. It contains the SiO_4^{4-} anion and the Zr^{2+} cation. **Write the formula** of the zircon mineral.

(2 marks) **KA4**

Two tetrahedra

Two tetrahedra can also link through one oxygen atom to form the $\text{Si}_2\text{O}_7^{6-}$ anion.



Notice how there is no charge on this oxygen atom - it is shared between two silicon atoms.

Figure 4.3.7: Diagram of the $\text{Si}_2\text{O}_7^{6-}$ ion

The Si:O ratio is 2:7, and there is sharing of one oxygen atom “corner”.

Question

25. Thortveitite is a rare mineral and the primary source of scandium. It contains the anion $\text{Si}_2\text{O}_7^{6-}$ and the cation Sc^{3+} . **Write the formula** for thortveitite.

(2 marks) **KA4**

Rings

Three tetrahedra or six tetrahedra can form closed rings, where each silicon atom shares two oxygen atoms. Cyclic structures contain either the $\text{Si}_3\text{O}_9^{6-}$ anion or the $\text{Si}_6\text{O}_{18}^{12-}$ anion.

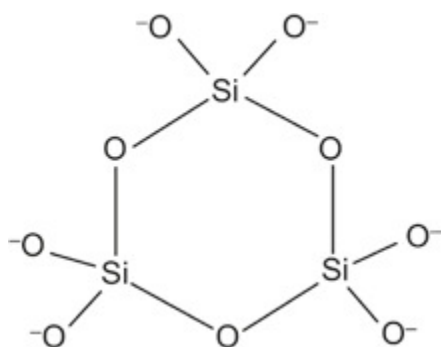


Figure 4.3.8: Diagram of the $\text{Si}_3\text{O}_9^{6-}$ anion

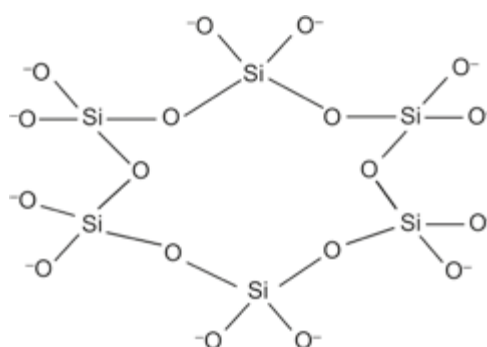


Figure 4.3.9: Diagram of the $\text{Si}_6\text{O}_{18}^{12-}$ anion

The Si:O ratios are 3:9 and 6:18, respectively.

Polymer chains of tetrahedra

Silicate anions can exist as single chains or double chains, where tetrahedra link by sharing two oxygen atoms each.

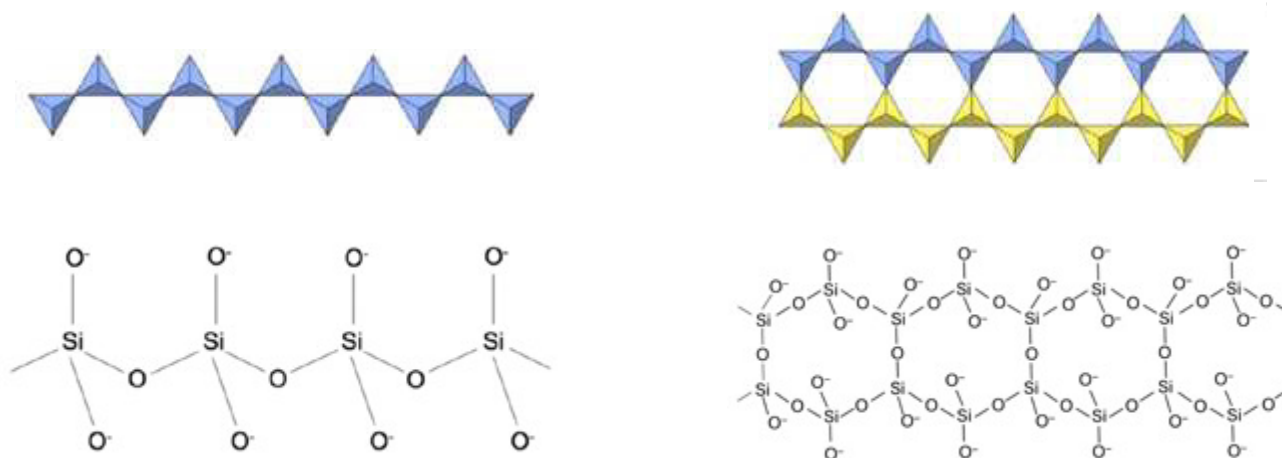


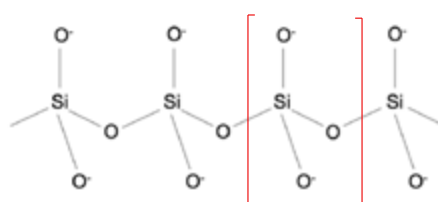
Figure 4.3.10: Diagram of silicate anions in a single chain and double chain.

These silicates tend to be fibrous in nature due to the strong bonds *within* the chain but weak attraction between the chains. An example of a silicate mineral with a fibrous structure is asbestos.

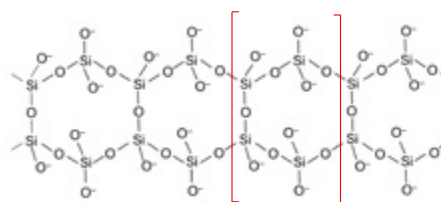


Figure 4.3.11: A close-up image of naturally occurring asbestos.

The formula of the silicate anion is derived from the repeating unit within the structure.



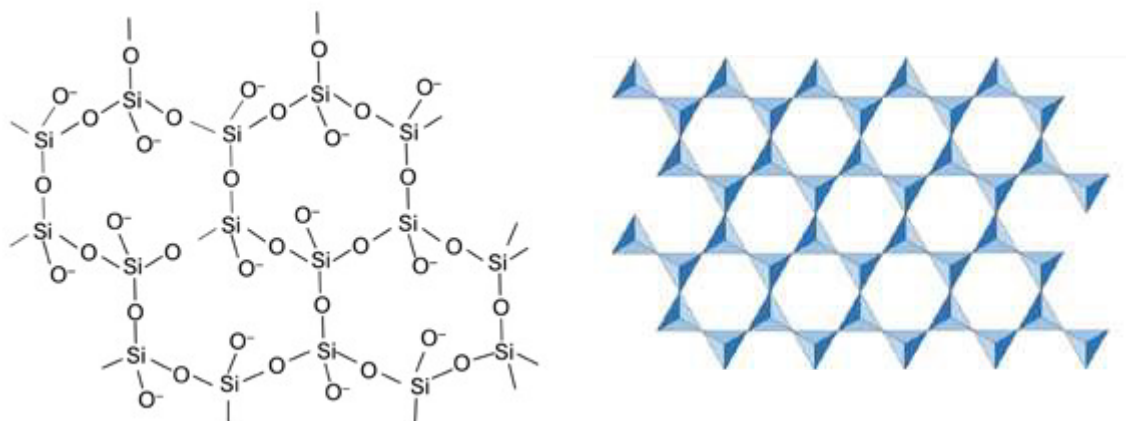
Single chain
Repeating unit: SiO_3^{2-}
Si:O ratio of 1:3



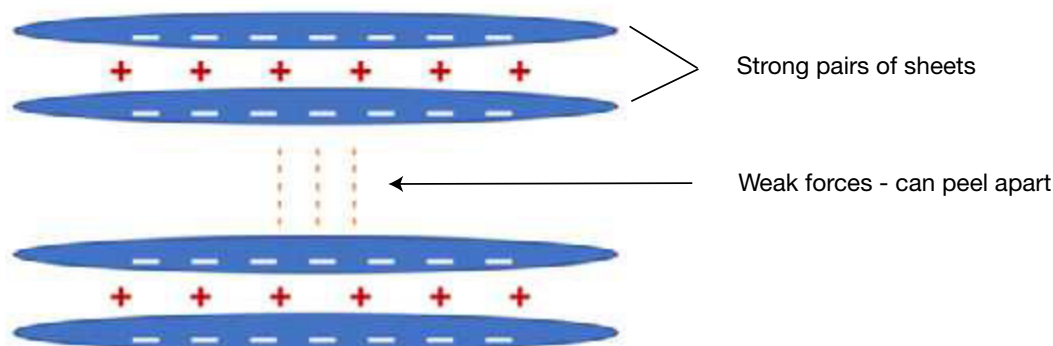
Double chain
Repeating unit: $\text{Si}_4\text{O}_{11}^{6-}$
Si:O ratio of 4:11

Sheets

In sheet silicates, tetrahedra share three of their four oxygen atoms with other tetrahedra.

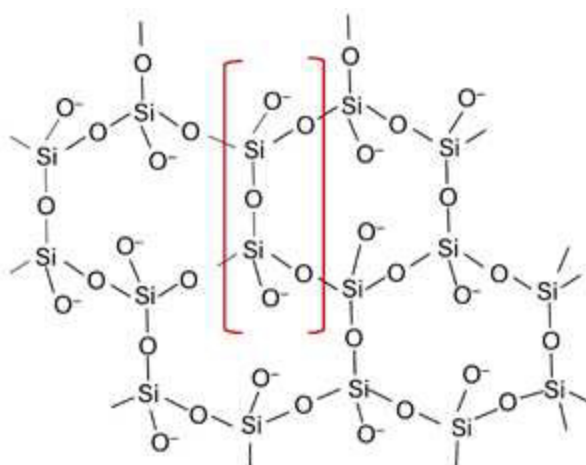


These silicates tend to be soft, flaky, and slippery. They can peel into layers, like layers of filo pastry sheets.



Extra understanding

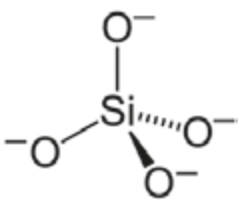
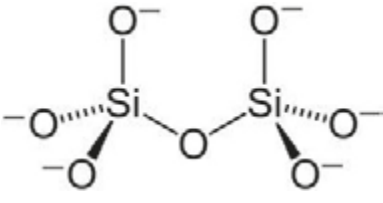
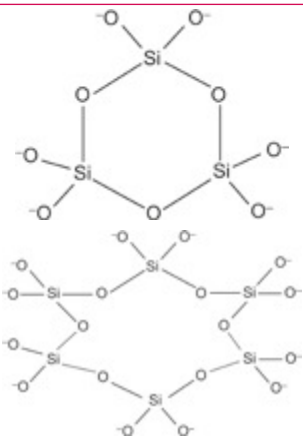
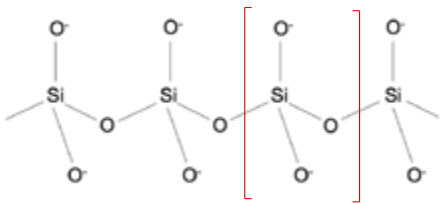
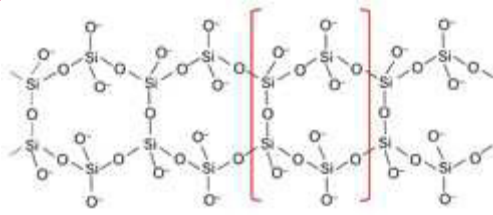
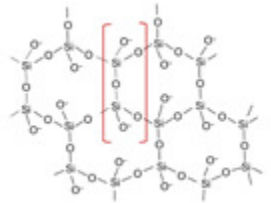
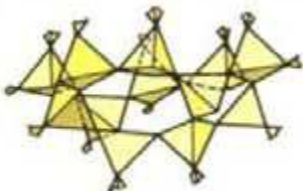
Sheet silicates are called phyllosilicates, from the Greek word “phyllo”, meaning “leaf”.



The repeating unit in silicate sheets is $\text{Si}_2\text{O}_5^{2-}$ or $\text{Si}_4\text{O}_{10}^{4-}$.

There are various ways that the silicate structural unit can be arranged in the many silicates, and this can lead to complex 3-D structures. Remember that a silicate is a large, negatively charged structure. Charged silicates will repel each other. The negative ions (anions) are balanced by cations.

Summary sheet

Structure	Structural formula	Anion
Single tetrahedron		SiO_4^{4-}
Two tetrahedra		$\text{Si}_2\text{O}_7^{6-}$
Rings		$\text{Si}_3\text{O}_9^{6-}$ $\text{Si}_6\text{O}_{18}^{12-}$
Structure	Structural formula & repeating unit	Anion
Single chain		SiO_3^{2-}
Double chain		$\text{Si}_4\text{O}_{11}^{6-}$
Sheets		$\text{Si}_2\text{O}_5^{2-}$ or $\text{Si}_4\text{O}_{10}^{4-}$
3-D network		SiO_2 (quartz)

Silicates are essential materials in numerous industries, including the manufacture of cement, ceramics, and glass. However, the extraction of silicate minerals through mining poses significant environmental challenges. Mining activities can lead to habitat destruction, soil erosion, and water pollution due to the release of sediments and chemicals. Additionally, the energy-intensive processing of silicate minerals contributes to greenhouse gas emissions. To mitigate these impacts, industries are exploring sustainable practices such as improved mine reclamation, reduced waste production, and alternative material sources. The development of eco-friendly mining practices is critical for balancing resource needs with environmental protection.



Science as a human endeavour

Balancing construction needs with environmental sustainability

The construction industry is one of the largest contributors to greenhouse gas emissions, largely due to the production of cement and concrete. Traditional concrete production relies heavily on calcium silicates from limestone, which must be heated at extremely high temperatures to produce cement. This process emits a significant amount of carbon dioxide (CO_2), contributing to global warming. Given the urgent need to reduce emissions, scientists and engineers are working to develop eco-friendly alternatives to traditional building materials. One innovative solution is "green concrete," which uses recycled materials, such as fly ash or slag, as partial replacements for cement. Other researchers are exploring bioconcrete, which incorporates bacteria to self-heal cracks, reducing the need for repairs and prolonging the material's lifespan.

These advancements in sustainable construction materials reflect the scientific community's response to the environmental challenges posed by urbanization and infrastructure development. Researchers and engineers face the responsibility of developing materials that meet societal demands for strong, durable structures while minimizing environmental impact. Innovations in silicate-based materials not only contribute to reducing emissions but also promote the conservation of natural resources by recycling industrial by-products.

4

Aluminosilicates

In a large number of silicate minerals, aluminium atoms are found in place of some of the silicon atoms. Aluminium atoms are **covalently bonded to oxygen atoms** within the silicate anion structure. Aluminium is a metalloid, so it behaves as a non-metal in the aluminosilicate framework. Aluminium is also a similar size to silicon.

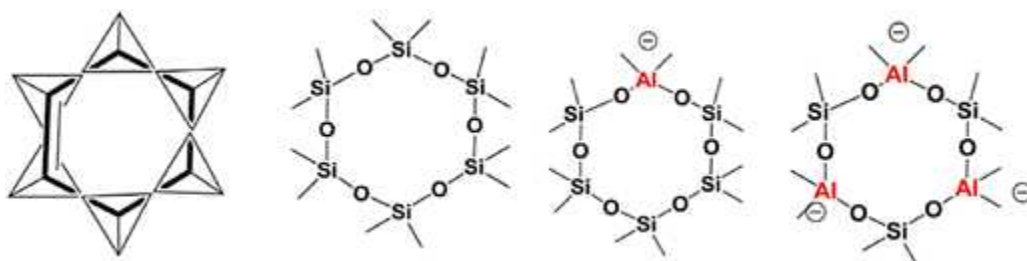


Figure 4.3.12: Diagram showing how aluminium atoms replace silicon atoms in aluminosilicates.

In the examples below, note how the formula and the overall charge of the silicate changes when Al replaces Si in the aluminosilicate framework.

Si_2O_4 : replacing one silicon atom with one aluminium atom gives AlSiO_4^-

Si_4O_8 : replacing one silicon atom with one aluminium atom gives $\text{AlSi}_3\text{O}_8^-$

Each time Al replaces Si, it results in having an extra negative charge on the frame.

Formulae of silicate and aluminosilicate anions

The charge of a silicate or aluminosilicate anion can be calculated using oxidation states. It is important to remember that, within a silicate, these species have the following oxidation states:

Element	Oxidation state within silicate
Si	+ 4
O	- 2
Al	+ 3

The charge of a silicate can also be calculated by the sum of the cations that are balancing the anion.

A few examples are shown below, using each method.

Example: Calculate the charge of the silicate anion in the mineral pyrope, $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$.

Using oxidation states

$$\begin{array}{rcl}
 & \textcolor{red}{+4} & \textcolor{red}{-2} \\
 & \text{Si} & \text{O}_4 \\
 \\
 & 1 \textcolor{red}{(+4)} & + & 4 \textcolor{red}{(-2)} \\
 = & 4 & - & 8 \\
 = & -4 & &
 \end{array}$$

$\therefore$ The charge on the silicate is 4 –
 SiO_4^{4-}

Balancing charges. Call the unknown silicate charge “x–”

$$\begin{array}{rclcl}
 \text{Mg}_3 & & \text{Al}_2 & & (\text{SiO}_4)_3 \\
 \textcolor{blue}{2+} & & \textcolor{blue}{3+} & & \textcolor{blue}{x-} \\
 \\
 3 \textcolor{blue}{(2+)} & + & 2 \textcolor{blue}{(3+)} & = & 3 \textcolor{blue}{(x-)} \\
 6 & + & 6 & = & -3 \textcolor{blue}{x} \\
 & & 12 & = & -3 \textcolor{blue}{x} \\
 & & -4 & = & \textcolor{blue}{x}
 \end{array}$$

$\therefore$ The charge on the silicate is 4 –
 SiO_4^{4-}

Example 2: Calculate the charge of the silicate anion in the mineral lawsonite, $\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$.

Using oxidation states

$$\begin{array}{rcl}
 & \textcolor{red}{+4} & \textcolor{red}{-2} \\
 & \text{Si}_2 & \text{O}_7 \\
 \\
 & 2 \textcolor{red}{(+4)} & + & 7 \textcolor{red}{(-2)} \\
 = & 8 & - & 14 \\
 = & -6 & &
 \end{array}$$

$\therefore$ The charge on the silicate is 6 –
 $\text{Si}_2\text{O}_7^{6-}$

Balancing charges. Call the unknown silicate charge “x–”

$$\begin{array}{rclclcl}
 \text{Ca} & \text{Al}_2 & (\text{OH})_2 & \text{H}_2\text{O} & \text{Si}_2\text{O}_7 & \\
 \textcolor{blue}{2+} & \textcolor{blue}{3+} & \textcolor{blue}{1-} & 0 & \textcolor{blue}{x-} & \\
 \\
 1 \textcolor{blue}{(2+)} & + & 2 \textcolor{blue}{(3+)} & + & 2 \textcolor{blue}{(1-)} & + & 0 & = & \textcolor{blue}{x-} \\
 2 & + & 6 & - & 2 & + & 0 & = & \textcolor{blue}{x-} \\
 & & & & 6 & = & \textcolor{blue}{x-} \\
 & & & & -6 & = & \textcolor{blue}{x}
 \end{array}$$

$\therefore$ The charge on the silicate is 6 –
 $\text{Si}_2\text{O}_7^{6-}$

Silicate or aluminosilicate?

Note that the lawsonite mineral in the example above – $\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$ – is not an aluminosilicate, as the aluminium is present as an aluminium ion, not aluminium covalently bonded within the silicate framework.

Examples of silicate minerals	Examples of aluminosilicate minerals
Tremolite $\text{Ca}_2\text{Mg}_5(\text{Si}_4\text{O}_{11})_2(\text{OH})_2$	Sodalite $\text{Na}_8(\text{AlSiO}_4)_6\text{Cl}_2$
Lawsonite $\text{CaAl}_2\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$	Leucite KAlSi_2O_6

It is also possible to determine the **percentage of silicon atoms that were replaced by aluminium atoms** in an aluminosilicate. Using this aluminosilicate as an example:



Aluminium atoms replace silicon atoms in aluminosilicates

- There are 2 Al and 3 Si in the example above
- Therefore, there were originally 5 Si, replaced by 2 Al
- 2 out of 5 Si atoms were replaced
- 40% of Si atoms were replaced

Question

26. **Find** the charge of $\text{Al}_2\text{Si}_4\text{O}_{12}^{x-}$

(2 marks) **KA4**

27. The mineral pyrope is the only member of the garnet group that always displays a red colour in natural samples. It has the formula $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_x$. Find the value of x.

(2 marks) **KA4**

28. What percentage of silicon atoms were replaced in AlSiO_4^- ?

(2 marks) **KA4**

Science understanding

Cations adsorbed on the surface of soil silicates and aluminosilicates are in equilibrium, and can be exchanged, with the cations in soil water, which are available as sources of plant nutrients.

© SACE 2025

Clays

Clays are one of the most important constituents of soils. They form through **weathering**, a process that involves the physical and chemical breakdown of rocks that contain silicates. They are then transported and deposited, or remain in place, forming various types of clay minerals depending on local conditions. This process typically occurs over long periods.

While clay particles are small, their molecular structure is complex. Here are some essential features of clays:

- Clays are composed of **silicate or aluminosilicate minerals** with **sheet structures** (phyllosilicates), stacked together to form layers.
- Water and cations can be stored between these layers.
- The surfaces of the sheets are negatively charged.
- Cations are adsorbed onto the surfaces to balance the charge.

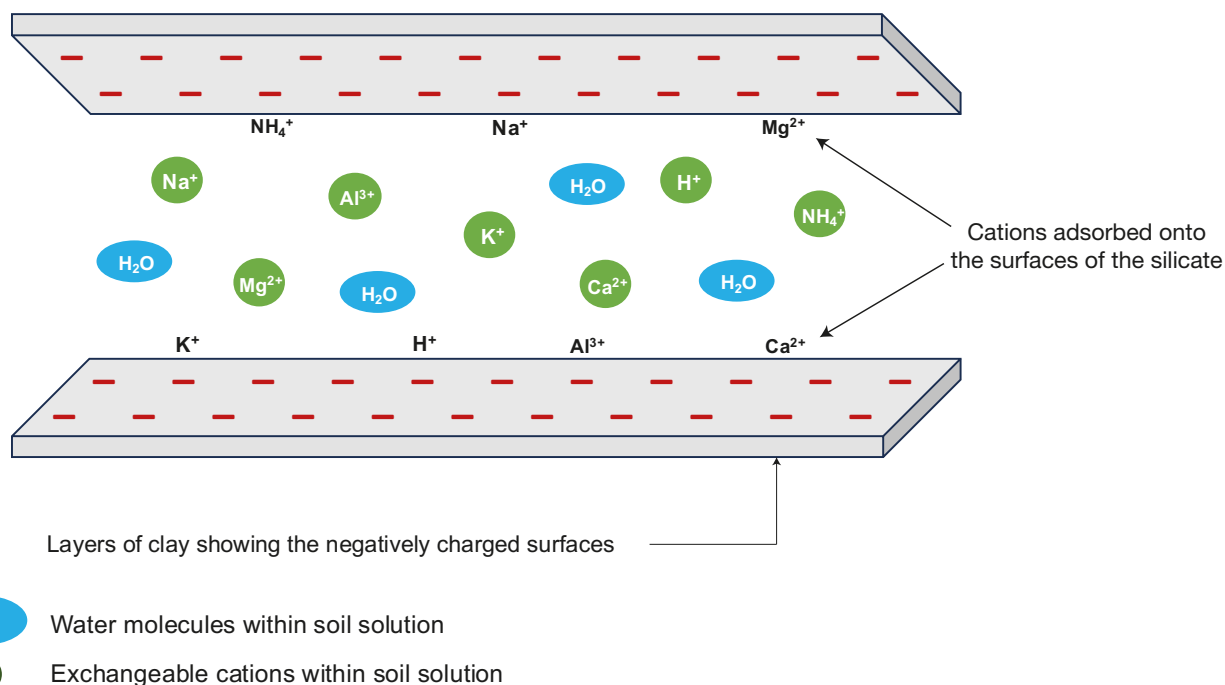


Figure 4.3.13: Close-up representation of negatively charged clay sheets with adsorbed cations and aqueous cations.

Clays are important for soil fertility as they adsorb nutrients and release these nutrients into the soil solution for plant uptake.

Cation exchange in soils

As silicate minerals have surfaces that are negatively charged, cations are adsorbed onto these surfaces to balance the charge. The soil water (soil solution) also contains cations. Figure 4.3.14 shows a closer look at what is occurring within the silicate structure.

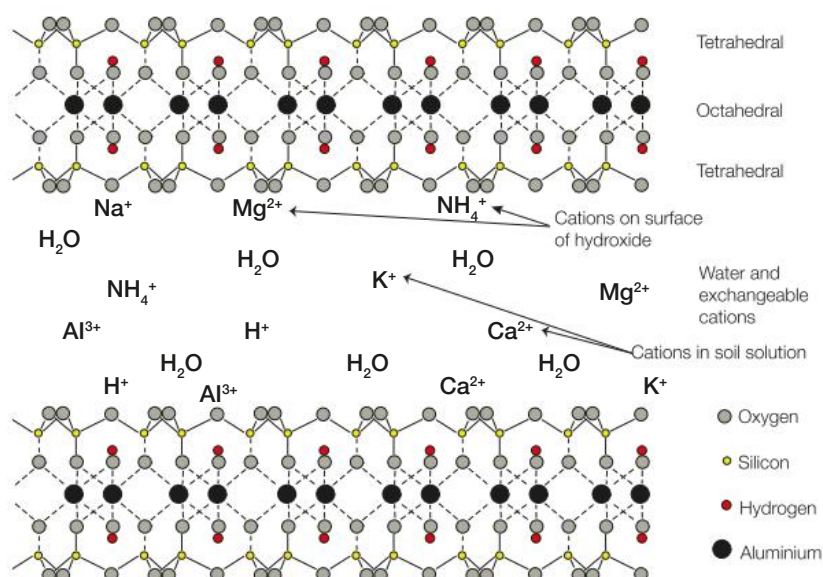


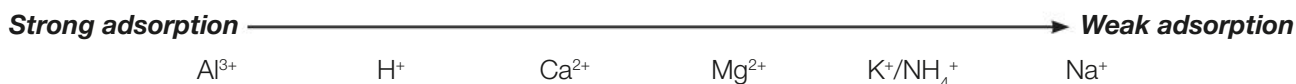
Figure 4.3.14: Layers of montmorillonite clay

Notice how there are cations in a few places. They can be:

- adsorbed onto the surface of the soil, balancing the charge.
- in soil water, available as sources of plant nutrients.
- part of the covalent silicate structure and trapped within the structure.

Cation exchange occurs between the **soil surface** and the **soil water** (*soil solution*), establishing an equilibrium. Cations that form part of the covalent silicate structure and cations that are trapped within the structure are *unable to be exchanged*.

Exchangeable ions are held weakly on the clay surface due to electrostatic attraction. This electrostatic attraction is determined by the charge density and size of the cation, and some cations are adsorbed more strongly than others.



The capacity of a soil to hold exchangeable cations is called its “cation exchange capacity” (CEC) and is an important indicator of soil fertility.

Different cations can be exchanged at any time. For example, K^{+} ions that are weakly adsorbed onto the surface of the clay can be exchanged with Ca^{2+} ions in soil water in a reversible equilibrium reaction. This is shown in the diagram and the equation below.

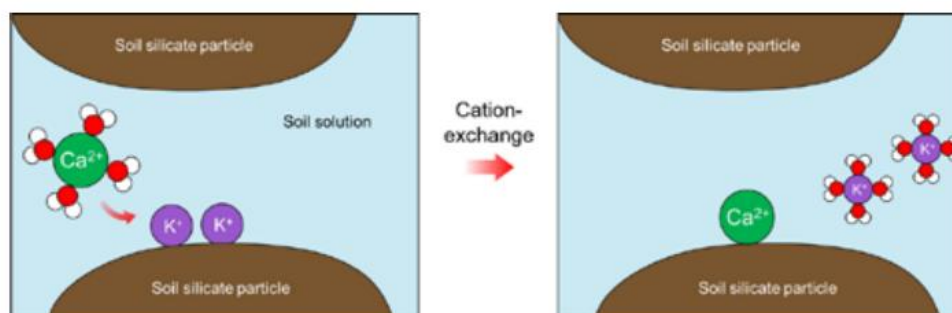
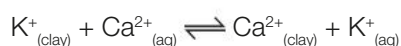


Figure 4.3.15: Layers of soil particles in clays



Note: the cations that are adsorbed onto the soil are given the state symbol (*clay*), while the cations that are in the soil water are given the state symbol (*aq*).

It is important to remember that cations in the soil water (soil solution) are doing several things. They are:

- Continuously being exchanged with cations on clay.
- Taken up by plants.
- Leached to ground and surface waters.



Science as a human endeavour

Enhancing Soil Fertility for Sustainable Agriculture

Silicates are not only valuable in construction and industry but also play a crucial role in agriculture and soil health. Soil structure and fertility are significantly influenced by minerals, especially aluminosilicates, which contribute to nutrient retention and cation exchange capacity. Cation exchange allows soil to hold essential nutrients like potassium, calcium, and magnesium, making them available for plant roots. In nutrient-poor or degraded soils, natural silicate minerals can be added as soil amendments to improve structure and boost fertility. For instance, research into using silicate rock dust as a soil amendment shows promise in enhancing plant growth and reducing the need for chemical fertilisers.

The application of silicate minerals in agriculture highlights the potential of leveraging natural processes to improve food security in a sustainable way. By using silicates to enhance soil quality, scientists are helping to develop farming practices that rely less on synthetic fertilisers, which can contribute to environmental problems such as water pollution from runoff. This approach also supports soil health over the long term, promoting resilience to erosion and drought. However, the implementation of silicate amendments requires a careful understanding of local soil composition and environmental factors to avoid unintended ecological impacts.

Cations: Sources of plant nutrients

Due to the extremely fine particle size of clays (less than 2µm), they have extensive surface area and are able to hold a large number of cations. These cations provide the “trace element” nutrients required by plants. The more cations available, the more fertile the soil.

During plant growth, there is a continuous movement of ions between the surface of the soil and soil water. An example using calcium and magnesium ions is shown below.

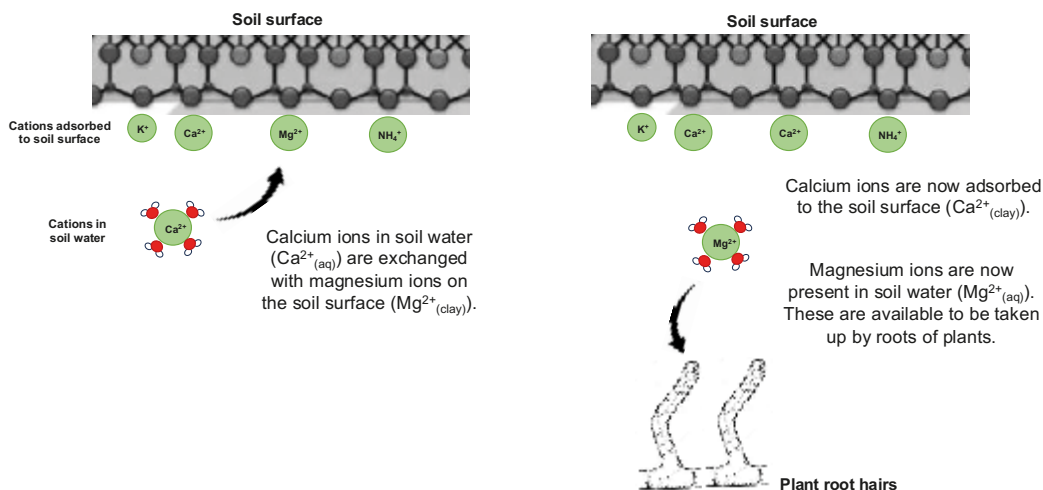
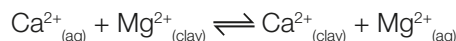
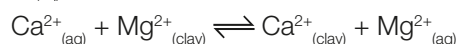


Figure 4.3.16: Close-up representation of negatively-charged clay sheets with adsorbed cations and aqueous cations.

This process can be represented by the following equilibrium equation:



When plant root hairs take up the $Mg^{2+}_{(aq)}$, they are removing it from the soil water.



↓
Taken up by plants.
Removed from soil water.

This causes a stress on the equilibrium system. According to Le Chatelier's principle, the system will counteract the change by shifting the equilibrium to favour the formation of products, to replace the $Mg^{2+}_{(aq)}$ lost. Consequently, more ions are exchanged from the clay surface and enter the soil water.

Science understanding

Soil silicates and aluminosilicates are able to adsorb H^+ and release cations.

- Explain how cations on the surface of soil silicates and aluminosilicates become available to plants.

© SACE 2025

Plants produce H^+ cations. These H^+ cations can be exchanged for the cations adsorbed onto the soil surface.

As shown in the diagram below, the soil surface adsorbs the H^+ cations and releases cations, providing the nutrients required by the plant.

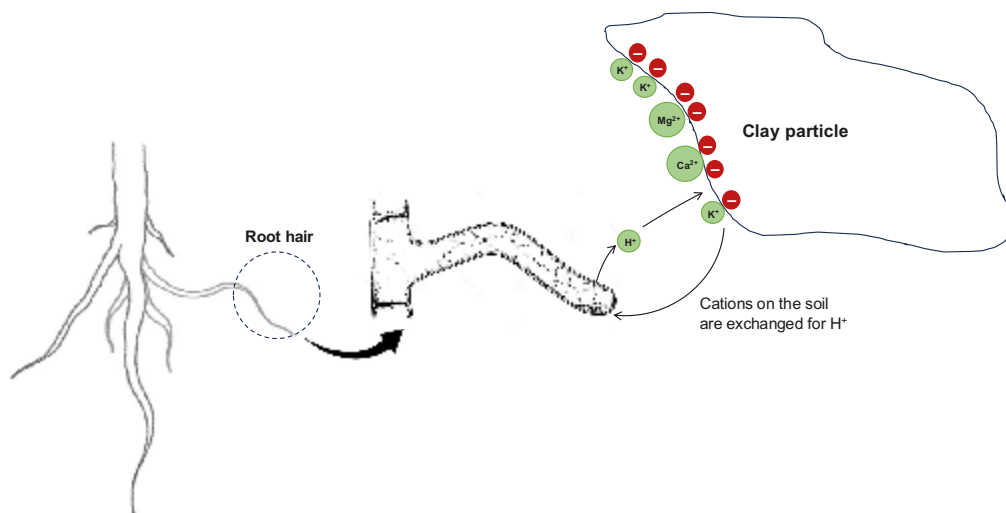
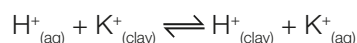


Figure 4.3.17: Diagram showing the cation exchange between hydrogen ions from the plant and adsorbed cations on the soil surface.

This cation exchange is in an equilibrium system, so the uptake of $K^+_{(aq)}$ by plants impacts the equilibrium.



Root hairs of plants are adapted for absorption because they are long, providing a large surface area, and they have a thin cell wall.

Science understanding

Nutrient cations on the surface of soil silicates and aluminosilicates are replaced if the concentrations of H^+ or Na^+ in soil water become too high.

Explain how acidic or saline conditions (i.e. high concentrations of H^+ or Na^+) deplete the nutrient value of soils.

© SACE 2025

Soil acidity

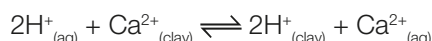
Soil pH affects both the availability of nutrients for plants and how these nutrients interact with one another. Soil acidity is present when the pH of soil drops below 7. This means that there is an increased concentration of H^+ in these soils.

If soils have a pH that is too low or too high, many nutrients become less available, and some elements become toxic to plants. A pH range between 5.0 and 7 is ideal for most plants as it strikes a balance where most nutrients are available without the risk of toxicity from some elements.

Several factors contribute to soil acidity. Some natural processes and human activities that increase the concentration of H^+ in soils are listed in the following table.

Natural processes	Human activities
- Weathering of rocks - Partial ionisation of carbonic acid present in rain: $\text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^-$ - Cation exchange at the root tips of plants	- Use of ammonium-based fertilisers in agriculture - Accumulation of atmospheric pollutants that lead to the formation of acid rain: $2\text{NO}_2 + \text{H}_2\text{O} \rightarrow \text{HNO}_2 + \text{HNO}_3$ $\text{SO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_3$ $\text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4$

When there is an increase in concentration of hydrogen ions in soil water, the $\text{H}^+_{(\text{aq})}$ ions undergo cation exchange with the nutrient cations on the surface of the soil ($\text{Ca}^{2+}_{(\text{clay})}$, $\text{Mg}^{2+}_{(\text{clay})}$, $\text{K}^+_{(\text{clay})}$, etc). Consequently, H^+ is adsorbed to the surface of the soil and the nutrient value of soils is depleted, while other cations are released into the soil water. The example below shows how Ca^{2+} is mobilised from the soil.



Adding lime (CaO) to soil will increase the pH and replace the lost Ca^{2+} .

Acid rain & aluminium

At pH values below 5.0, aluminium becomes soluble in toxic levels for plants. For regions that experience high acid rain, there are several negative side effects for plant and aquatic life.

The diagram below shows cation exchange between hydrogen ions from acid rain and aluminium ions on the soil surface.

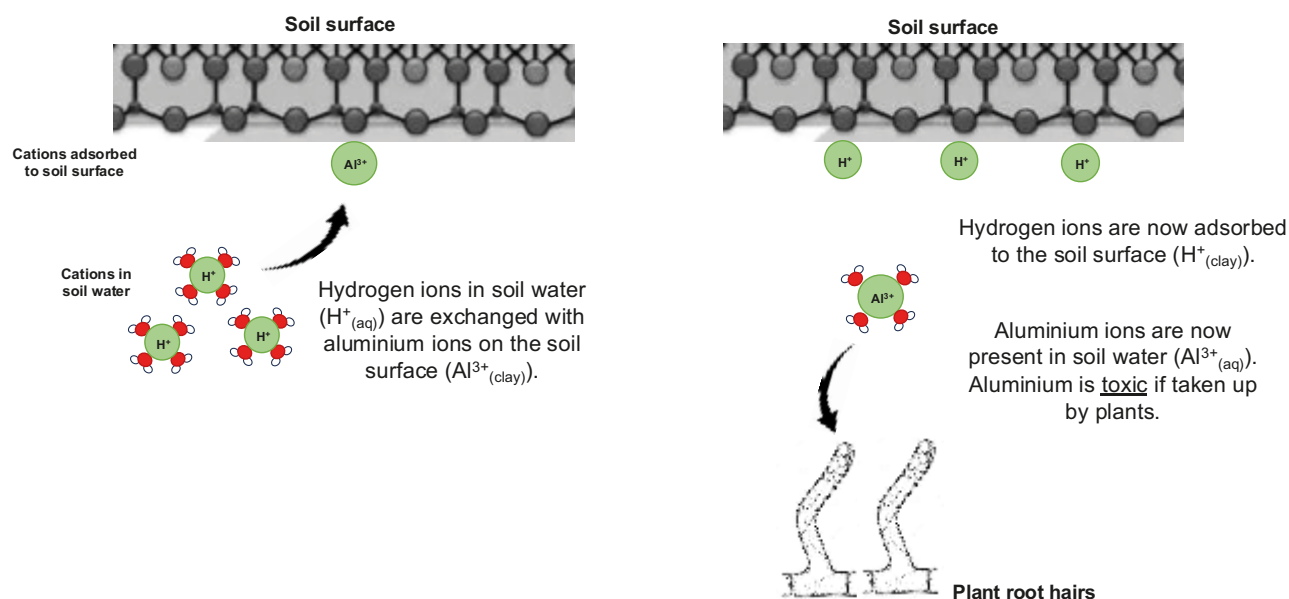
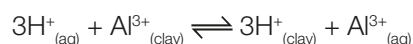


Figure 4.3.18: Diagram showing the cation exchange between hydrogen ions from acid rain and aluminium ions on the soil surface.

This process can be represented by the following equilibrium equation:



In regions of high acid rain, the concentration of $\text{H}^+_{(\text{aq})}$ increases. According to Le Chatelier's principle, this causes a stress on the system, and equilibrium moves to the formation of products. Consequently, the concentration of hydrogen ions on the surface of the soil ($\text{H}^+_{(\text{clay})}$) increases and the soil becomes acidic. Furthermore, aluminium ions are now soluble and, in this very acidic environment, toxic to plants. Additionally, $\text{Al}^{3+}_{(\text{aq})}$ can be leached (washed away) from the soil with rain and/or excess watering, entering lakes and rivers, and causing the flocculation of clay particles. Aluminium is also toxic to gill-breathing animals such as fish and invertebrates.

Soil sodicity & salinity

Sodicity refers to the amount of **sodium** held in a soil – the sodium cations that are **adsorbed** onto the **soil surface**. When sodium makes up more than 5% of all cations adsorbed to the surface of the soil, structural problems begin to occur, and the soil is said to be sodic.

Salinity is a measure of the concentration of **soluble salts** contained in the soil – those that are free to move in the **soil water** and are taken up by plants. These can be cations and anions.

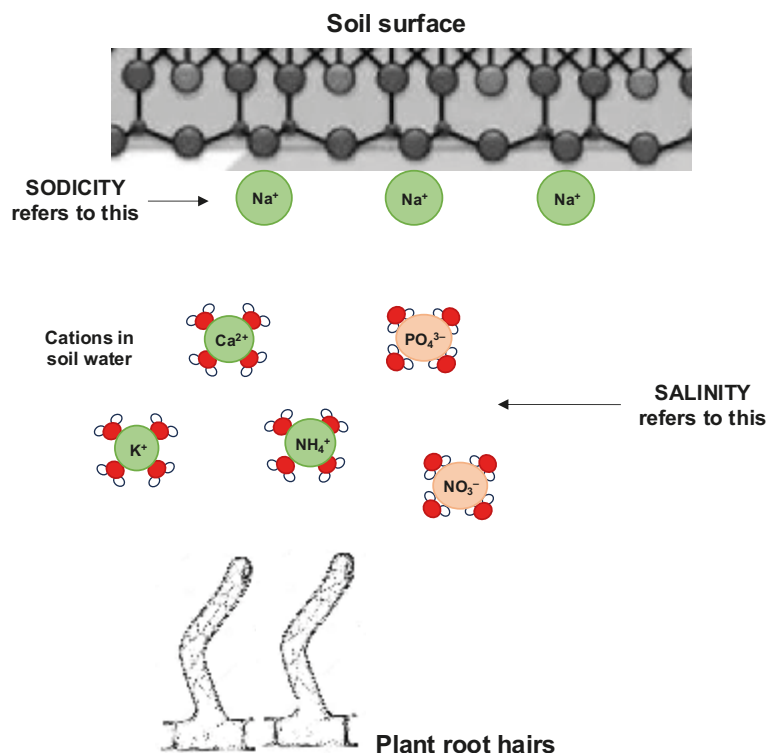


Figure 4.3.19: Sodium ions on the soil surface and soluble ions in soil water.

Because cations in soil water will undergo cation exchange with those on the soil surface, saline water with a high proportion of $\text{Na}^+_{(\text{aq})}$ will exchange with cations on the clay, hence increasing the amount of $\text{Na}^+_{(\text{clay})}$ adsorbed to the soil surface. This is shown in the example below.

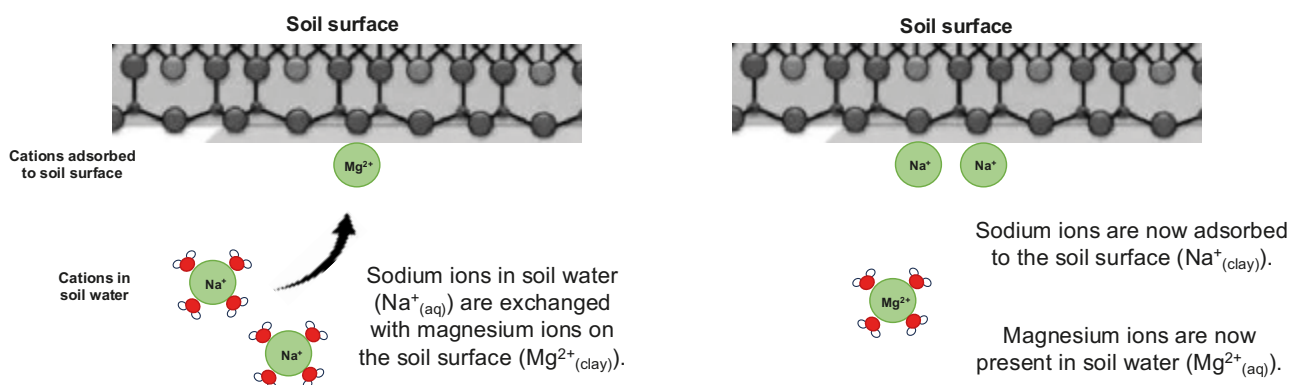
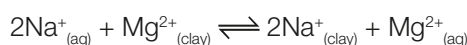


Figure 4.3.20: Sodium ions in soil water (saline water) undergoing cation exchange with cations on the soil surface.

Mg^{2+} is removed from the surface of the soil and is now in soil water. Na^+ is adsorbed to the surface of the soil, forming sodic soil.



The increased concentration of sodium ions in soil water ($\text{Na}^+_{(\text{aq})}$) shifts the equilibrium to the right. Hence, more sodium ions adsorb to the surface of the soil ($\text{Na}^+_{(\text{clay})}$), causing the soil to be sodic.

Consequences

Sodicity disrupts soil formation. Clay particles disperse, making the soil compact, dense, and hard. Consequently:

- Water drainage is reduced.
- Water cannot penetrate through the soil, causing waterlogging or drought-like conditions at root level.
- Lack of aeration makes it difficult for roots to access water, oxygen, and nutrients.
- Excess sodium can displace other essential plant nutrients like K^+ , Mg^{2+} , and Ca^{2+} .

Adding gypsum – $CaSO_4$ – is a solution to soil sodicity. When gypsum is added to soil or water, the Ca^{2+} dissociates and the concentration of calcium in the water is increased. The calcium ions undergo cation exchange with the sodium ions that are causing the soil to be sodic.

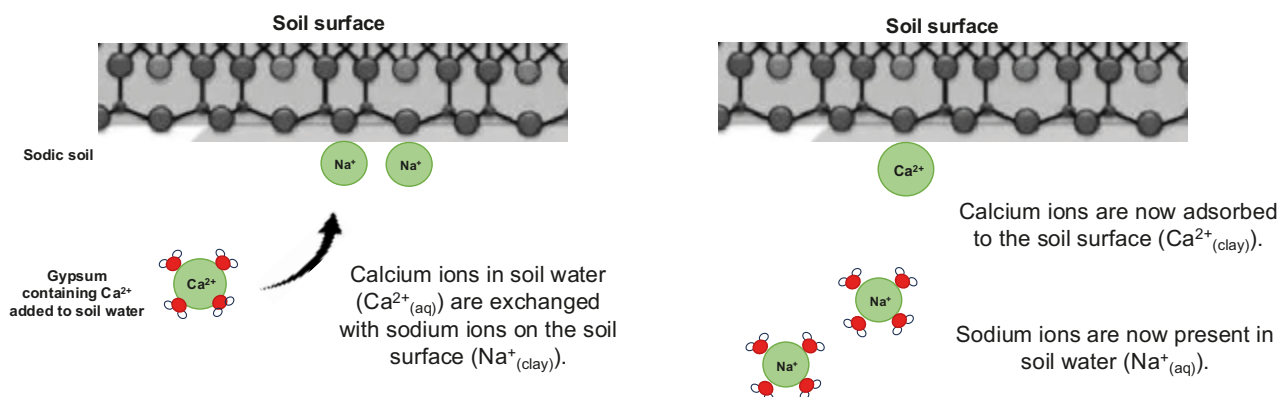
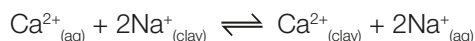


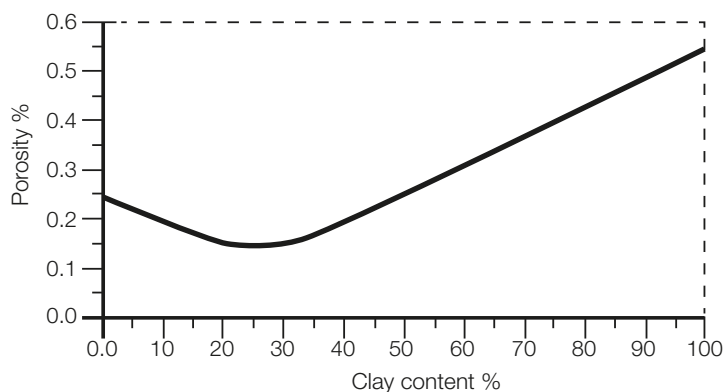
Figure 4.3.21: Calcium ions undergoing cation exchange with sodium ions.



The increased concentration of calcium ions in soil water ($Ca^{2+}_{(aq)}$) shifts the equilibrium to the right. Calcium ions adsorb to the surface of the soil ($Ca^{2+}_{(clay)}$), and sodium ions are now in soil water ($Na^+_{(aq)}$).

Question

29. Soils are prepared for the cultivation of grass for turf cricket pitches across Australia. Soils chosen are tested for pH, cation exchange capacity, and porosity (swelling).
- (a) The clay content of prepared soils used for the growth of a turf cricket pitch are selected for desired levels of porosity.



- (i) **Describe** the trend shown in the graph of clay content and porosity for the soil.

(2 marks) IAE3

- (ii) **Suggest** why clay content is related to soil porosity.

(2 marks) **KA2**

- (b) The pH values of clay soils used for cricket pitches are maintained between 6.5 and 7.5. Acidic soils, where pH values drop below 6, result in a reduction in the swelling of the clay leading to cracking of the pitch and poor growth of the turf (grass).

- (i) **Calculate** the hydrogen ion (H^+) concentration for soil measuring a pH of 5.7.

(2 marks) **KA4**

- (ii) **Explain**, with the aid of an equation, how an increased concentration of hydrogen ions present in soil solution leads to the removal of cations from the surface of clays.

4

(4 marks) **KA2**

- (iii) **Suggest** how cation exchange with hydrogen ions (H^+) leads to a loss of swelling in clays and the cracking of the pitch.

(2 marks) **KA2**

- (iv) **State** why acidic conditions result in the poor growth of turf.

(1 mark) **KA2**

- (v) Lime (hydrated calcium hydroxide, $Ca(OH)_2$) was once used to mark the white lines on cricket pitches, but has been replaced.

- (1) Calcium hydroxide can elevate the pH of soils through neutralisation.

Write a fully balanced chemical equation for the neutralisation of acidic water in soils.

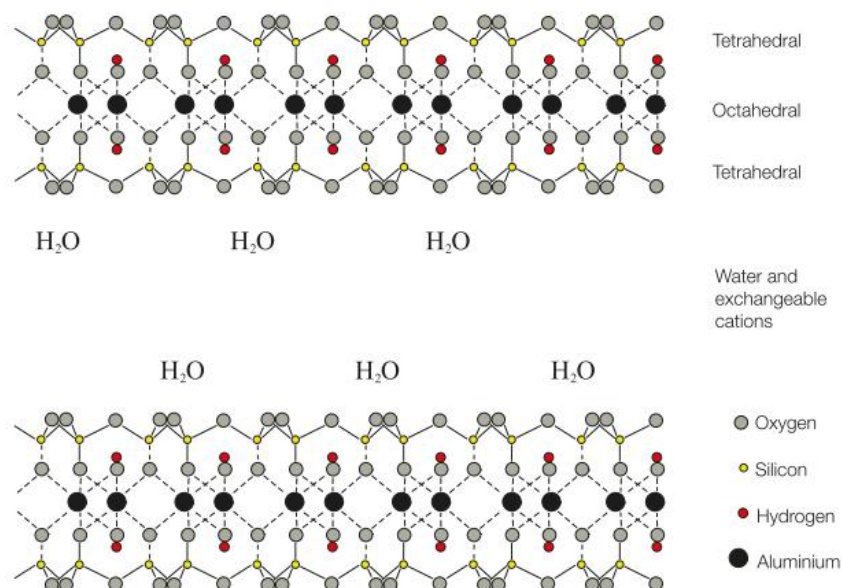
(2 marks) **KA4**

- (2) Calcium hydroxide is caustic.

Suggest one reason why it is no longer used for marking lines on pitches and sporting fields.

(1 mark) **KA3**

- (c) Montmorillonite clays make the greatest impact on the expansion and contraction of soils under a turf cricket pitch.



Explain, using the diagram above, why soil moisture content also determines the extent of expansion (swelling) and contraction (leading to cracking) in the soil of turf cricket pitches.

(2 marks) **IAE3**

- (d) Constant irrigation of cricket pitches with water containing high concentrations of sodium can lead to high levels of soil sodicity.
- (i) **State** and **explain**, using equilibrium principles, the effect of increased concentrations of aqueous sodium ions on the concentration of calcium ions present on the clay surface.

(3 marks) **KA1**

- (ii) **Explain** how increased soil sodicity leads to a turf cricket pitch that crumbles after very little use.

(2 marks) **KA2**

4.4 Materials

Science understanding

Polymers are produced from monomers by addition or condensation reactions.

- Identify whether a molecule could undergo polymerisation, given its structural formula and, if so, the type of polymerisation.
- Identify a polymer as being the product of an addition polymerisation or a condensation polymerisation, given its structural formula.
- Identify the repeating unit of a polymer, given its structural formula.

© SACE 2025

Polymers

Polymers are large molecules made from smaller molecules linked together by covalent bonds. The smaller molecules that make up polymers are called *monomers*. Examples of common polymers are shown below (some of which you have already seen in Chapter 3):

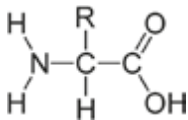
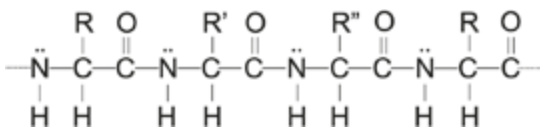
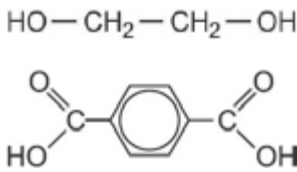
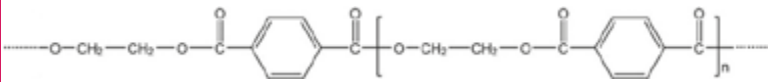
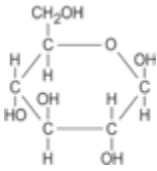
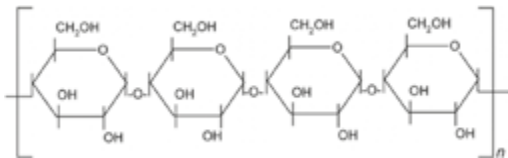
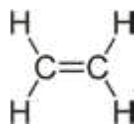
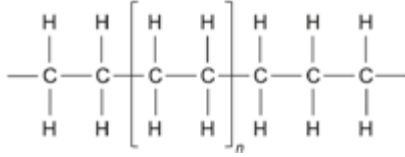
Monomer/s	Polymer	Uses
 Amino acids	 Proteins	DNA, enzymes, energy source, hormones
 Alcohol Carboxylic acid	 Polyester	Fabrics, water hoses, ropes, nets
 Glucose	 Starch	Energy storage, biodegradable polymers, pharmaceuticals
 Alkene (ethene)	 Polyethylene plastic	Plastic bags, bottles, toys, electrical insulation

Figure 4.4.1: Examples of common polymers and their monomers

Polymers are both naturally occurring and synthetic. A variety of polymers have been covered in the course, and these can be found in the flowchart in figure 4.4.2..

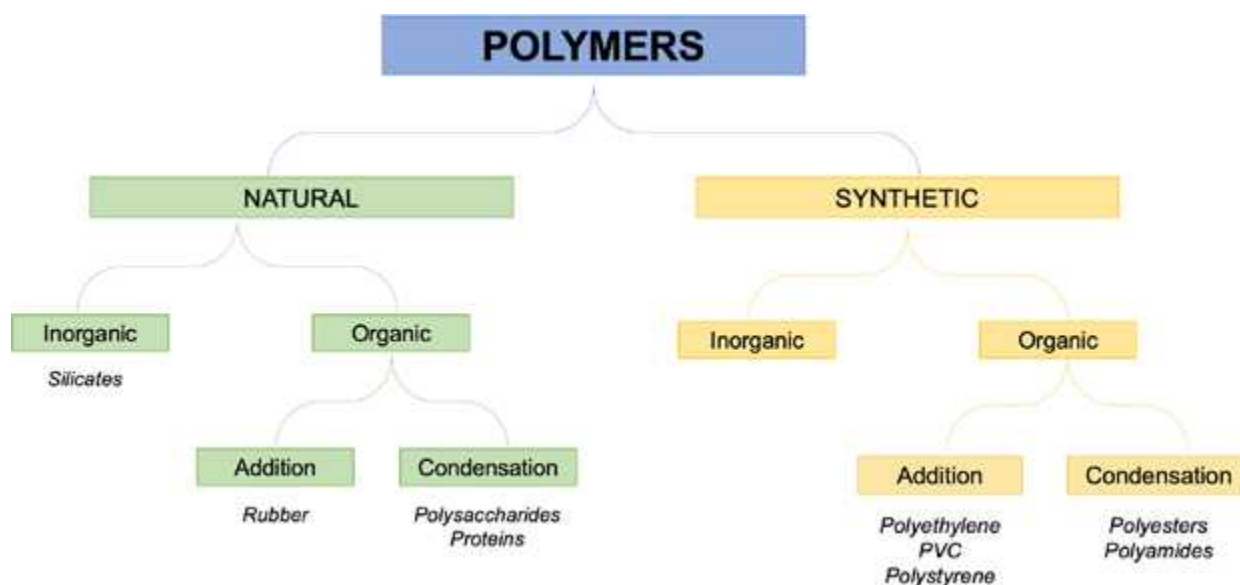


Figure 4.4.2: Flowchart of natural and synthetic polymers covered in the course.

Organic polymers contain carbon. Both natural and synthetic organic polymers are formed by addition or condensation reactions.

Addition polymers

Addition polymers are formed from monomers containing carbon-carbon double bonds ($C=C$), such as alkenes. During the polymerisation process, these unsaturated monomers react to form a long polymer chain, where one of the double bond's pairs of electrons is used to link monomers together through single carbon-carbon bonds ($C-C$). This type of polymerisation, common in plastics like polyethylene and polystyrene, creates a stable, continuous backbone of carbon atoms that makes addition polymers durable and versatile. However, these same properties often make them resistant to natural decomposition, posing environmental challenges when disposed of improperly.

The example below is a general representation of addition polymerisation. The repeating unit is identified with square brackets.

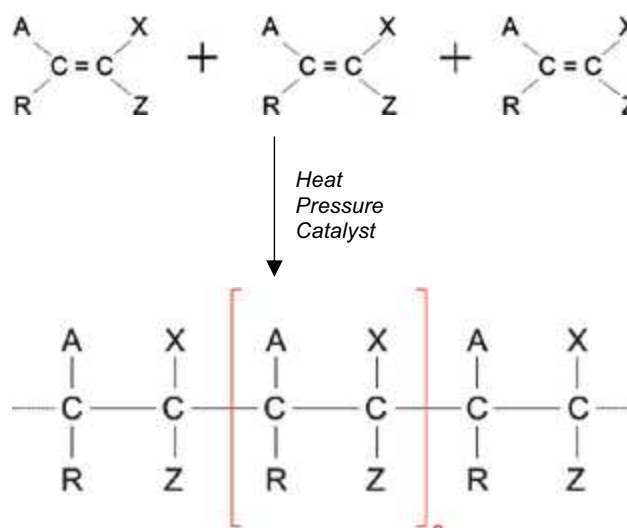
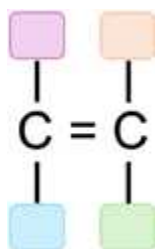


Figure 4.4.3: General reaction showing addition polymerisation of alkene monomers to the polymer.

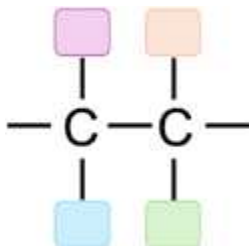
Drawing polymers from monomers

When drawing addition polymers from monomers, the following steps make the process more straightforward.

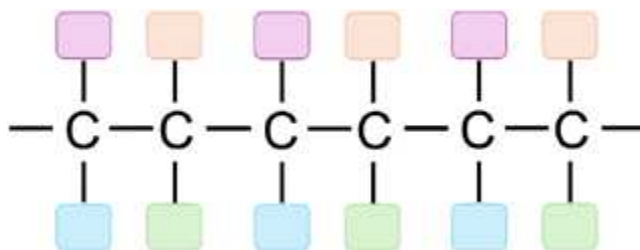
1. If required, redraw the monomer so the C=C bond is in the centre, with four bonds branching out as shown:



2. Next, “open up” the double bond so that each carbon forms a new bond:



3. These new bonds link repeating units together to form a polymer chain.



Example

This method can be useful when the monomer appears more complex; for example, if asked to draw the polymer from the monomer but-1-ene.

The structural formula of but-1-ene is typically drawn as shown below:

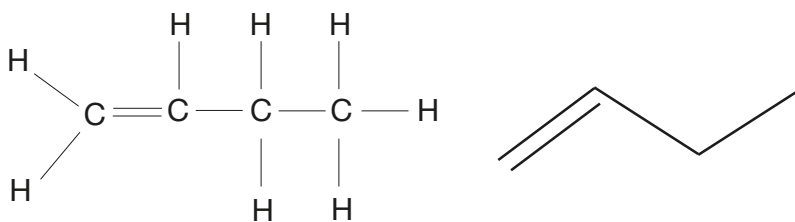
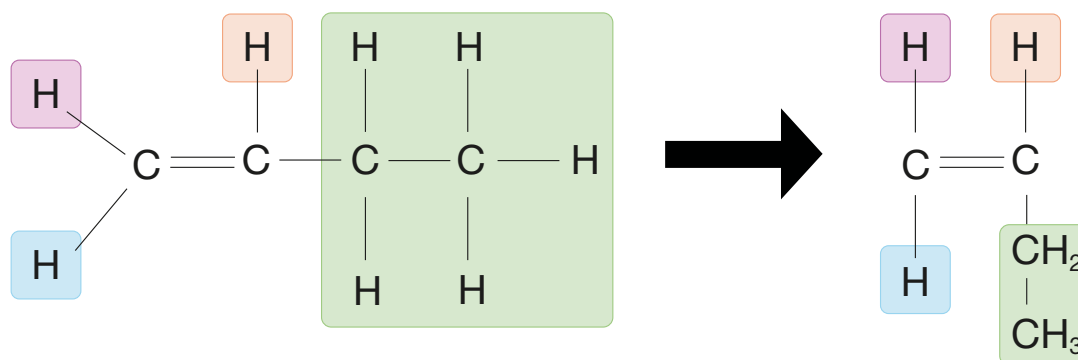


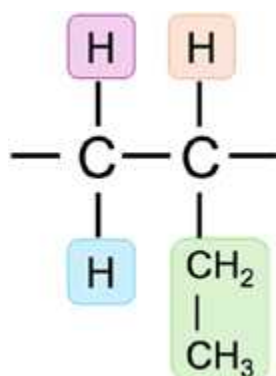
Figure 4.4.4: Complete structural formula and skeletal formula of but-1-ene

Using the method above for how to draw polymers:

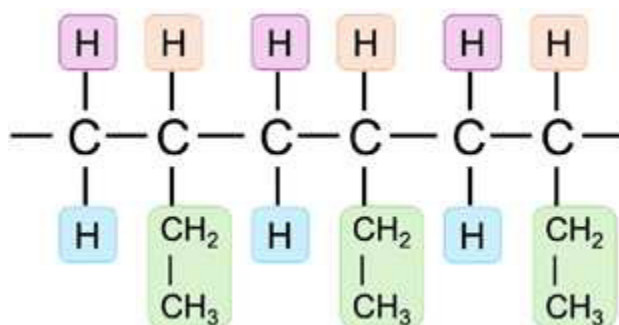
1. Redraw the monomer but-1-ene:



2. "Open up" the double bond so that each carbon forms a new bond:



3. These new bonds link repeating units together to form a polymer chain.



There is a difference between a monomer and a repeating unit.

Monomers: single molecules that make up the polymer. In addition polymers, the monomer structure includes the C=C double bonds.

Repeating unit: the structure that repeats itself within the polymer chain, formed after the monomer has polymerised. Repeating units are identified with square brackets.

An example is shown below using PVC, polyvinyl chloride.

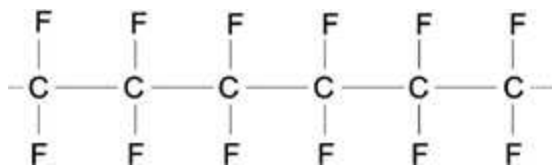
Polymer	Repeating unit	Monomer

How to identify an addition polymer:

- Monomers are unsaturated.
- No other molecules or by-products, like water, are produced.
- Continuous carbon chain (carbon backbone) running centrally through the polymer.

Question

30. Teflon is used as a non-stick surface on cooking pots and pans. Part of its structure is shown below.



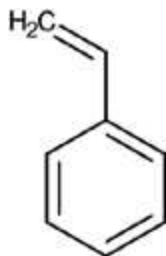
(a) **Draw brackets** to identify the repeating unit of the polymer.

(1 mark) **KA4**

(b) **Draw the structural** formula of the monomer.

(1 marks) **KA4**

31. Polystyrene is a polymer whose uses include Styrofoam insulation. Its monomer is shown below.



Draw a section of the polystyrene polymer with at least three repeating units.

(3 marks) **KA4**

32. Polymerisation of methyl propene produces synthetic rubber.

(a) **Draw** the monomer *methyl propene*.

(2 marks) **KA4**

(b) **Draw** a section of the polymer that is formed from methyl propene monomers.

(3 marks) **KA4**

Condensation polymers

Condensation polymers are formed in condensation reactions between monomers. An inorganic molecule, such as water, is eliminated. Two classes of condensation polymers are **polyesters** and **polyamides**.

Polyesters contain ester links and are formed from monomer/s that contain carboxyl and hydroxyl functional groups.

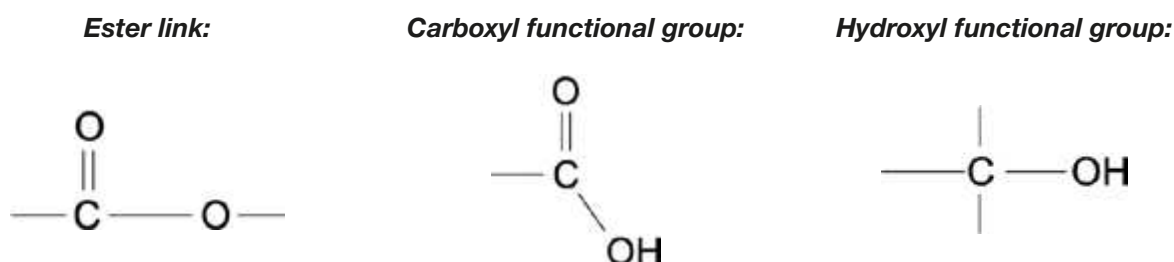


Figure 4.4.5: Ester, carboxyl and hydroxyl functional groups.

Some polyesters can be formed from a single monomer that contains both the hydroxyl and carboxyl functional groups, resulting in one ester group within the repeating unit of the polymer. A general example is shown below:

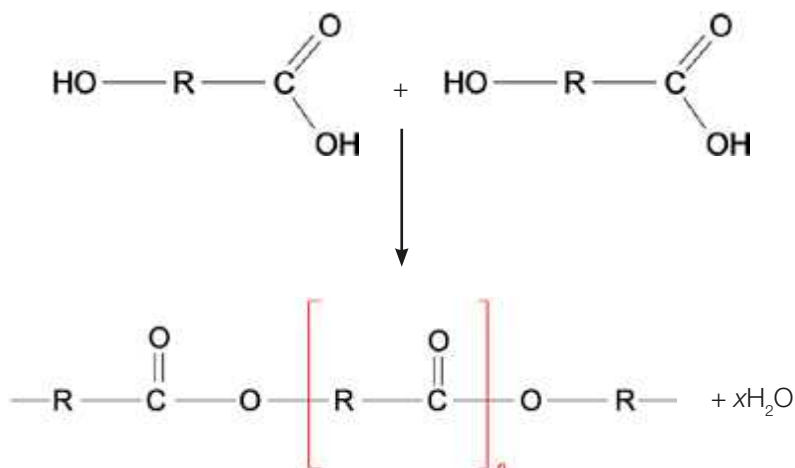


Figure 4.4.6: General condensation reaction for a polyester formed from a single monomer.

Polyesters are more commonly formed from two monomers – one a **dicarboxylic acid** and one a **diol** – resulting in two ester groups within the repeating unit of the polymer. A general example is shown below:

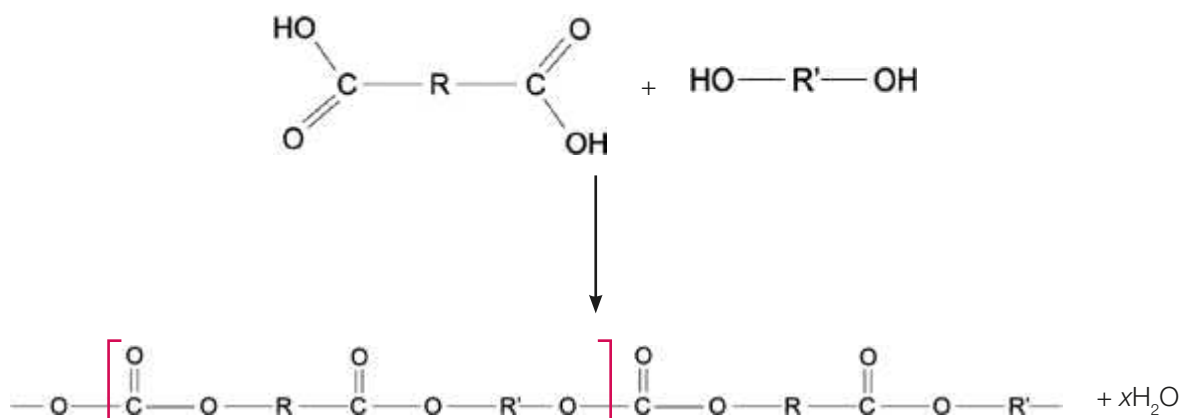
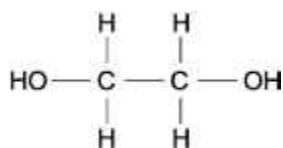


Figure 4.4.7: General condensation reaction for a polyester formed from two monomers

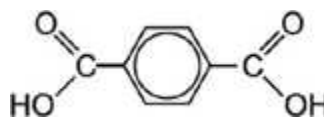
Question

33. **Draw** a section of the polyester formed by the two monomers below and identify the repeating unit.

(3 marks) **KA4**



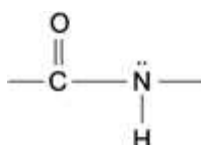
ethane-1,2-diol



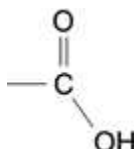
benzene-1,4-dioic acid

Polyamides contain amide links and are formed from monomer/s that contain carboxyl and amino functional groups.

Amide link:



Carboxyl functional group:



Amino functional group:

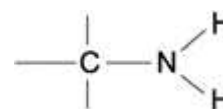


Figure 4.4.8: Amide, carboxyl, and amino functional groups.

Polyamides like **proteins** are formed from single amino acid monomers that contain both the amino and carboxyl functional groups, as shown below:

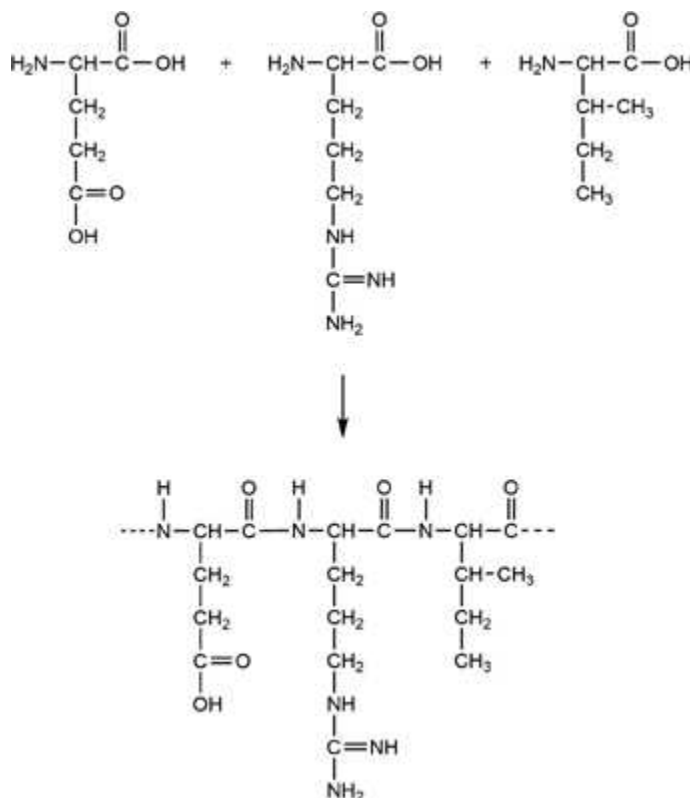


Figure 4.4.9: Condensation reaction for a protein from single amino acid monomers.

Synthetic polyamides are more commonly formed from two monomers – one a **dicarboxylic acid** and one a **diamine** – resulting in two amide groups within the repeating unit of the polymer. A general example is shown below:

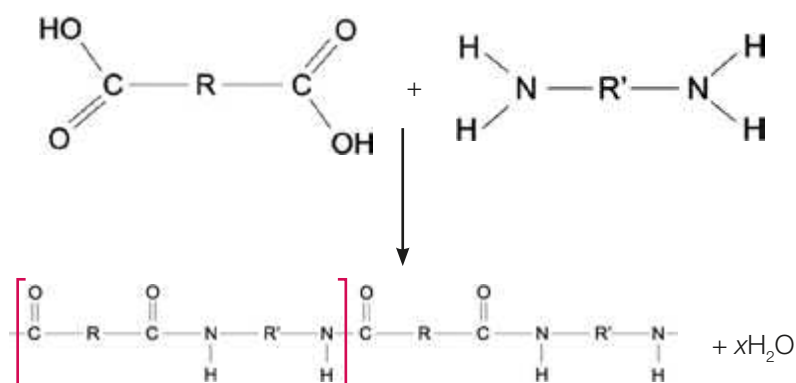
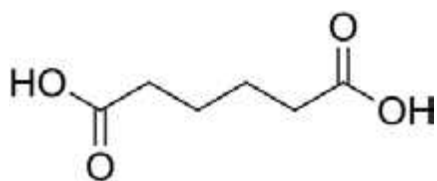


Figure 4.4.10: General condensation reaction for a polyamide.

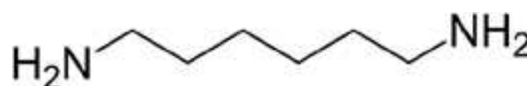
Question

34. Draw a section of the polyamide formed by the two monomers below and identify the repeating unit.

(3 marks) **KA4**



hexanedioic acid



hexane-1,6-diamine

How to identify a condensation polymer:

- Monomers are linked by ester or amide groups (or other functional groups resulting from condensation reactions).
- Molecules or by-products, like water, are produced.

Remember: **natural** condensation polymers are carbohydrates (polysaccharides) and proteins.

Science understanding

Organic polymers can have different properties, such as rigidity, depending on the monomers and the degree of cross-linking between chains.

- Compare the physical properties of polymers with different degrees of cross-linking and secondary interactions between polymer chains.
- Compare the effects of heating on thermoplastic and thermoset polymers.

© SACE 2025

Organic polymer properties

Organic polymers can have different properties, such as rigidity, density, hardness, and thermal and electrical conductivity. The properties of organic polymers depend on several factors:

- Length of polymer chains
- Monomers used
- Degree of branching
- Degree of cross-linking between polymer chains

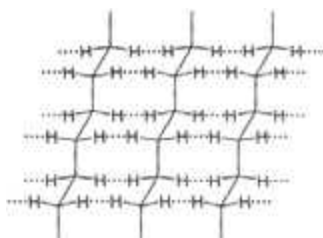
Length of polymer chains

Polymers vary in molecular size. Dispersion forces operate along the length of the chains, and the size of the chains affects the strength of dispersion forces. The strength of the dispersion forces increases as the length of the chains increases.

Monomers used

The specific characteristics of the monomers – including size, structure, and functional groups – also influence the chemical and physical properties of polymers. Polymers that contain ester and amide groups can experience dipole-dipole interactions and hydrogen bonding between chains. Similarly, if their branches contain hydroxyl, carboxyl, or amino functional groups, the polymers will experience dipole-dipole interactions and hydrogen bonding between chains. The examples below show how different interactions between polymer chains affects the properties of the polymer.

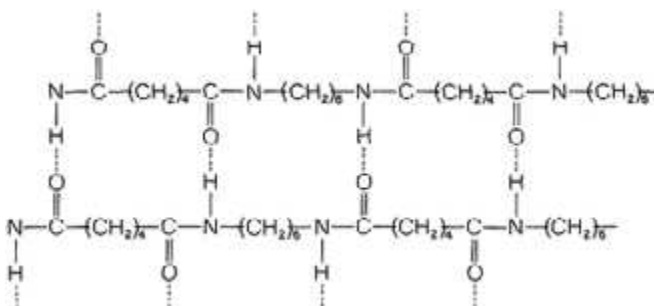
Dispersion forces between polymer chains



Properties:

- Soft
- Flexible
- Non-elastic
- Low melting points (and softening points)
- Can be reshaped repeatedly (suitable for recycling)

Hydrogen bonding between polymer chains



Properties:

- Greater strength
- Greater rigidity
- Greater elasticity

Figure 4.4.11: The effect of different interactions between polymer chains on the polymer's properties.

Branching

Branching affects the ability of chains to pack closely, changing the density of the polymer. For example, polyethylene can be “low-density” (LDPE) or “high-density” (HDPE). LDPE has extensive branching, which prevents molecules from stacking closely, while HDPE has minimal branching, allowing the molecules to stack, as shown in the images below.

Low-density polyethylene – extensive branching prevents close stacking



Properties:

- Soft
- Flexible
- Lightweight

Uses:

- Shopping bags
- Flexible bottles

High-density polyethylene – minimal branching allows molecules to stack



Properties:

- Strong
- Durable
- Chemically resistant

Uses:

- Garbage bins
- Cutting boards
- Pipes

Figure 4.4.12: The effect of branching on the polymer's properties.

Cross-linking

Cross links connect atoms in one polymer chain with atoms in another polymer chain through primary bonds. They are very strong links that cannot be broken easily by heating. If a polymer has few cross links, the individual chains can move a little, and the polymer is elastic and flexible. If a polymer has extensive cross links, the individual chains cannot move as freely, therefore the polymer has lower elasticity and flexibility, and is more rigid.

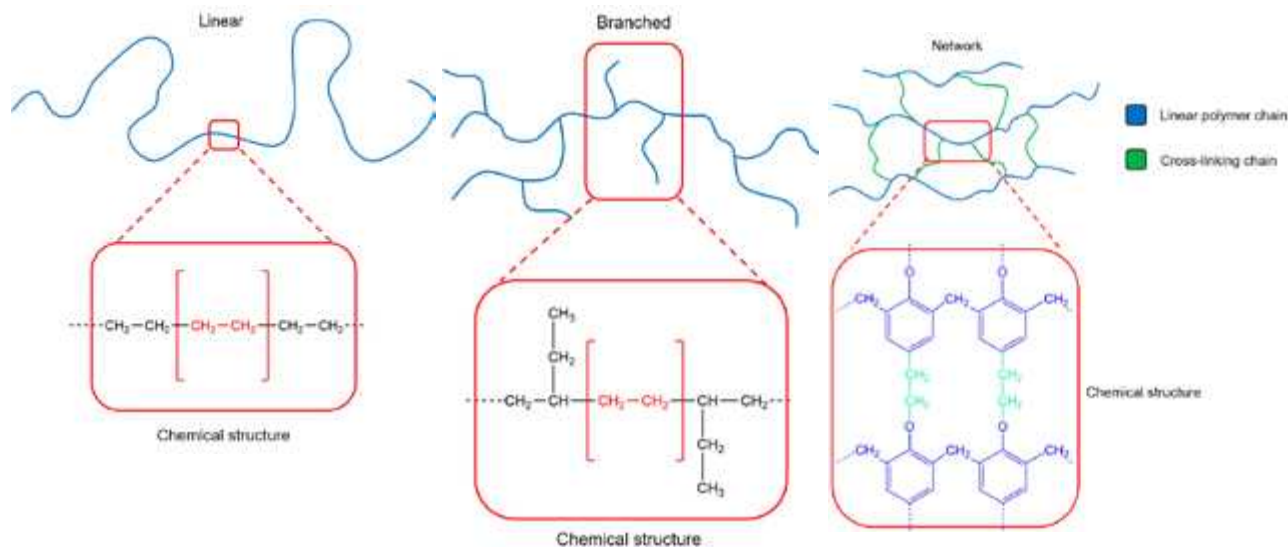


Figure 4.4.13: The effect of cross-linking on the polymer's properties.

Cross links are either formed during the polymerisation reaction, or they are introduced by reacting a polymer with a cross-linking agent.

The greater the degree of cross-linking, the greater the rigidity of the polymer, as well as the hardness, brittleness, durability, and melting point.

Thermoplastic & thermosetting polymers

The differences between thermoplastic and thermosetting polymers can be related to their structures.

Thermoplastic polymers are flexible. They can be softened by heating, remoulded, and reset to a new shape upon cooling.

A schematic diagram of thermoplastic polymers is shown below.

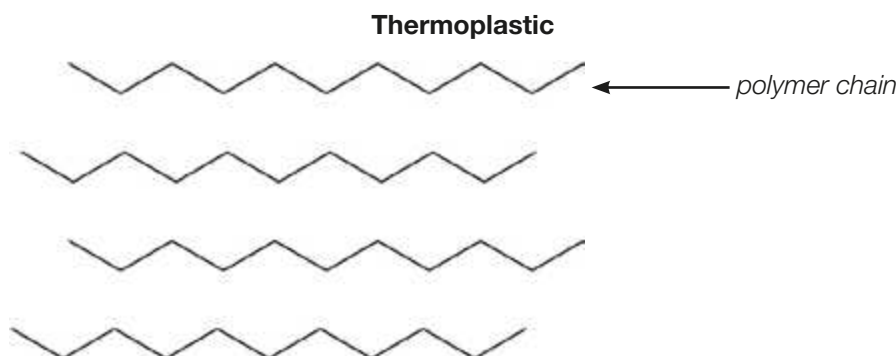


Figure 4.4.14: A schematic diagram of thermoplastic polymers (no cross-links).

These polymers are composed of long polymer molecules with minimal cross-linking between chains. Upon heating, secondary interactions are overcome, and the chains are able to slide past each other and flow. The polymers soften and become fluid. Upon cooling, the polymer solidifies. Reversible process, allowing the polymers to be recycled.

Thermosetting polymers are rigid and cannot be reshaped by heating. They char when heated.

A schematic diagram of thermosetting polymers is shown below.

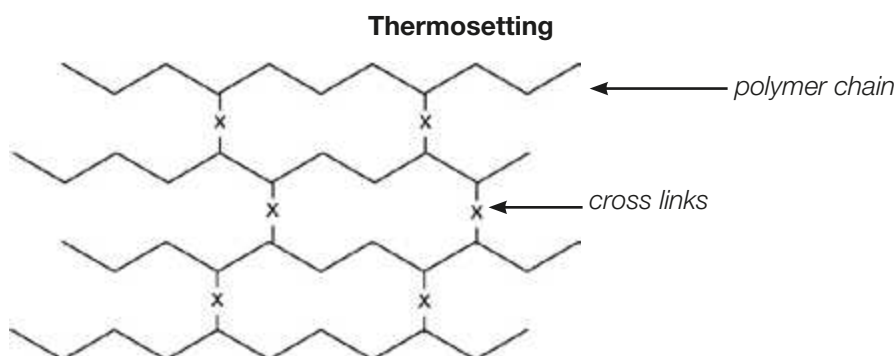


Figure 4.4.15: A schematic diagram of thermosetting polymers (cross-links).

Atoms form primary bonds between chains, called cross-links. The high degree of cross-linking sets the polymer firmly into shape. Neighbouring chains are held firmly in position, so heating does not allow the chains to slide over each other, and reshaping is not possible. The high degree of cross-linking forms three-dimensional networks with increased rigidity. These polymers are difficult to recycle.

Question

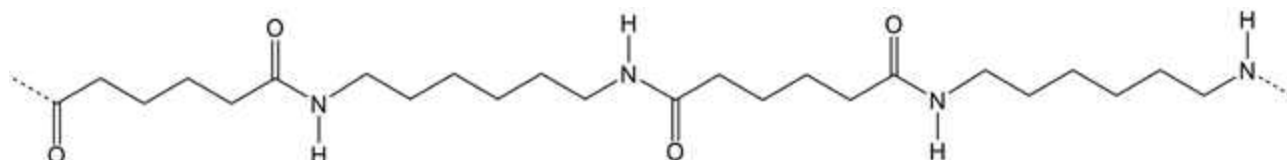
35. Polymer development has had significant impact on materials applied to sporting equipment such as tennis racquets.

(a) Tennis racquet strings were traditionally made from gut (animal intestines made of collagen). Modern strings are predominantly made of nylon, often braided with other synthetic polymers.

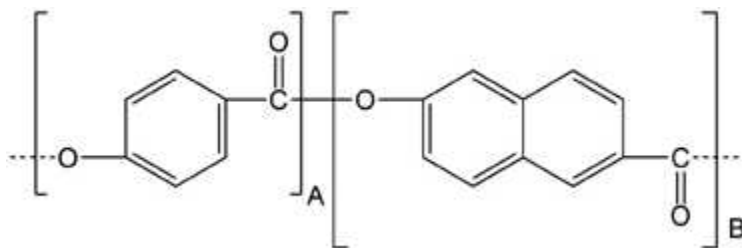
(i) **Suggest** the name of the class of natural condensation polymers present in gut strings.

(1 mark) **KA1**

(ii) A section of the nylon-6,6 polymer used for modern strings is shown below.



- (1) **Identify** whether nylon is a product of addition or condensation polymerisation. (1 mark) **IAE3**
- (2) **Bracket** the repeating unit on diagram of nylon-6,6 on the previous page. (1 mark) **IAE3**
- (iii) Vectran® is an aromatic polyester used on modern strings to emulate the rigidity of natural gut strings. The repeating units of the monomers present in Vectran® are shown below.



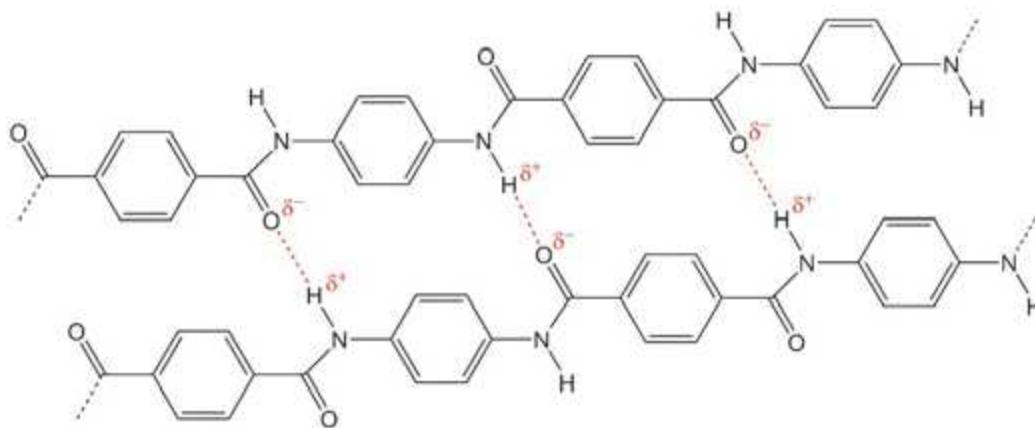
- (1) **Suggest**, in terms of secondary interactions, why Vectran® would offer similar rigidity to natural gut.

(2 marks) **KA2**

- (2) **Draw** the two monomers used to form the polymer.

(4 marks) **KA4**

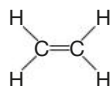
- (iv) Kevlar is braided through nylon strings to increase durability. Kevlar offers exceptional strength, making strings difficult to break. The structure of Kevlar is shown below.



Identify the functional group that links the monomers in Kevlar, and explain its significance in forming strong and durable fibres.

(3 marks) **IAE3**

- (v) Polyolefin polymers offer the softest strings; they are made from the monomer shown below.



- (1) **Identify** the type of polymer produced from the monomer above.

(1 mark) **KA1**

- (2) **State** and **explain** whether the polymer produced from this monomer is classified as a thermoplastic or thermoset.

(3 marks) **IAE3**

- (3) **Suggest** why the polymer produced is a soft polymer.

(1 mark) **KA2**

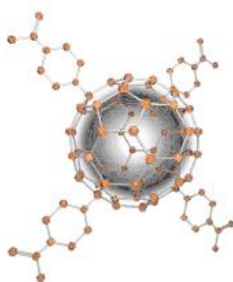
- (b) Tennis grips and vibration dampeners in the frame of racquets are often made from the polymer polyurethane. Polyurethanes used in tennis racquets are elastic due to limited cross-linking in the polymer.

Explain how limited cross-linking leads to an elastic material, whereas an absence of cross-linking will not produce an elastic material.

4

(3 marks) **KA2**

- (c) New technologies used in the manufacture of racquet frames use carbon fullerenes (X-fullerenes) that have the ability to form cross-links. The structure of the fullerene is shown below.



- (i) **Explain** how the inclusion of X-fullerenes increases the rigidity of the carbon polymer structure.

(2 marks) **KA2**

- (ii) **Suggest** one advantage of producing a tennis racquet with greater rigidity.

(1 mark) **KA3**

Science understanding

The production of synthetic polymers allows the manufacture of materials with a diverse range of properties.

- Discuss the advantages and disadvantages of synthetic polymers.

Polymers can be made from fossil resources or from renewable materials.

- Discuss the advantages and disadvantages of making polymers from fossil resources or from renewable materials.

© SACE 2025

Synthetic polymers

Synthetic polymers have become essential in modern society, replacing traditional materials like wood, glass, leather, and metal due to their versatility, cost-effectiveness, durability, and ease of mass production. Despite these benefits, the widespread use of synthetic polymers has introduced significant environmental challenges. Many synthetic polymers are derived from non-renewable fossil fuels and are non-biodegradable, meaning they can persist in the environment for hundreds of years. As a result, plastic waste accumulates in landfills and oceans, causing ecological harm to wildlife and contributing to pollution. Addressing these issues has become a priority for researchers, who are working to develop sustainable alternatives and improve recycling technologies.

The advantages and disadvantages associated with the use of synthetic polymers are outlined in the table below.

Advantages of synthetic polymers	Disadvantages of synthetic polymers
Can be produced to offer a diverse range of structures and properties.	Many are made from finite (non-renewable) resources such as oil and coal.
Relatively cheap to produce compared to processed metals and timber.	Many persist in the environment for tens to hundreds of years. On land and in the oceans, they are ingested by or entrap wildlife.
Easily shaped, low density, do not corrode, can be coloured – compared to something like metal.	Many are non-biodegradable (or have limited degradability), are difficult to recycle, and are difficult to separate from composite materials.
Can mimic natural materials like glass, wool, cotton, metal, stone, with equal or better chemical and physical properties, such as density, flammability, thermal & electrical conductivity.	Many have limited use (often once) before discarding. Their use in packaging and disposable products worldwide means they are buried as wastes in landfill.
Through the inclusion of additives, can be produced with specific properties, such as increased rigidity, durability, thermal stability, chemical or UV resistance.	Synthetic polymers and their additives leach harmful chemicals into the soil and groundwater. Combustion of these polymers and their additives can also result in the formation of toxic products.

Table 4.4.1: The advantages and disadvantages of synthetic polymers.



Science as a human endeavour

Towards a Sustainable Future: Reducing Plastic Waste with Biodegradable Polymers

The environmental impact of conventional plastics has led scientists to explore biodegradable and compostable polymers as sustainable alternatives. Biodegradable polymers, such as polylactic acid (PLA), are derived from renewable resources like corn starch and can break down into non-toxic byproducts, reducing plastic waste in landfills. These polymers are increasingly used in products like disposable cutlery, compostable bags, and even medical applications, such as sutures that naturally decompose in the body. However, not all biodegradable polymers break down readily in natural environments; many require specific industrial composting conditions to decompose effectively.

Most synthetic polymers are derived from **petrochemicals** as a feedstock. However, a renewed focus on sustainability has led to the development of **synthetic biopolymers**.

Synthetic biopolymers are derived from **renewable plant material** as a feedstock for raw materials, called **biomass**. The following can all be used in the production of biopolymers:

- Polysaccharides – starch, cellulose, and lignin from plant crops
- Proteins – zein from corn
- Triglycerides – canola, castor, and soybean oils

The advantages and disadvantages of polymer production from both petrochemicals and biomass are considered in the tables below.

Polymer production from petrochemicals	
Advantages	Disadvantages
Petroleum and natural gas are relatively abundant feedstock. Petroleum and natural gas are easily extracted and processed into petrochemicals used as raw materials. Well-established industries exist for a multitude of polymer products derived from petroleum and associated petrochemicals. A wide variety of polymers with varying polymer properties can be derived from petrochemicals.	Petroleum and natural gas reserves are being depleted at an accelerated rate. Rate of depletion is much faster than geological rate of formation. Petroleum and natural gas are non-renewable feedstock.
Polymer production from biomass	
Advantages	Disadvantages
Carbohydrates, proteins, and oils derived from biomass are relatively abundant as feedstock. Raw materials are easily extracted and processed from biomass. Source of biomass can often be a by-product or waste product of other industries such as agriculture. Biomass is a renewable feedstock.	Limited range of polymers derived from biomass are currently possible. Use of biomass for polymer production may compete directly with land cropped for food production.

Table 4.4.2: The advantages and disadvantages of polymer production from petrochemicals and biomass.

Science understanding

Some polymers are biodegradable — being able to be broken down by microorganisms and other living things.

- Explain how the structure of a polymer relates to its biodegradability.
- Explain the advantages of polymers that are biodegradable.

© SACE 2025

Degradable polymers

Many synthetic polymers persist in the environment for years after their disposal. For example, the strong covalent carbon-carbon bonds present in many addition polymers are difficult to break down. In response to environmental concerns, the development of **degradable polymers** has accelerated.

Degradable polymers are able to break down into non-toxic, environmentally friendly, smaller components (monomers or other molecules) under specific conditions, thereby reducing the accumulation of plastic waste in landfills and oceans. Degradable polymers include **natural** polymers (carbohydrates, proteins, nucleic acids) and **synthetic** polymers derived from petroleum and biomass.

Some degradable polymers are classified as **biodegradable**. Biodegradable polymers break down to form gases, water, and biomass. There are two primary mechanisms through which biodegradation can occur:

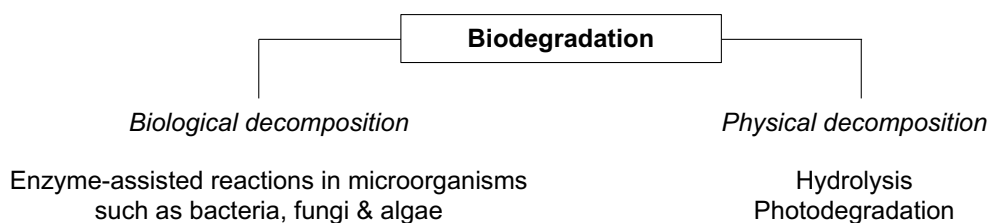


Figure 4.4.16: Two primary mechanisms through which biodegradation can occur.

Biological decomposition

The **enzymes** in microorganisms break down the polymer into small molecular weight fragments (eg dimers and monomers). These small molecular weight fragments can be further degraded to gases and water. Aerobic degradation produces CO_2 , H_2O , and microbial biomass, $\text{C}_{\text{biomass}}$. Anaerobic degradation produces CH_4 , H_2S , and microbial biomass, $\text{C}_{\text{biomass}}$.

Physical decomposition

Hydrolysis is a chemical process that breaks down biodegradable polymers into smaller fragments by reacting them with water molecules. Many biodegradable polymers contain **ester** and **amide** groups (or other functional groups that may be hydrolysed). The long polymer chains are broken down into smaller ones upon their reaction with water molecules, causing a decrease in the molecular weight of the polymer. Examples include polylactic acid (PLA), which is derived from corn starch and used for compostable bags, and polyglycolic acid (PGA), which is derived from sugar cane and used for dissolvable stitches.

Photodegradation is a process in which polymers can be decomposed by absorbing energy from light. Photodegradable polymers have functional groups (such as the $\text{C}=\text{O}$ **carbonyl** group) with bonds that absorb UV radiation. This absorption of light can initiate a number of reactions that result in the breakdown of the polymer. Light-sensitive additives can also be incorporated to catalyse the reaction. As a result of their photodegradation process, these polymers become brittle and are finally broken down into small particles by natural erosion, rain, and wind.

Also note from Chapter 1: Rubber is susceptible to degradation from ozone, as ozone attacks the $\text{C}=\text{C}$ double bonds in the main chain.

Advantages of biodegradable polymers

Biodegradable polymers offer several advantages over conventional synthetic polymers, some of which are listed below.

- They break down into natural substances over time, reducing landfill waste and pollution.
- Many are derived from renewable resources, such as sugar cane or starch, meaning fewer greenhouse gas emissions during production.
- They generally produce fewer toxic byproducts when they decompose.
- They are being designed for more versatile applications.



Science as a human endeavour

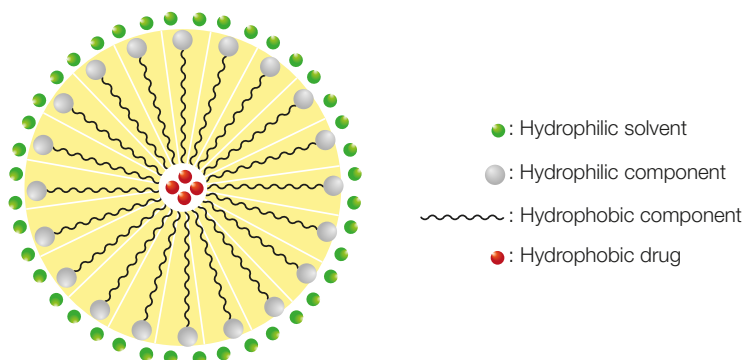
Limitations of degradable polymers

There is much debate between scientists whether the advantages offered by degradable polymers outweigh some of their disadvantages and whether recycling of non-degradable polymers is more effective in terms of the use of resources and in terms of environmental impact.

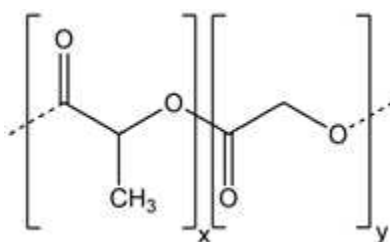
Many of the polymers we use end up in landfill. It is estimated that 20700 tonnes of plastic (polymer) are disposed of in landfill sites around Australia every year. In landfill, degradable synthetic polymers are exposed to limited oxygen, water and sunlight. Without sunlight, photodegradable reactions will not occur, halting the break down of photodegradable polymers. When these polymers are exposed to sunlight, they simply break down to smaller particles of polymer, which persist in the environment with unknown consequences. With limited exposure to water and oxygen in landfill, biodegradable polymers degrade at much slower rates and persist longer in the environment.

Question

36. Polylactic-co-glycolic acid (PLGA) is used in applications of drug delivery due to its degradability in the human body. The polymer surrounds the drug being delivered as shown in the diagram below.



- (a) The PLGA polymer is shown below.



- (i) **Circle** one ester group in the section of polymer. (1 mark) **KA1**
- (ii) **State** whether PGLA is an addition or condensation polymer. (1 mark) **KA1**
- (iii) **Draw** the structural formulae of the two monomers (lactic acid and glycolic acid) used to form the polymer.

(4 marks) **IAE3**

- (b) PGLA has hydrophilic regions, providing solubility in the human body, while also being degradable in this aqueous environment.

- (i) **State** the interaction that occurs between water and the hydrophilic regions. (1 mark) **KA1**
- (ii) **Explain** how the presence of ester groups in the PGLA polymer leads to the polymer's degradability in the human body.

(2 marks) **KA2**

- (iii) **Suggest** one advantage of the use of a degradable polymer in drug delivery.

(1 mark) **KA3**

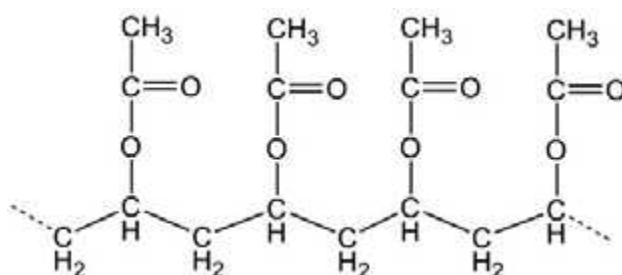
- (c) The PGLA polymer can be altered with the inclusion of long non-polar (hydrophobic) monomers into the polymer structure to increase the solubility of non-polar drugs.

State and **explain** the effect of the inclusion of long non-polar monomers on the rate of degradation of the polymer in the human body.

(3 marks) **IAE3**

37. Laundry bags in hospitals are being made from soluble polymers to reduce the risk of infection from soiled garments. Polyethenol is one dissolvable polymer used for laundry bags.

- (a) The synthetic polymer, polyethenol, is made from another polymer, polyethenyl ethanoate. The structure of polyethenyl ethanoate is shown below.



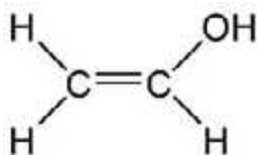
- (i) **State** whether polyethenyl ethanoate is formed through a condensation or an addition reaction.

(1 mark) **KA1**

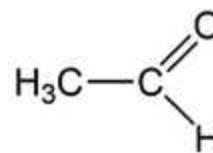
- (ii) **Draw** the structural formula of the monomer of polyethenyl ethanoate.

(2 marks) **KA4**

- (b) Polyethenol is made from an ester exchange rather than polymerisation due to the unstable nature of ethenol. Ethenol and the aldehyde it forms are shown below.



ethenol



aldehyde

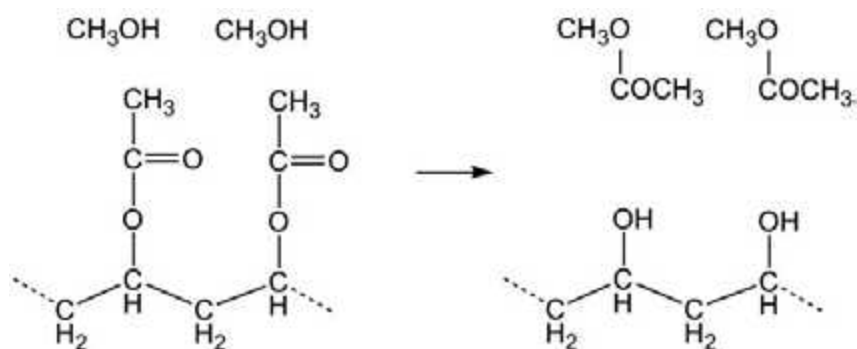
- (i) Ethenol and the aldehyde share the same molecular formula but have different structural formula. **State** the name given to this occurrence.

(1 mark) **KA1**

- (ii) **State** the systematic name of the aldehyde.

(2 marks) **KA4**

- (c) Methanol is the reactant used to generate the ester exchange. The ester exchange reaction is shown below.



- (i) **State** the systematic name of the ester that is formed as a product of the exchange. (2 marks) **KA4**
- (ii) The extent of ester exchange determines the percentage of hydroxyl groups that are formed on the surface of the polymer. The solubility in water for different percentages of exchange are summarised in the table below.

% of ester groups replaced	Solubility in water
100 – 99	Soluble
99 – 97	Soluble in warm water
96 – 90	Soluble in hot water
Less than 90	Insoluble

State and **explain** the trend in solubility shown in the table.

- (3 marks) **IAE3**
- (iii) **Suggest** one alternative use for the polymer based on the information provided in the table and provide one reason for its use in this application.

(2 marks) **KA3**

Science understanding

The occurrence of metals in combined or uncombined form in the Earth's crust is related to the reactivity of the metal.

Given the position of a metal in the activity series of metals:

Predict whether the metal is likely to occur in nature in a combined or uncombined form.

Predict and explain the likely method of reduction of the metal compound, including electrolysis of the molten compound, electrolysis of an aqueous solution of the metal compound, and use of carbon as a reducing agent.

© SACE 2025

Occurrence of metals

Most metals in the Earth's crust exist in the form of minerals, often embedded within ores. Minerals are naturally occurring compounds that can vary significantly in metal content. When a mineral contains a high enough concentration of metal to justify the cost of extraction, it is considered economically viable for mining. Metals such as gold, silver, and copper can sometimes be found in their elemental, uncombined form due to their low reactivity, which makes them more resistant to oxidation and other natural processes. This natural occurrence of metals is closely related to their position in the reactivity series, which determines whether they are found in pure or combined forms. It is possible to find some metals in their **native** form as an element. Elemental gold, silver, copper, platinum, arsenic, bismuth, and alloys of these and other metals, occur uncombined in nature due to their low activity. The activity of selected metals in comparison to hydrogen are shown in the table below.

Activity	Metal		Reactivity	Ion	Reduction of ions
Most active metal → least active metal	potassium	K	Displaces H ₂ gas from water, steam and acids and forms hydroxides	K ⁺	Most difficult to reduce → most easily reduced
	sodium	Na		Na ⁺	
	lithium	Li		Li ⁺	
	calcium	Ca		Ca ²⁺	
	magnesium	Mg	Displaces H ₂ gas from steam and acids and forms hydroxides	Mg ²⁺	
	aluminium	Al		Al ³⁺	
	zinc	Zn		Zn ²⁺	
	iron	Fe	Displaces H ₂ gas from acids only and forms hydroxides	Fe ³⁺	
	nickel	Ni		Ni ²⁺	
	tin	Sn		Sn ²⁺	
	lead	Pb		Pb ²⁺	
	hydrogen	H ₂	Included for comparison		
	copper	Cu	Combines with O ₂ to form oxides and cannot displace H ₂	Cu ²⁺	
	mercury	Hg	May be found uncombined in nature. Oxides decompose with heating	Hg ²⁺	
	silver	Ag		Ag ⁺	
	gold	Au		Au ³⁺	

Methods of reduction

The choice of reduction method to convert metal ions into their elemental form largely depends on the metal's reactivity. Highly reactive metals, such as potassium and sodium, require energy-intensive processes like molten electrolytic reduction, where water cannot be present as it would be reduced preferentially over the metal ions. In contrast, less reactive metals like iron can be reduced using cheaper methods, such as chemical reduction with carbon or carbon monoxide. Beyond reactivity, factors like energy costs, environmental considerations, and the feasibility of sustaining high temperatures influence the chosen reduction process. This highlights the importance of balancing economic viability with environmental responsibility in metal production. The costs associated with maintaining high-temperature furnaces and the release of vast quantities of pollutants during this process have favoured the use of electrolytic reduction (both molten and aqueous). The potential methods of reduction based on chemical activity are summarised for selected metals of economic importance in the table on the next page.

Activity	Metal		Methods of reduction	Compound in mineral	Reduction of ions
Most active metal → least active metal	potassium	K	Molten electrolytic reduction Water cannot be present, as it is reduced in preference to the metal ions	KCl	Most difficult to reduce → most easily reduced
	sodium	Na		NaCl	
	lithium	Li		LiCl	
	calcium	Ca		CaCl ₂	
	magnesium	Mg		MgCl ₂	
	aluminium	Al		Al ₂ O ₃	
	water	H ₂ O	Included for comparison		
	zinc	Zn	Aqueous electrolytic reduction Reduction of an aqueous solution as the metal ions are reduced in preference to water or Chemical reduction Chemical reduction utilising carbon or carbon monoxide as a reducing agent	ZnO	
	iron	Fe	Chemical reduction Reduction utilising carbon or carbon monoxide as a reducing agent	Fe ₂ O ₃	
	nickel	Ni		NiO	
tin	Sn	SnO ₂			
lead	Pb	PbO			
copper	Cu	Chemical reduction Roasting in oxygen, utilising oxygen as the reducing agent	Cu ₂ S		
mercury	Hg		HgS		
silver	Ag	May be found uncombined in nature	Ag		
gold	Au		Au		

Production of metals

Once a body of ore has been identified, the geological and environmental impact of mining is considered for the region and a mine site may be established. Atomic absorption spectroscopy (AAS) (refer to Page 90) is commonly used to identify the concentration of metals present in minerals in the ore; this analysis is used to establish the viability of the mine. Typically, five stages may be undertaken in the production of metals. It must be noted that not all stages outlined are required, depending upon the percentage of mineral present in the ore, cost of processing, and the desired purity and applications of the final product. The five common stages involved in metal production are summarised in the table below.

Stage	Explanation
Extraction	An identified ore body must be economically viable to be mined. The ore deposit is extracted (mined) from the Earth's crust. Open-cut or underground mining techniques may be undertaken.
Concentration	The ore is crushed and ground and the mineral present is concentrated by removal of unwanted minerals and waste rock (gangue). Higher concentrations of mineral are achieved at the mine site to reduce costs associated with transportation and disposal of waste rock. This stage is not required if the percentage of the mineral present in the ore is substantial or conversion is viable with wastes present.
Conversion	One or more stages of chemical conversion may be required to convert the mineral to a compound suitable for the reduction stage. This stage is not required if the mineral already exists as a compound suitable for reduction.
Reduction	Chemical reduction at high temperatures or molten or aqueous electrolysis is used to reduce metal ions to the metal.
Refining	Electrolysis or further chemical reactions are undertaken to remove remaining impurities. The metal may also be alloyed at this stage to improve upon properties. This stage is not required if the reduction stage yields a metal of sufficient purity for its desired application.

Science understanding

The production of some metals requires the conversion of minerals to a form suitable for reduction.

Explain, with the aid of equations, the methods chosen for the conversion of a mineral to a metal, given sufficient information.

Explain the benefits of one method of reduction compared with another, given relevant information.

© SACE 2025

Aluminium, iron, copper, zinc and titanium are five of the most commonly used metals. The stages required for the production of aluminium and zinc are outlined.

Example

Production of aluminium

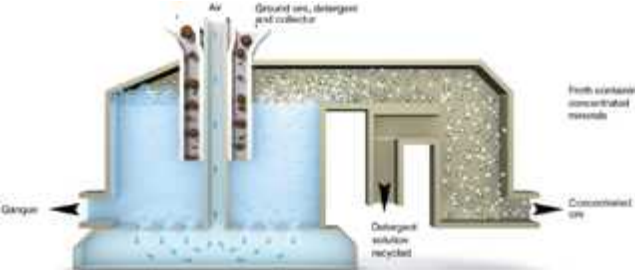
Stage	Explanation
Mining (Extraction)	Aluminium is extracted from the ore bauxite. Bauxite is one of the most abundant ores in the world. Aluminium occurs in the ore primarily as the mineral gibbsite (aluminium hydroxide $\text{Al}(\text{OH})_3$).
Concentration	A concentration stage is not required as the ore contains a sufficiently high percentage of the mineral containing aluminium.
Conversion	Bauxite contains the mineral gibbsite, which is aluminium hydroxide, $\text{Al}(\text{OH})_3$. To remove impurities, especially iron oxides but also oxides of silicon, calcium, and titanium, the aluminium hydroxide is converted to soluble sodium aluminate and then back to aluminium hydroxide. Powdered bauxite is first mixed with sodium hydroxide solution and heated to 150–200 °C to form sodium aluminate. $\text{Al}(\text{OH})_{3(s)} + \text{NaOH}_{(aq)} \rightarrow \text{NaAlO}_{2(aq)} + 2\text{H}_2\text{O}_{(l)}$ Oxides of iron, silicon, calcium, and titanium remain insoluble and settle as a waste product called bauxite residue or red mud. The filtered solution is cooled and seeded with pure aluminium hydroxide to allow crystallisation of solid aluminium hydroxide. $\text{NaAlO}_{2(aq)} + 2\text{H}_2\text{O}_{(l)} \rightarrow \text{Al}(\text{OH})_{3(s)} + \text{NaOH}_{(aq)}$ Aluminium hydroxide is filtered off and heated in a kiln to produce aluminium oxide (alumina). $2\text{Al}(\text{OH})_{3(s)} \rightarrow \text{Al}_2\text{O}_{3(s)} + 3\text{H}_2\text{O}_{(l)}$
Reduction (electrolytic)	The carbon cathode lines a molten electrolytic cell. Aluminium ions are reduced to molten aluminium, which is denser than other components in the cell. The molten aluminium collects at the bottom and can be tapped off and cast. $\text{Al}_{(l)}^{3+} + 3\text{e}^- \rightarrow \text{Al}_{(s)}$ At the carbon anode, oxide ions are oxidised to form oxygen gas. $2\text{O}_{(l)}^{2-} \rightarrow \text{O}_{2(g)} + 4\text{e}^-$ Aluminium is produced with at least 99% purity using this method.
Refining	A refining stage is not required due to the high purity of the metal obtained from electrolysis.

Comparing methods of reduction for aluminium

Molten electrolytic reduction is required for aluminium ions, as aluminium is an active metal. This is a highly energy intensive process. If an aqueous electrolytic cell was employed, water would be reduced in preference to aluminium ions, thus producing hydrogen gas rather than aluminium. Chemical reduction is not suitable to reduce aluminium ions.

Example

Production of zinc

Stage	Explanation
Extraction	The majority of zinc is obtained from zinc sulfide ores (also containing lead, cadmium iron and silver). The most common ore mined to obtain zinc is sphalerite (ZnS).
Concentration	The ore is mined, crushed, ground in a ball-mill and concentrated using froth flotation (see the following diagram). The powdered ore is mixed with water in a large tank to form a slurry. Detergent and collector (ions containing a charged region and a non-polar region) are added, and compressed air is forced through the mixture to generate bubbles. The zinc mineral adheres to the bubbles and is carried to the surface of the froth where it is skimmed off. Heavier clays and silicates settle at the bottom of the tank. This waste product is referred to as gangue. The purpose of froth flotation is to concentrate the mineral present in the ore. 
Conversion	The ore is roasted in a large furnace in the presence of a stream of air to achieve the high temperatures required for conversion of zinc sulfide to zinc oxide. $2\text{ZnS}_{(s)} + 3\text{O}_{2(g)} \rightarrow 2\text{ZnO}_{(s)} + 2\text{SO}_{2(g)}$ Sulfur dioxide gas is removed as a by-product. If released into the atmosphere it may contribute to environmental pollution. It is of greater environmental and economic benefit to generate sulfuric acid as a by-product for later stages of zinc production and to on-sell to the fertiliser industry. $2\text{SO}_{2(g)} + \text{O}_{2(g)} \rightleftharpoons 2\text{SO}_{3(g)}$ $\text{SO}_{3(g)} + \text{H}_2\text{O}_{(l)} \rightarrow \text{H}_2\text{SO}_{4(aq)}$ Zinc oxide is leached with sulfuric acid (as a by-product or regenerated during electrolysis) to allow conversion to aqueous zinc sulfate, a suitable electrolyte for electrolytic reduction. $\text{ZnO}_{(s)} + \text{H}_2\text{SO}_{4(aq)} \rightarrow \text{ZnSO}_{4(aq)} + \text{H}_2\text{O}_{(l)}$ The mixture containing zinc sulfate is then filtered to remove suspended solids and treated with powdered zinc dust (offering large surface area) to precipitate less-active metals such as cadmium, copper, nickel and cobalt. Ions of less-active metals are displaced by relatively active zinc metal. $\text{Cd}^{2+}_{(aq)} + \text{Zn}_{(s)} \rightarrow \text{Zn}^{2+}_{(aq)} + \text{Cd}_{(s)}$ The precipitated metals are another valuable by-product of the process; this is the principal method of cadmium production.
Reduction (electrolytic)	In the final stage, zinc sulfate is electrolysed to produce purified zinc (99.96%). Zinc is reduced onto aluminium cathodes, periodically stripped from the electrodes, melted and cast. $\text{Zn}^{2+}_{(aq)} + 2e^- \rightarrow \text{Zn}_{(s)}$ At the anode, oxygen is evolved as the electrolyte is regenerated. $2\text{H}_2\text{O}_{(l)} \rightarrow \text{O}_{2(g)} + 4\text{H}^{+}_{(aq)} + 2e^-$
Refining	Refining is not undertaken due to the high purity of the metal obtained from electrolysis. Changing parameters in the electrolytic cell can yield zinc of even higher percentage purity.
Reduction (chemical)	The thermal method uses a blast furnace charged with coke (carbon) to generate carbon monoxide (CO) as the chemical reducing agent. $2\text{C}_{(s)} + \text{O}_{2(g)} \rightarrow 2\text{CO}_{(g)}$ $\text{ZnO}_{(s)} + \text{CO}_{(g)} \rightarrow \text{Zn}_{(s)} + \text{CO}_{2(g)}$ The zinc that forms is turned into a vapour at the high temperatures encountered. It is collected with gases and condensed.

Comparing methods of reduction for zinc

Chemical reduction of zinc using the thermal process employs a blast furnace operating at approximately 1000°C. High temperatures needed for the reaction are generated and maintained by the combustion of fossil fuels. Large quantities of carbon dioxide gas and atmospheric pollutants are produced. Because of the high costs of production and emissions, most zinc production uses electrolytic reduction. More than 90% of world zinc production is from the electrolytic method. Electrolytic reduction of an aqueous zinc sulfate solution does not require elevated temperatures to allow operation of the cell. This provides a considerable cost saving when compared to the energy requirements of the thermal process or a molten cell.

Science understanding

Electrolytic cells are used to produce required substances.

Identify the anode and cathode and their charges, as well as the direction of ion and electron flow in an electrolytic cell, given sufficient information.

Write electrode half-equations for an electrolytic cell, given sufficient information.

© SACE 2025

Electrolytic cells

Electrolytic cells are electrochemical cells that generate redox reactions when an electrical current is applied. Electrical energy is converted to chemical energy. A power supply is used to generate a potential difference between two electrodes (anode and cathode). Electric current flows between the anode and cathode; this current initiates non-spontaneous redox reactions at the surface of each electrode (Figure 4.4.11). Electrolysis is commonly used to decompose chemical compounds and to reduce metal ions to metals.

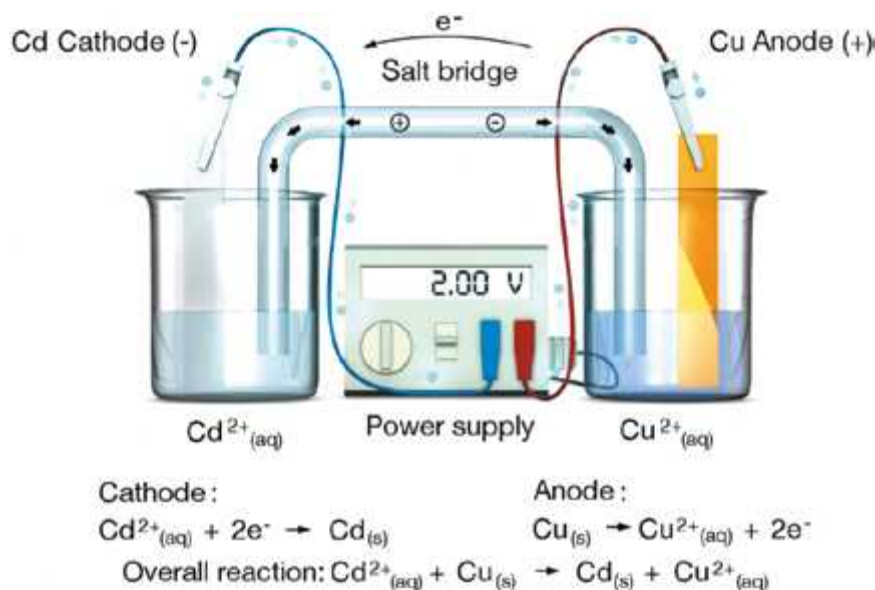


Figure 4.4.11: Copper-cadmium electrolytic cell

The operation of an electrolytic cell can be summarised as follows.

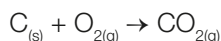
Electrolytic cell	
Energy conversion (forced)	Electrical energy to chemical
Anode reaction	Oxidation
Cathode reaction	Reduction
Electron flow	Anode to cathode
Sign of anode	Positive (+)
Sign of cathode	Negative (-)
Anion movement	Anode
Cation movement	Cathode

Electrolytic cells used in metal production

Electrolytic cells are often used for the reduction and refining stages in metal production.

Reduction of aluminium (molten cell)

The cell is lined with graphite (carbon) as the cathode (–). Blocks of graphite (carbon) are suspended in the molten electrolyte as the anode (+). Aluminium oxide (alumina, Al_2O_3) is introduced to the cell along with cryolite (acting as a flux to lower the melting point of the alumina) to form the electrolyte. The mixture is still required to be heated to above 1000°C to form a molten electrolyte. Strong ionic bonding is overcome in the compounds to provide a molten electrolyte capable of conduction due to free ions. Electrical current is applied for the reduction in the electrolytic cell. Aluminium ions are reduced to molten aluminium at the cathode. The molten aluminium is denser than the molten cryolite and settles as a layer in the bottom of the cell and can be periodically tapped off and cast. At the anode, oxide ions are oxidised to form oxygen. Combustion of the carbon occurs at the anode, which must be replaced periodically.



Reduction of aluminium is an extremely energy-intensive process that requires high temperatures to be maintained and an effective supply of electricity (Figure 4.4.12).

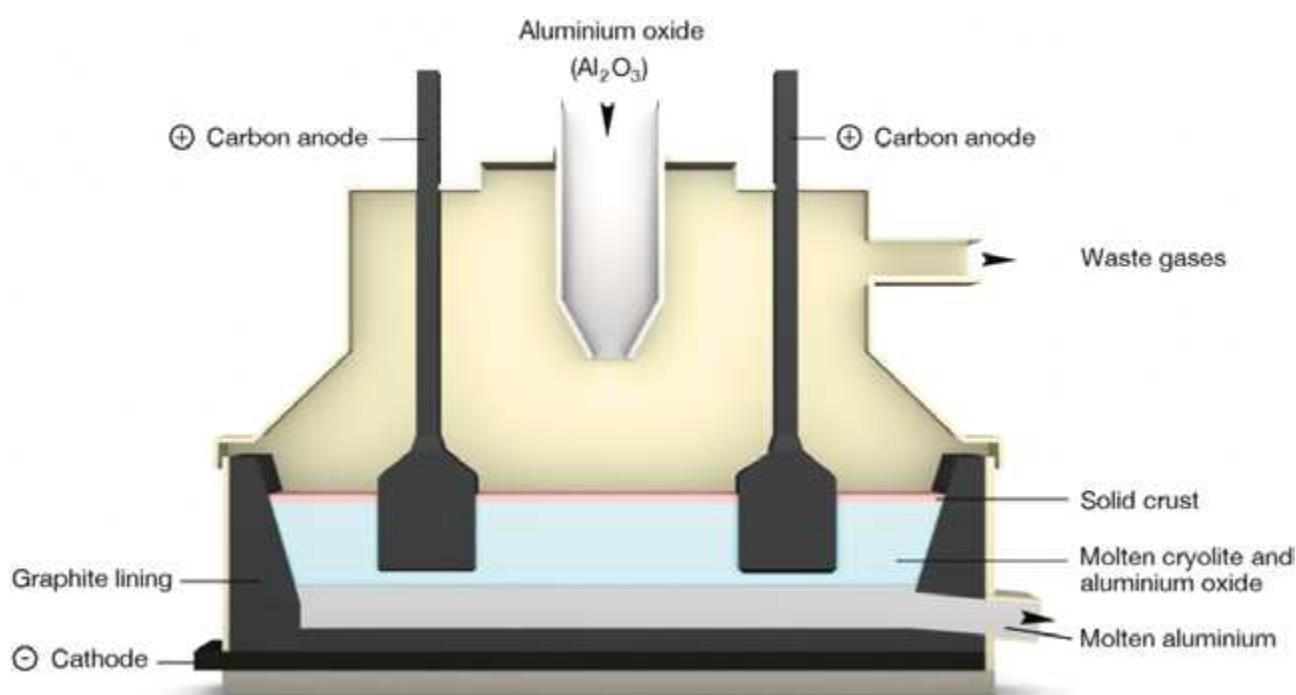


Figure 4.4.12: Aluminium production, electrolytic cell.

Cell features	
Electrolytic (molten cell)	
Anode (+)	$2\text{O}_{(\text{l})}^{2-} \rightarrow \text{O}_{2(\text{g})} + 4\text{e}^-$
Cathode (–)	$\text{Al}_{(\text{l})}^{3+} + 3\text{e}^- \rightarrow \text{Al}_{(\text{s})}$
Electron flow	Anode (+) to cathode (–)
Anion movement	$\text{O}_{(\text{l})}^{2-}$ ions migrate to the anode
Cation movement	$\text{Al}_{(\text{l})}^{3+}$ ions migrate to the cathode

Reduction of zinc (solution cell)

Lead is chosen as the anode due to the metal being relatively inert. Water in the cell is oxidised in preference to lead, eliminating the need to replace the anode. The direction of electron flow in the cell is from the lead anode (+) to the aluminium cathode (–), driven by the potential difference of the power supply. Zinc ions are reduced to high-purity zinc at the cathode. The relative activity of zinc compared to water allows zinc ions to be reduced using aqueous electrolysis. An aqueous cell is preferred to a molten cell because the process is less energy-intensive, as it does not require high temperatures to be maintained. The electrodes sit in a single container of zinc sulfate (ZnSO_4) as the electrolyte. Zinc cations migrate towards the cathode and water molecules migrate towards the anode (Figure 4.4.13).

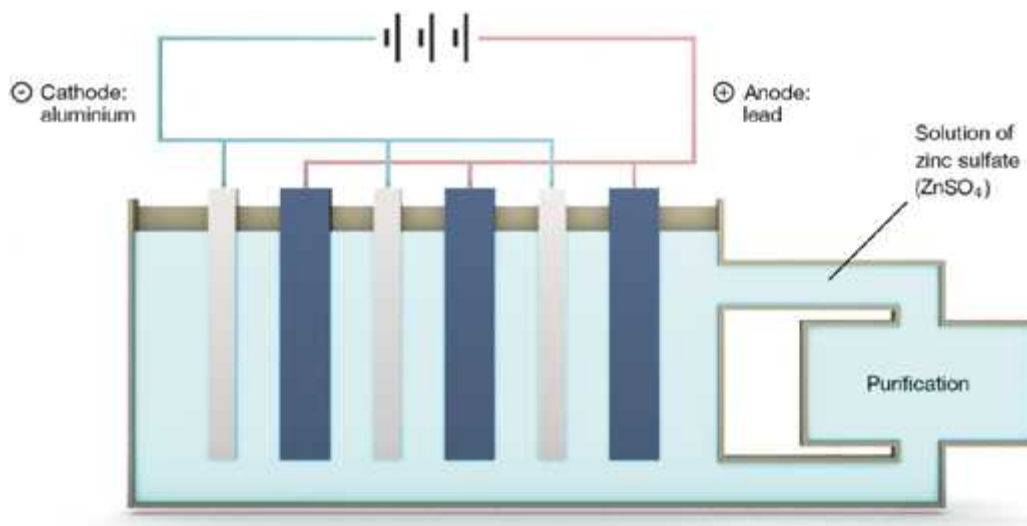


Figure 4.4.13: Zinc production, electrolytic cell.

Cell reactions	
Electrolytic (solution cell)	
Anode (+)	$2\text{H}_2\text{O}_{(l)} \rightarrow \text{O}_{2(g)} + 4\text{H}^+_{(aq)} + 2\text{e}^-$
Cathode (–)	$\text{Zn}^{2+}_{(aq)} + 2\text{e}^- \rightarrow \text{Zn}_{(s)}$
Electron flow	Anode (+) to cathode (–)
Anion movement	H_2O molecules migrate to the anode
Cation movement	$\text{Zn}^{2+}_{(aq)}$ ions migrate to the cathode

Question

38. Copper is one of the most widely used metals in the world, used extensively in electrical wiring and in alloys.
- (a) Approximately 80% of the world's primary source of copper comes from copper ores containing sulfide minerals. Chalcopyrite is the most abundant copper ore.

Calculate the percentage composition of Cu in chalcopyrite (CuFeS_2).

(2 marks) **KA2**

- (b) The copper ore is crushed and ground and then undergoes froth flotation.
- (i) **State** the purpose of crushing and grinding the ore prior to froth flotation.

(1 mark) **KA1**

- (ii) **State** the purpose of froth flotation.

(1 mark) **KA1**

- (iii) Froth flotation is commonly undertaken at the mine site rather than during final processing.

- (1) **Discuss** one advantage to the manufacturer of undertaking froth flotation at the mine site.

(2 marks) **KA3**

- (2) **State** one advantage to the environment of undertaking froth flotation at the mine site.

(1 mark) **KA3**

- (c) Copper is commonly produced using chemical reduction at elevated temperatures.

- (i) Solid copper(II) sulfide, CuS , is heated in a blast furnace with oxygen-enriched air to form copper and sulfur dioxide gas.

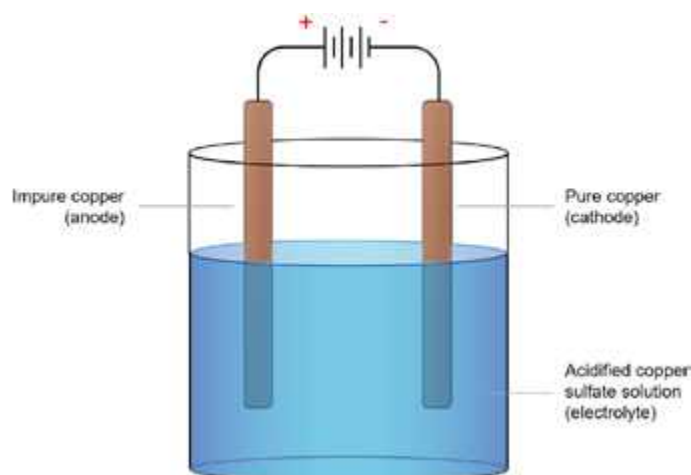
Write a fully balanced chemical equation for this process.

(2 marks) **KA4**

- (ii) **Explain** why chemical reduction is used for the production of copper.

(2 marks) **IAE3**

- (d) The product of chemical reduction is blister copper with a lower purity. This is placed at the anode of an electrolytic cell for refining. A simplified diagram of the cell is shown below.



- (i) **State** how the refining stage increases the purity of copper.

(1 mark) **KA1**

- (ii) **Suggest** why, in the application of electrical wiring, high-purity copper is required.

(1 mark) **IAE3**

- (iii) **State** the charge on the electrode at which pure copper is produced.

(1 mark) **IAE3**

- (e) Copper was produced via a different method from an ore containing a mixture of compounds containing copper and calcium. The ore was roasted in air and then digested in acid to produce an aqueous solution. The solution, containing $\text{Cu}_{(\text{aq})}^{2+}$ and $\text{Ca}_{(\text{aq})}^{2+}$, was then placed in an electrolytic cell to reduce the metals.

- (i) **Write a half equation** for the reduction of $\text{Cu}_{(\text{aq})}^{2+}$ at the cathode.

(2 marks) **KA4**

- (ii) After all of the copper had been reduced from aqueous solution, a different reaction began to occur at the cathode.

State and **explain** the reaction that occurred at the cathode at the conclusion of the reduction of copper.

(3 marks) **IAE3**

- (f) Bacteria can be used to obtain copper. Acidified water is sprayed onto mining tailings (left over rock from mining processing) which contain low levels of copper minerals.

- (i) As acidic water penetrates through the crushed rock, bacteria break down the iron sulfides and convert iron(II) to iron(III).

- (1) **State** whether this conversion represents oxidation or reduction.

(1 mark) **IAE3**

- (2) **Suggest** one reason why this method of obtaining copper is not adopted over conventional methods of copper production.

(1 mark) **KA3**

- (ii) Iron(III) oxidises the sulfides of the copper sulfides to sulfates in tailings. Copper(II) sulfate remains in solution and can be recovered and reduced with the addition of scrap iron.

Explain, with the aid of an equation, how solid scrap iron can reduce copper.

(3 marks) **KA2**

39. Magnesium is the third-most-commonly-used structural metal, widely employed in a variety of applications. It is valued for being lightweight, making it essential in industries such as automotive and aerospace. It is also known for its excellent strength-to-weight ratio and good corrosion resistance. Despite being abundant in the Earth's crust, the extraction of magnesium can be complex and energy-intensive. The Pidgeon process is currently the most commonly used method for extracting magnesium.

(a) The mineral dolomite, $\text{CaMg}(\text{CO}_3)_2$, is used as the precursor for producing magnesium oxide in the Pidgeon process.

(i) **Calculate** the percentage composition of magnesium in dolomite.

(2 marks) **KA1**

(ii) **Write a balanced chemical equation** for the decomposition of dolomite to form magnesium oxide, calcium oxide, and carbon dioxide.

(2 marks) **KA4**

(b) In the Pidgeon process, magnesium oxide is reduced to magnesium metal using silicon as a reducing agent.

Write a balanced chemical equation for the reduction of magnesium oxide and calcium oxide with silicon to produce magnesium metal and calcium silicate, Ca_2SiO_4 .

(2 marks) **KA1**

(c) The Pidgeon process is carried out at elevated temperatures. **Explain** why high temperatures are necessary for the reduction of magnesium oxide.

(2 marks) **IAE3**

(d) During the production of magnesium via the Pidgeon process, magnesium is produced in its gaseous form and then condensed.

(i) **Explain** how the condensation of magnesium gas allows for a high-purity product to be obtained.

(2 marks) **IAE3**

(ii) **State** one advantage to the manufacturer of obtaining high-purity magnesium as a product of the reduction reaction.

(1 mark) **IAE3**

- (e) In September 2021, China reduced magnesium production due to energy concerns. **Suggest** and **explain** one possible effect of a significant reduction in global magnesium production.

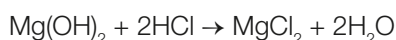
(2 marks) IAE3

- (f) Another method for extracting magnesium is via electrolysis from seawater. In this process, calcium hydroxide is used to precipitate magnesium hydroxide from seawater.

- (i) **Write** a balanced chemical equation for the reaction of magnesium chloride with calcium hydroxide.

(2 marks) KA4

- (ii) Magnesium hydroxide is poorly soluble in water and can be collected by filtration. It reacts with hydrochloric acid to give magnesium chloride.



- (1) **Write** the oxidation states for each atom in the equation above.

(1 mark) KA1

- (2) Hence, **state** whether this is a redox reaction.

(1 mark) KA1

- (iii) Magnesium metal is obtained by the electrolytic reduction of magnesium chloride. **Write** a half-equation showing the conversion of magnesium ions to elemental magnesium.

(2 marks) KA4

- (iv) **Suggest** one advantage of producing magnesium from seawater as opposed to using the Pidgeon process.

(1 mark) KA3



Science as a human endeavour

Platinum Group Metals

The platinum group metals (PGMs)—platinum, palladium, rhodium, iridium, osmium, and ruthenium—are highly valuable due to their unique catalytic properties, which are indispensable in various industries. For example, platinum is widely used in catalytic converters but is also popular as jewellery. Smaller amounts are used in chemical production, electrical applications, and specialised fields like medicine and glassmaking.

Historically, the world has relied heavily on Russia and South Africa for the supply of PGMs, with these countries dominating global production. However, geologists continually explore for new deposits, often found in conjunction with nickel or copper in layered igneous formations. A recent breakthrough came in 2020 with Chalice Mining's discovery of the Gonneville deposit in Western Australia. This find marks the largest PGM discovery in Australian history—before this, Australia had produced PGMs only in small quantities, primarily as by-products from nickel sulfide mines.

The extraction and refinement of PGMs is a complex process that heavily depends on chemistry. Once ore containing PGMs is mined, it is crushed and subjected to flotation, which concentrates the PGM minerals. Hydrometallurgical techniques such as leaching and solvent extraction follow, allowing for the separation and purification of specific metals.

Mining and chemical engineers are responsible for scaling up the extraction and refining processes, designing efficient equipment and integrating automation to improve productivity. Environmental scientists play a crucial role in assessing the ecological impact of mining and refining and developing waste reduction strategies to minimise environmental damage. Meanwhile, materials scientists and physicists are exploring new uses for PGMs in cutting-edge technologies like fuel cells, driving innovation and increasing demand for these metals.

40. (a) **Explain** how the discovery and development of the Gonneville deposit discovery in Western Australia required evidence from multiple sources and scientific disciplines.

(3 marks) KA3

- (b) **Explain** how effective communication between geologists, chemists, and environmental scientists is crucial in the discovery, extraction, and refining of PGMs. **Suggest** and **explain** one potential negative outcome of poor communication between these fields.

(3 marks) KA3

- (c) **Identify** and **explain** how new technology has improved the process of extracting and refining PGMs, and suggest why this technological development is important for the mining industry.

(3 marks) KA3

- (d) **Explain** how advances in fuel cell technology, which use Platinum Group Metals (PGMs), could influence future demand for PGMs. **Suggest** another area of science or technology that this development might influence.

(3 marks) KA3

4

Science understanding

There is a finite amount of materials on Earth. Materials that can be recycled reduce the amount of new materials that need to be produced from the Earth's crust.

Explain the advantages of recycling materials.

Some objects are difficult to recycle.

Explain the difference in the ease of recycling thermoplastic and thermoset polymers.

© SACE 2025

Recycling

Recycling involves the processing of waste products to extract raw materials or make them suitable for reuse. Recycling materials means that finite resources extracted from the Earth can be reused. Recycling also reduces energy demands from the extraction and processing of raw materials.

Recycling of polymers

Polymers have become an essential material in everyday life, but also generate an abundance of waste products. Certain polymers may be recycled or converted into fuels. One of the most labour and energy-intensive stages in polymer-recycling is the sorting of polymer types prior to recycling. Polymers can be separated based on physical and chemical properties such as colour, IR absorption, and density.

Recycling thermoplastic and thermoset polymers

Thermoplastic polymers can be cleaned, ground, melted and used to form new materials. As temperatures are raised, the large molecular chains move freely past one another and flow, allowing them to be extruded and recast. The polymers may be recycled many times before the polymer chains begin to decompose.

As the degree and density of cross-linking is increased, the ease of recycling is reduced. As the polymers are heated, covalent cross-links hold the network of polymer chains in fixed positions, until eventually the polymer decomposes by combustion. Recycling codes have been established to assist in separating polymers. A higher recycling code indicates increased difficulty in recycling. The higher number reflects an increase in the extent of cross-linking in the polymer. This increase also represents a change in the type of polymer, from a thermoplastic to a thermoset, as extensive cross-linking is introduced.

Recycling code	Polymer	Category	Uses	Recycled products
1 PET	polyethylene terephthalate (polyester)	Thermoplastic	Plastic soft-drink bottles	Polar fleece fabric
2 HDPE	High-density polyethylene	Thermoplastic	Bottles	Plastic decking and benches
3 PVC	polyvinyl chloride	Thermoplastic	Piping, detergent bottles, food wrap	Speed bumps
4 LDPE	Low-density polyethylene	Thermoplastic	Shopping bags	Bin liners
5 PP	polypropylene	Thermoplastic	Sauce and medicine bottles	Brooms and pallets
6 PS	polystyrene	Thermoplastic	Packaging, cups, plates	Packaging and insulation
7 OTHER	Melamine	Thermoset	Kitchen benchtops	Not easily or often recycled

Depolymerisation

Some classes of polymers can be depolymerised to reform monomers. The monomers are then isolated through fractional distillation and reused to make the polymer again.

Example

PET used for plastic bottles is dissolved in benzene-1,4-dioic acid (terephthalic acid) and heated with methanol under pressure to reform the monomers benzene-1,4-dioic acid and ethane-1,2-diol.

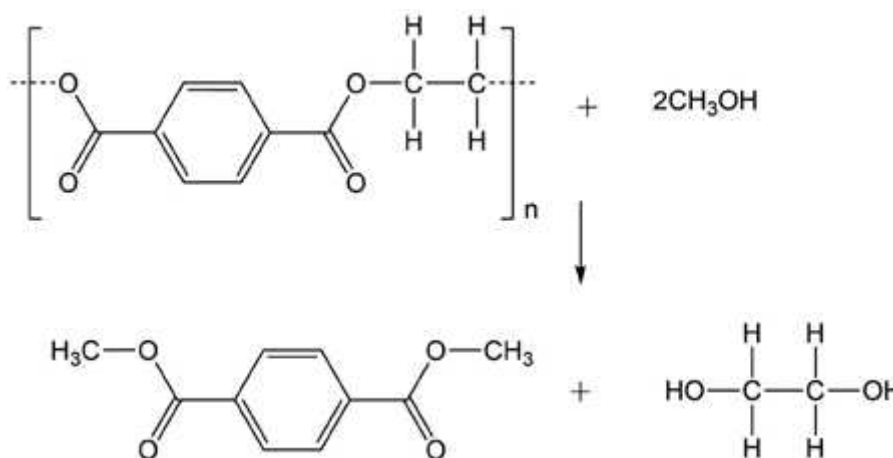


Figure 4.4.14: Depolymerisation of PET.



Science as a human endeavour

Recycling thermoset polymers

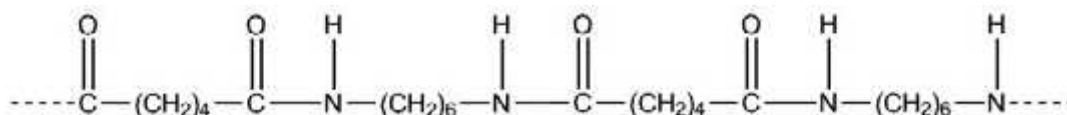
A proportion of the polymers that are disposed of as waste comprise thermoset polymers. Applications that require rigid polymers such as kitchen utensils, benchtops, and computer components are made from thermosetting polymers. As a result of curing, once set, the three-dimensional structure that is produced through extensive cross-linking is extremely difficult to break down and will not melt on heating. Therefore it cannot be recycled.

Researchers are investigating the production of recyclable thermosetting polymers that can be broken down and reformed. These are known as polyhexahydrotriazines (PHTs). PHTs break down on the addition of a strong acid. The monomers were able to be recovered from this process and used to produce new polymers. PHTs have been shown to demonstrate many of the properties of traditional thermosets: thermal and environmental stability, chemical resistance, and rigidity. By varying the composition of the monomers, researchers were also able to produce elastomers (elastic polymers). These new thermosets have the potential to replace traditional thermosets in applications in electronics and the automotive industry. Importantly, this will provide a new class of thermosets that can be recycled like thermoplastics, leading to less disposal in landfill.

Question

41. Many synthetic carpets are made from nylon-6 and nylon-6,6, due to the versatility and durability of the fibres.

(a) A section of nylon-6,6 is shown below.



(i) **State** the type of polymerisation reaction used to form nylon-6,6.

(1 mark) IAE3

(ii) **Name** the functional group linking the monomer units.

(1 mark) KA1

(iii) Hydrogen bonding occurs between polymer chains. **Describe** hydrogen bonding.

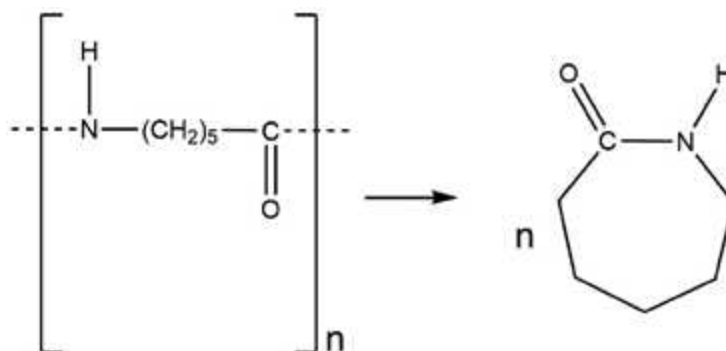
(2 marks) KA2

(iv) **State** and **explain** whether synthetic carpets made from nylon-6,6 would be expected to be easily recycled.

(3 marks) IAE3

- (b) Nylon-6 used in carpets can be turned back into its monomer, caprolactam. The carpet is shredded and pulverised before heating to depolymerise the nylon-6.

The reaction for the process is represented below.



- (i) **State** the feature of caprolactam that allows it to form the polymer nylon-6.

(1 mark) IAE3

- (ii) **Discuss** two advantages to the manufacturer of recycling carpets made of nylon-6 using this process.

(4 marks) KA3

- (iii) **Discuss** one advantage to the environment of recycling carpets using this method.

(2 marks) KA3

Recycling of metals

The recycling of metals (secondary production) is increasing as resources become scarce and cost of production and environmental emissions increase. Significant quantities of aluminium, lead, zinc, copper and iron are produced through recycling.

Recycling of metals means that less ore needs to be mined from the Earth's crust. Less mining leads to reduced environmental impact and fewer emissions associated with mining practices. The removal of some of the stages associated with metal production also reduces energy requirements and consequent emissions of environmental pollutants. After recycling, the stages of metal production typically follow the stages in the traditional production of the metal, so existing techniques and infrastructure can be utilised.

Examples

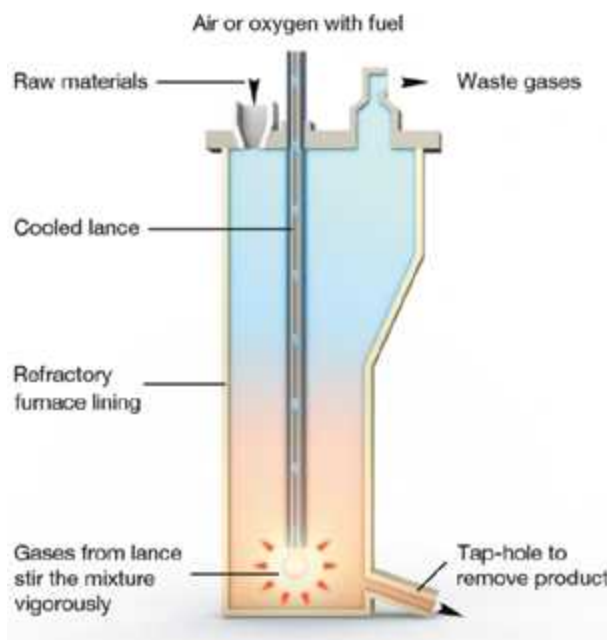
More than 50% of the aluminium used to make new products comes from recycled wastes. Aluminium is easily recycled at very low cost simply through melting and reforming. The aluminium wastes are sorted into like alloys, introduced into a furnace and run off as molten aluminium, which is cast as ingots (blocks of metal). The gases released from the combustion of printed labels can be used as a fuel source for the furnace. Aluminium can be recycled repeatedly.

More than 35% of the zinc used to make new products comes from recycled wastes (new scrap and old products). A large proportion of this is galvanised products such as roofing iron. The wastes containing zinc are placed in an

electric-arc furnace used for recycling steel. The zinc has a relatively low boiling point and exits the furnace with other gases. As it cools it forms zinc dust, which can be collected. It is then roasted, leached, and electrolytically reduced utilising the same stages as zinc production.

Question

42. The Isasmelt process is used for the recycling of lead paste from lead–acid batteries in a single-stage process.



- (a) The lead paste, as a raw material, is fed into a furnace and melted using a lance, which burns fuel and oxygen-enriched air to produce the high temperatures required.

(i) **Identify** two raw materials in the process.

(2 marks) **KA1**

(ii) **Explain** why the combustion of fuel in oxygen-enriched air increases the rate of reaction compared to combustion in air.

(3 marks) **KA2**

- (b) Coal, which contains carbon, is introduced as a reducing agent.

(i) **Explain** why lead ions can be reduced using this method.

(2 marks) **KA1**

(ii) **State** why this method is preferable to electrolytic reduction.

(1 mark) **KA1**

- (c) More than 50% of the lead used globally comes from recycled methods.

State one advantage to the manufacturer and one advantage to the environment of recycling lead.

(2 marks) **KA3**

Science understanding

Composite materials comprise two or more constituent materials to produce a material with properties different from the individual components.

Explain the advantages using of composite materials.

Explain the difficulties associated with recycling materials and objects comprising two or more different materials with different properties.

© SACE 2025

Composite materials

Composite materials consist of two or more different materials combined to create a material with enhanced properties that are often superior to those of the individual components. These materials are commonly used to increase strength, durability, and flexibility, making them valuable in various applications, from construction to high-tech industries. For example, concrete is a composite made of cement, sand, and aggregate, sometimes reinforced with steel, offering excellent structural support in buildings and bridges.

In synthetic composites, the materials generally consist of a **matrix** (a continuous phase that binds everything together) and **reinforcement fibres** (a dispersed phase that adds strength or rigidity). For instance, carbon fibre-reinforced polymers (CFRPs) combine a resin matrix with carbon fibres, resulting in a material that is incredibly lightweight yet very strong. These composites are commonly used in aerospace, automotive racing, and sports equipment due to their high strength-to-weight ratio and durability.

Natural composites

Nature also provides examples of composite materials. Wood, for example, is a natural composite made from cellulose fibres bonded together by lignin. This combination gives wood its strength and resilience, allowing it to support weight and withstand various environmental conditions. Similarly, human bones are natural composites made of collagen and hydroxyapatite, which provide both flexibility and strength.

Synthetic composites

Synthetic composites, created by humans, offer even more control over material properties, allowing for customisation for specific uses. Examples include fibreglass, which combines glass fibres with a plastic resin for use in boat hulls, and carbon fibre composites in aircraft for lightweight durability.

Concrete is a widely used example of a composite. Concrete consists of aggregate, sand, cement and sometimes steel reinforcement. Together the materials generate a strong, versatile building material.

Modern synthetic composite materials are typically made of two components: the **matrix** (binder) and the material acting as the **reinforcement** (fibres). Many high-performance synthetic composites consist of a matrix of thermoplastic or thermosetting polymer and a reinforcement of fibres of carbon, aramid, glass, or metals such as titanium (Figure 4.4.15).

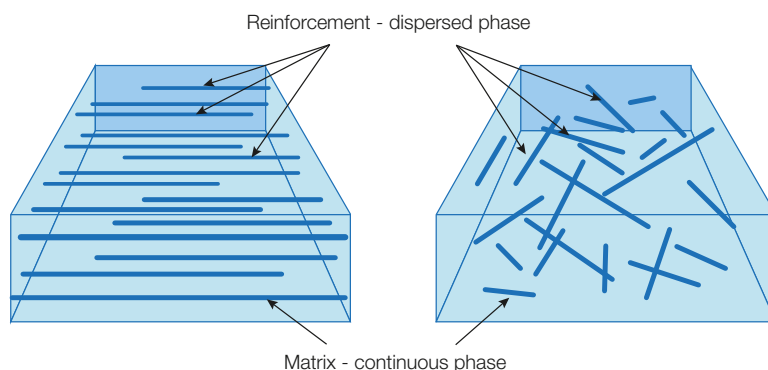


Figure 4.4.15: Matrix and reinforcement fibres in a synthetic composite.

Carbon fibre reinforced polymer (CFRP) is used in sporting goods, automotive racing, and aircraft. The matrix is often a thermoset resin such as epoxy or a thermoplastic polyester or polyamide. The reinforcement is typically carbon fibre (carbonised polymers such as rayon), sometimes mixed with metal fibres or even carbon nanotubes. The resulting composite can be moulded into a variety of shapes to suit its application, with the fibres set and woven in different arrangements to alter the properties offered. Carbon-fibre composites offer exceptional strength-to-weight and rigidity.

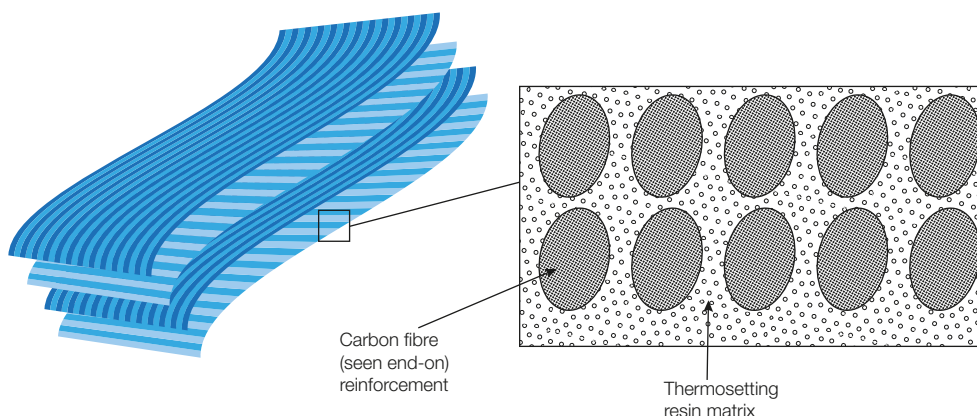


Figure 4.4.16: Synthetic composite, sheets of woven carbon fibres set in resin.



Science as a human endeavour

The Future of Recycling: Turning Waste into High-Quality Resources

As the use of high-performance composites like carbon-fibre-reinforced polymers (CFRP) grows in sectors like aerospace, automotive, and sports, the question of what happens to these materials at the end of their life cycle becomes critical. Traditional recycling methods struggle to recover usable materials from composites, often resulting in degraded components that are unsuitable for high-quality reuse. However, recent advancements in recycling technology are changing the game. Innovative chemical processes, such as depolymerisation, allow scientists to break down polymers back into their original monomers. This process enables the recovery of raw materials in near-pristine form, making it possible to reuse them in new high-performance products without compromising quality.

Recycling composite materials

Recycling composite materials poses significant challenges due to their complex structure and the strong bonds between different components. Unlike single-material products, composites are heterogeneous, meaning they contain multiple phases that are often difficult to separate. Traditional recycling methods, such as mechanical grinding, thermal melting, or chemical hydrolysis, can partially recover some components, but the process is often costly, energy-intensive, and results in lower-quality recycled materials.

Thermosetting polymers, which are commonly used in composite matrices, cannot be remelted or reshaped, making the separation of matrix and reinforcement difficult. As a result, only a limited percentage of composite materials are currently recycled, highlighting the need for innovation in recycling technologies and sustainable design practices. Advancements in chemical recycling and the development of recyclable thermoset composites offer potential solutions for the future.

Recycling composites is essential for conserving resources, reducing waste, and lowering the environmental footprint of manufacturing industries. For example, recycling carbon fibre can save significant amounts of energy compared to producing new fibres. As composite materials are used increasingly in various industries, addressing recycling challenges is crucial for sustainable resource management. Research into new recycling techniques and policies to support the recycling of composites is ongoing, with a focus on reducing costs and improving the quality of recycled materials.



Science as a human endeavour

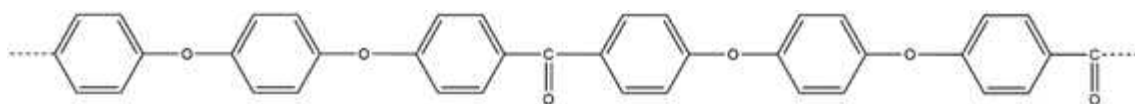
Smart composites

With the increase in fibre-reinforced composites being used in aircraft, aerospace and engineered structures, scientists are interested in real-time monitoring of materials, via sensors built into the composite material. Advancements in nanotechnology have allowed researchers to develop extremely small sensors that can be incorporated along with composite fibres. Embedded sensors are networked throughout the load-bearing structure and relay live data about forces and stresses experienced, leading to the early detection of potential failure. The ultimate goal in future composite technology is to produce lighter, stronger, self-diagnosing and self-healing composites with computational and communication abilities – robotic materials!

Question

43. Since the 1980s, polyaryletherketones (PAEKs) have been used as biomaterials for orthopaedic and spinal implants as the individual polymer and as a composite.

(a) The structure of a section of the PAEK polymer is shown below.



- (i) **Bracket** the repeating unit on the section of polymer above. (1 mark) **KA4**
- (ii) PAEK is a high-temperature thermoplastic.

Identify the predominant interaction that would occur between polymer chains.

(1 mark) **IAE3**

- (b) PAEK can be used as the matrix added to carbon-fibre reinforcement in the creation of spinal implants.

- (i) **Explain** two advantages of creating an implant for the human spine made from a composite material containing carbon fibre and a polymer.

(3 marks) **IAE3**

- (ii) **Suggest** why a composite made from carbon fibre and PAEK polymer would be easily recycled.

(1 mark) **IAE3**

- (iii) **Suggest** one property required of a composite that is introduced to the human body.

(1 mark) **KA3**

44. Biodegradable polymers are increasingly used in packaging to reduce environmental waste. Polylactic acid (PLA) is a common biodegradable polymer derived from renewable resources, such as corn starch.

(a) PLA decomposes into water and carbon dioxide under specific conditions.

Explain why PLA is considered a sustainable alternative to traditional plastic polymers.

(2 marks) **KA3**

(b) PLA has a lower melting point than many traditional plastics like polyethylene.

Describe one advantage and one disadvantage of this lower melting point in the context of packaging applications.

(2 marks) **IAE3**

(c) PLA is primarily used in applications that do not require high strength or durability, such as disposable cutlery and food packaging. **Suggest** one reason why PLA is less suitable for long-term use compared to traditional plastics.

(1 mark) **KA1**

(d) Scientists are researching ways to improve the mechanical properties of PLA by blending it with other biodegradable materials. **Explain** how blending PLA with other materials could potentially enhance its properties and expand its applications.

(2 marks) **IAE3**

Summary test 4: Managing resources

1. Motorsports have often been the testing ground for advancements in technologies, such as alternative fuels and materials, as manufacturers pursue greater performance with less impact on the environment.
- (a) In recent years, the V8 supercar series in Australia has substituted the use of high-octane petrol for E85, a blend of petrol with up to 85% bioethanol.

- (i) Sucrogen[®], bioethanol used by the V8 supercar series, is produced from sucrose extracted from sugarcane. The disaccharide, sucrose, is converted into the monosaccharide, glucose, prior to fermentation.

Write a fully balanced chemical equation for the fermentation of glucose to produce ethanol.

(2 marks) **KA4**

- (ii) Ethanol undergoes combustion in fuel blends or as a pure liquid.

Write a thermochemical equation for the complete combustion of ethanol, which releases 1371 kJ of energy for every mole of fuel.

(4 marks) **KA4**

- (iii) **Calculate** the specific energy, in kJ g⁻¹, for ethanol.

(2 marks) **KA4**

- (iv) Specific energy and energy density can be determined for a fuel.

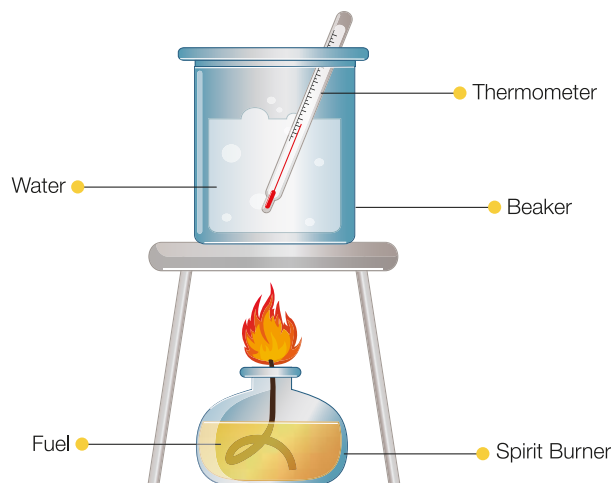
Suggest why energy density is important to car racing.

(1 mark) **KA3**

- (v) **Discuss** one advantage of the production and use of an E85 bioethanol blend compared to high-octane petrol derived from crude oil.

(2 marks) **KA1**

- (b) Many drag-racing cars run on pure methanol as a fuel, to produce engine outputs well in excess of 1000 horsepower.
- (i) The molar enthalpy of combustion for pure methanol was determined experimentally using the apparatus shown below.



- (1) A sample of pure methanol was burnt in a spirit burner under a beaker containing 100 mL of distilled water. The burner remained alight until a temperature change of 30°C was obtained. The mass of the spirit burner decreased by 1.8 g. (Specific heat capacity of water $c = 4.18 \text{ J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$.)

Calculate the molar enthalpy of combustion of methanol in kJ mol^{-1} .

(4 marks) **KA4**

- (2) **Suggest** one reason why the value obtained was considerably lower than the expected reference value for methanol.

(1 mark) **IAE4**

- (ii) Methanol and octane, present in petrol, are both burnt in internal combustion engines in different categories of drag racing.

When methanol is burnt, a significantly greater proportion the fuel undergoes complete combustion, rather than incomplete combustion, when compared with octane. **State** why this is so.

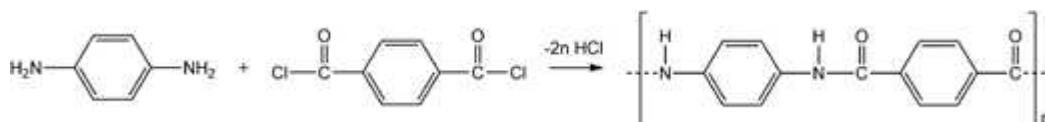
(1 mark) **KA2**

- (iii) Nitrous oxide (N_2O) is also added to the combustion of the fuels in the some drag cars. At elevated temperatures, nitrous oxide decomposes, releasing oxygen.

Explain how nitrous oxide allows fuel to undergo combustion at a faster rate, thus producing more power from the engine.

(3 marks) **KA2**

- (iv) The engines and transmission in drag cars are surrounded by a Kevlar blanket in the event of catastrophic failure.

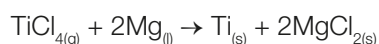


- (1) **State** the name of the type of polymerisation reaction undertaken to form Kevlar.
(1 mark) **IAE3**
- (2) As a fabric, the polymer fibres offer exceptional strength between polymer chains. **State** the name of the secondary interaction that accounts for this strength.
(1 mark) **KA1**
- (c) Many advanced materials have been engineered for Formula One racing.
- (i) Alloys and composites of titanium used extensively in Formula One cars offer exceptional strength to weight. Most of the world's titanium is extracted from ores containing titanium dioxide.
- (1) Titanium can be mined economically from beach sand containing rutile (TiO_2) and ilmenite (FeTiO_3) as well as smaller quantities in the silicate zircon (ZrSiO_4).

State the charge on the silicate anion present in zircon.

(1 mark) **KA4**

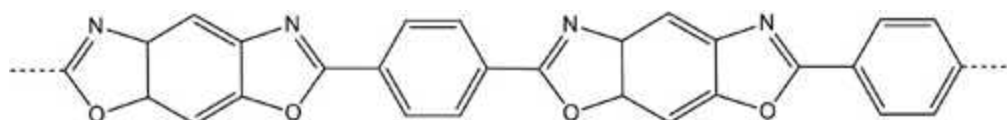
- (2) Titanium dioxide is converted to titanium chloride, suitable for chemical reduction with magnesium according to the equation below.



Explain how magnesium is able to reduce titanium ions.

(2 marks) **IAE3**

- (ii) The polymer Zylon® is used to create fibres. The fibres are used to tether wheels to the chassis of Formula One cars, and are also used in the formation of epoxy-composites to line the cockpit of the car. In both applications, the materials provide safety to the driver and spectators.



- (1) **Bracket** the repeating unit in Zylon® on the diagram above.
(1 mark) **KA4**
- (2) Epoxy resins have the ability to form extensive cross-linking within the composite.
State the effect of cross-linking on the rigidity of the composite.

(1 mark) **KA1**

- (3) Zylon® fibres are used as reinforcement and combined with an epoxy resin polymer as the matrix, to form an impenetrable composite that lines the driver's cockpit.

State one advantage of using a composite in this application.

(1 mark) **KA1**

- (4) **Describe** one difficulty in recycling car components made of composites containing thermoset polymers.

(2 marks) **KA2**

- (d) The many composite materials used in modern motorsports result in composite waste from damaged and redundant components. New research has revealed promising methods to recycle carbon fibre plastics CFRP, a common material used in racing cars.

Advances in materials development of carbon fibre reinforced plastics, CFRP, have led to their increased use for innovations in the motorsports and aviation industries. The materials are applicable in these industries due to their low density, producing incredible strength to weight ratios as composite materials. CFRP offers enhanced properties as a composite in comparison to the original materials in its composition.

Carbon fibres, as the reinforcement, are encased in thermosetting polymers as a matrix material. The polymer resins are often cured to create extensive crosslinking to bind the aligned or woven fibres. The composite does not breakdown naturally due to the strong covalent bonds present in both the carbon fibre and resulting polymer, persisting in the environment for hundreds of years. Conventionally, recycling has also been difficult due to the thermosetting nature of the polymer. Heating the composite to high temperatures results in decomposition of both the reinforcement and matrix material. Hence, it is extremely difficult to return the composite to the original materials it was made from.

Initial efforts from researchers to recycle the composite materials have focused on mechanical methods of chopping or grinding, or the use of highly caustic chemicals to dissolve components. Both methods have proven ineffective as they destroy the original matrix material as well as the costly to produce carbon fibres. Undesirable and even hazardous wastes also result from the process leading to further issues of disposal.

Researchers have developed a new technique for recycling using mild acids as a catalyst along with ethanol. When warmed, the ethanol causes the composite to expand and the catalyst permeates to break down crosslinking in the polymer, allowing the carbon fibres to be separated. This allows both the reinforcement and matrix to be recovered and reused.

With reference to the key concepts of application and limitation or development, **explain** how the process for recycling carbon fibre plastics exemplifies science as a human endeavour.

4

(4 marks) **KA3**

2. South Australia, a global leader in renewable energy, installed the world's first lithium-ion "big battery" at the Hornsdale Power Reserve in 2017. Since then, the state's battery capacity has grown significantly, soon to exceed 260 MW and 480 MWh, cementing its position at the forefront of energy storage innovation.
 - (a) In 2023, South Australia's energy generation from renewables was approximately 75%, with a target to reach 100% net renewable energy by 2030. However, nationally, most electricity is still obtained from coal and gas-fired power stations, where fuels undergo combustion to generate steam that drives turbines.
 - (i) Soot is released into the atmosphere during the combustion of coal. Some of this soot is deposited in populated areas.

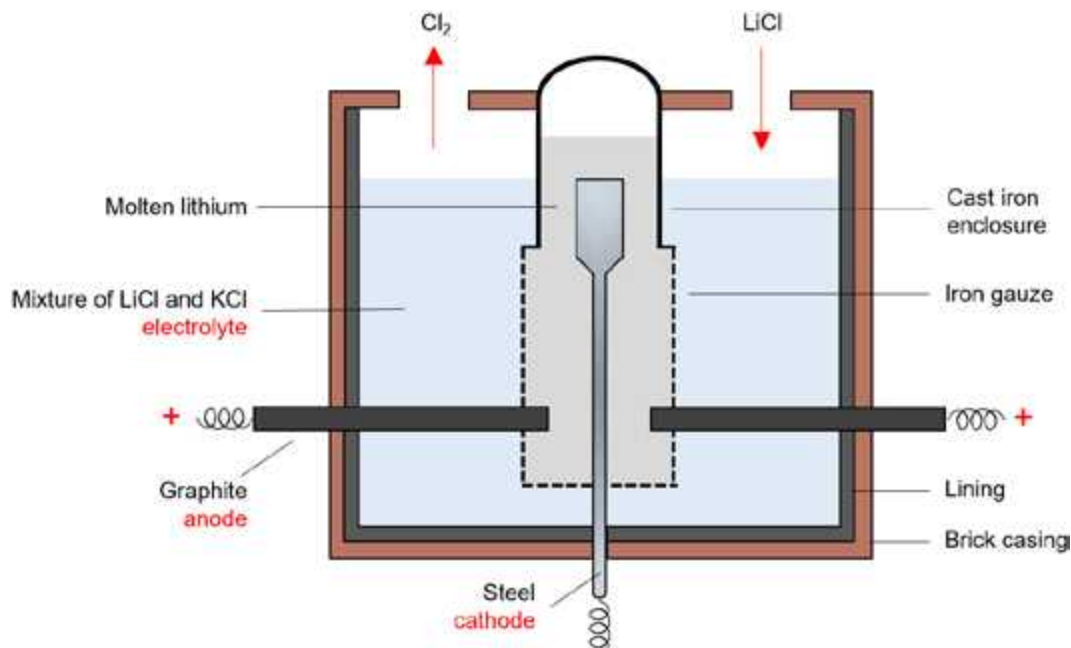
Describe one undesirable consequence of the inhalation of soot by humans.

(2 marks) **KA1**

- (ii) **State** one other disadvantage of this method of electricity generation.

(1 mark) **KA1**

- (b) Lithium, used in batteries, is an element in worldwide demand. Lithium can be produced from the electrolysis of molten lithium chloride. A simplified diagram of the cell is shown below.



- (i) **Suggest** why the product at the anode must be extracted carefully.

(1 mark) **KA3**

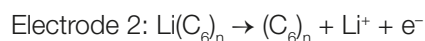
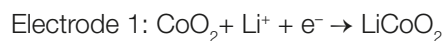
- (ii) **Write a balanced half-equation** for the formation of lithium at the cathode.

(2 marks) **KA4**

- (iii) **Explain** why molten electrolytic reduction is chosen for the production of lithium.

(2 marks) **IAE3**

- (c) The lithium-ion battery is a rechargeable battery. Cell half-equations for the battery during discharging are shown below.



- (i) **State** the type of cell during recharging.

(1 mark) **KA1**

- (ii) **State** and **explain** which electrode (1 or 2) is the anode during recharging.

(2 marks) **IAE3**

- (iii) The Hornsdale Power Reserve is located in rural South Australia and is co-located with the Hornsdale Wind Farm.

(1) **State** one advantage of electricity produced from wind turbines.

(1 mark) KA1

(2) **Discuss** one advantage of establishing a battery in conjunction with a wind farm.

(2 marks) KA3

- (iv) Lithium-ion batteries are limited in their ability to be recharged over time, due to the formation of lithium oxide on overdischarge and cobalt oxide on overcharge. This build-up removes reactants from the battery.

(1) **Suggest** one implication for the use of the lithium-ion batteries as a reserve power supply.

(1 mark) KA3

(2) Flow batteries could also be used in this application.

State one advantage of a flow battery over a lithium-ion battery used for power storage and supply.

(1 mark) KA2

3. Silicates play a key role in sustainable farming practices by replenishing essential soil nutrients that are often depleted through agriculture.

(a) Muscovite, $\text{KAl}_3\text{Si}_3\text{O}_x(\text{OH})_2$, is a common silicate mineral that gives some rocks a sparkly appearance.

(i) Using subshell notation, **write the electron configuration** for the potassium cation found in muscovite.

(2 marks) KA4

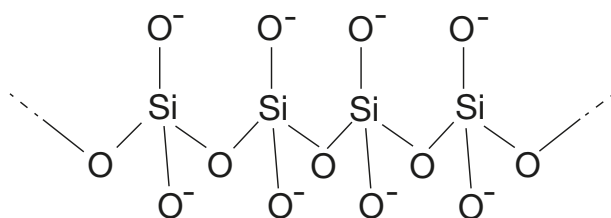
(ii) **Calculate** the charge on the silicate anion, Si_3O_x .

(2 marks) KA4

(iii) Hence, **calculate** the value of x in the silicate anion, Si_3O_x .

(1 mark) KA4

- (b) Another silicate mineral, sodium silicate, is soluble in water. A section of this silicate anion has the following structural formula:



(i) On the structural formula above, **mark** the repeating unit.

(1 mark) KA4

- (ii) Using the repeating unit that you identified in part (b)(i), **write the formula** for sodium silicate.

(2 marks) **KA4**

- (iii) **Explain** how the sodium cations held onto the surface of the soil silicate are made available to plants.

(4 marks) **KA1, KA4**

- (iv) Sodium silicates are often preferred in detergent mixtures than compounds that contain phosphorus because they do not lead to excessive algal growth in waterways.

Explain why, when there is excessive algal growth in waterways, the water may be unable to support life.

(3 marks) **KA1, KA4**

- (c) Farming practices can deplete soils of essential nutrients, reducing their fertility over time and increasing the demand for fertilisers. However, silicate rock powders (SRP) provide a sustainable solution by replenishing both the macronutrients and micronutrients that plants require. Furthermore, studies have shown that SRPs have the potential to adsorb contaminants from water, and they can capture atmospheric CO₂. One particular study showed a positive correlation between the application of SRPs and increased tomato plant growth.

- (i) What are the potential environmental impacts of using SRPs in large-scale agriculture?

(4 marks) **KA3**

- (ii) What are the potential economic impacts of using SRPs in large-scale agriculture?

(4 marks) **KA3**

4. The aviation and automotive industries have increasingly adopted composite materials to improve performance and reduce weight. One common composite used is carbon fibre reinforced polymer (CFRP).
- (a) **Describe** the main structural advantage of CFRP compared to traditional metals like aluminium or steel.
- (2 marks) **KA1**
- (b) **Explain** why CFRP's high strength-to-weight ratio is beneficial in applications such as aircraft and racing cars.
- (2 marks) **KA2**
- (c) One challenge of using CFRP in these industries is its limited recyclability. **Discuss** one difficulty associated with recycling CFRP compared to recycling metals.
- (2 marks) **KA3**
5. Thermoset composites, which are widely used in automotive and sports industries, are challenging to recycle due to their cross-linked structure.
- (a) **Explain** how the cross-linking in thermoset polymers affects their recyclability compared to thermoplastics.
- (2 marks) **KA2**
- (b) New methods for recycling thermosets involve breaking down cross-links using mild chemical treatments. **Describe** one benefit and one limitation of using chemical recycling for thermoset composites.
- (2 marks) **KA3**
- (c) Epoxy resins, a type of thermoset polymer, are commonly used as matrix materials in high-performance composites.
- State** how cross-linking within epoxy resins contributes to the rigidity of the composite.
- (1 mark) **KA1**
6. The recycling of composite materials, particularly carbon fibre, has significant environmental and economic implications.
- (a) **Explain** one environmental advantage of developing effective recycling processes for carbon fibre composites.
- (2 marks) **KA2**
- (b) **Discuss** how the high cost of carbon fibre production influences efforts to develop recycling technologies and the potential impact on industries such as automotive and aviation.
- (3 marks) **KA3**

- (c) New recycling techniques for composites include the use of mild acids and solvents that can break down the matrix without damaging the reinforcement fibres.

Describe one technological advancement in composite recycling that allows for both matrix and fibre recovery, and explain its importance in sustainable materials management.

(3 marks) **KA3**

- (d) With reference to Science as a Human Endeavour (SHE), **discuss** how advancements in composite recycling reflect society's commitment to sustainable resource management. Include one example of how recycled composites could be used in a new application.

(4 marks) **KA3**

7. Polyolefins are the largest class of organic *thermoplastic* polymers. Their properties range from soft and flexible to rigid, and they are used in plastic bags and bottles. However, as a result of their extensive use in society, polyolefins are also the largest components of today's plastic waste stream.

- (a) One polyolefin is polypropene, formed from the propene monomers.

(i) Draw the structure of propene.

(2 marks) **KA4**

(ii) Draw a section of the polymer formed from propene monomers.

(2 marks) **KA4**

(iii) State whether polypropene is an addition polymer or condensation polymer.

(1 mark) **KA4**

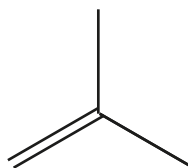
- (b) Polyolefins account for almost 60% of all produced plastic. However, the recycling rate for polyolefin packaging materials is very low.

Explain why polyolefins are able to be recycled.

(2 marks) **KA1**

- (c) In order to reduce polyolefin plastic waste, chemists from the University of Berkely, California, have developed a catalytic process that can turn polyolefin plastic bags and bottles into gases – propene gas and isobutylene gas, hydrocarbon building blocks for new plastics.

(i) The structure of isobutylene is shown below. Name this organic compound systematically.



isobutylene

Systematic name:

(2 marks) **KA4**

(ii) Draw the polymer formed from isobutylene monomers.

(2 marks) **KA4**

- (iii) According to UC Berkeley chemistry professor John Hartwig, “Everyday objects, from lunch bags to laundry soap bottles to milk jugs, are made of these polyolefins. What we can now do, in principle, is take those objects and bring them back to the starting monomer.”

Discuss one advantage of converting plastic waste back into the monomers used to make polymers.

(2 marks) **KA3**

- (iv) Two years ago, Hartwig and his UC Berkeley team came up with a similar process; however, it required the use of expensive heavy metal catalysts iridium, ruthenium, and palladium, which were irrecoverably lost as part of the process. The new process uses inexpensive solid catalysts that can be scaled up to industrial production, making this a potentially viable means of creating a circular economy for these throw-away plastics.

“Polyolefins are cheap, and they have good properties, so everybody uses them,” Hartwig said. “People say if we could figure out a way to make them circular, it would be a big deal, and that’s what we’ve done. One can begin to imagine a commercial plant that would do this.”

(1) **State** and **explain** the function of a catalyst in a chemical reaction.

(3 marks) **KA4**

- (2) **Discuss** two benefits of replacing expensive heavy metals with solid, inexpensive catalysts in industrial processes.

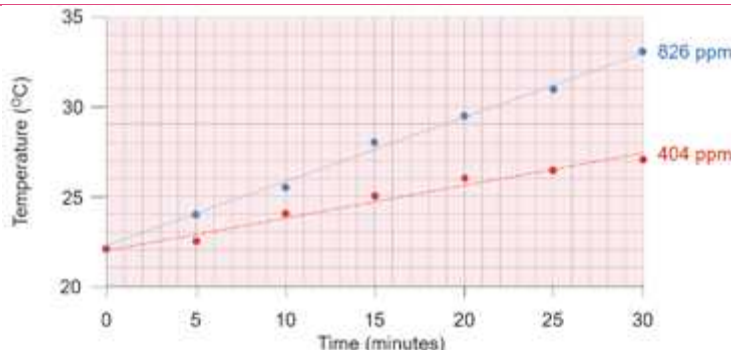
(4 marks) **KA3**

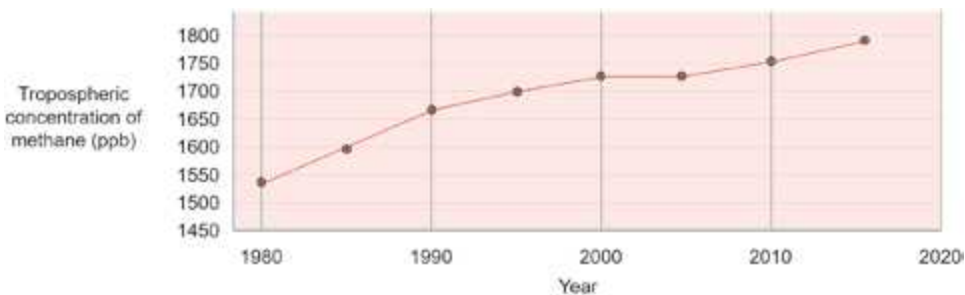
- (3) Using one or more SHE concepts, **explain** how the innovation of turning polyolefin polymers back into their original monomers shows science as a human endeavour.

(4 marks) **KA3**

Topic 1 solutions: Monitoring the environment

Question	Part	Author's response	Marks
1	(a)	The collaboration between scientists using satellite data, ground-based measurements, and historical ice-core data has revolutionised understanding of climate change. For example, the integration of data from Mauna Loa Observatory and the Argo float network provides a comprehensive picture of atmospheric and oceanic changes. These diverse sources are valuable because they ensure accuracy, allow cross-validation, and offer a broader temporal and spatial scope.	3
	(b)	The development of the Argo float network has significantly improved climate monitoring. By measuring temperature and salinity at depths of up to 2000 m, the floats provide real-time data on ocean heat content and acidification patterns. This advancement enables scientists to detect trends and predict future climate scenarios, ensuring informed policymaking.	3
	(c)	Data from climate monitoring, such as satellite measurements of ice sheet melting and ocean temperature from the Argo float network, allows scientists to predict future sea level rise and its impacts on coastal regions. A key benefit of climate monitoring data is its ability to provide reliable long-term trends, enabling accurate predictions of phenomena like sea level rise and supporting informed policy and infrastructure planning. A major limitation of relying on this data is the uncertainty caused by unanticipated variables or feedback mechanisms, such as methane release from melting permafrost, which can complicate predictions and limit precision.	3
2	(a) (i)	–17 °C	1
	(ii)	Greenhouse gases such as carbon dioxide and methane are able to absorb and emit thermal IR radiation that has been reradiated from the surface of the Earth.	1
		Thermal IR radiation is transferred between greenhouse gases, directed back to the surface, and lost to space.	1
		A thermal balance is established, maintaining the average global temperature in the Earth's troposphere.	1
	(iii)	Human activity has increased the concentration of greenhouse gases in the atmosphere.	1
		Due to the increase in greenhouse gases, less thermal energy is escaping from the Earth than it is absorbing.	1
		This thermal imbalance causes the Earth's temperature to rise.	1
	(b)	If there is greater reflectivity in the atmosphere and on the surface of the Earth, less energy from the Sun is absorbed at the surface of the Earth. Hence, less energy is reradiated as thermal IR radiation, reducing warming.	1 1
	(c) (i)	The atmosphere of Venus contains an extremely high concentration of the greenhouse gas carbon dioxide (95%).	1
		The greenhouse effect is much stronger due to this high concentration, as more thermal IR radiation is absorbed.	1
	(ii)	Although the concentration of carbon dioxide in the atmosphere is high, a very thin atmosphere results in a small amount present to absorb thermal IR radiation.	1

Question	Part	Author's response	Marks										
3	(a) (i)	<table><thead><tr><th>Factor</th><th>Importance</th></tr></thead><tbody><tr><td>Same 2L volume</td><td>To allow comparisons to be made for the same volumes of gases</td></tr><tr><td>Use the same carbon dioxide sensor, calibrated to the same value in ppm</td><td>To ensure accurate readings of carbon dioxide</td></tr><tr><td>Calibration of temperature sensors</td><td>To ensure initial readings are consistent</td></tr><tr><td>Same distance from the same lamp</td><td>To ensure that each bottle receives the same radiant heat</td></tr></tbody></table>	Factor	Importance	Same 2L volume	To allow comparisons to be made for the same volumes of gases	Use the same carbon dioxide sensor, calibrated to the same value in ppm	To ensure accurate readings of carbon dioxide	Calibration of temperature sensors	To ensure initial readings are consistent	Same distance from the same lamp	To ensure that each bottle receives the same radiant heat	1+1
		Factor	Importance										
		Same 2L volume	To allow comparisons to be made for the same volumes of gases										
		Use the same carbon dioxide sensor, calibrated to the same value in ppm	To ensure accurate readings of carbon dioxide										
	Calibration of temperature sensors	To ensure initial readings are consistent											
	Same distance from the same lamp	To ensure that each bottle receives the same radiant heat											
(ii)	The concentration of carbon dioxide.	1											
(iii)	Increasing the concentration of carbon dioxide will result in an increase in recorded temperature.	2											
(b) (i)		1 1 1 1 1 1											
	(ii)	A higher concentration of carbon dioxide resulted in a final higher temperature. Carbon dioxide is acting as a greenhouse gas.	1										
4		Any two examples (one from each list): Similarities Both the Earth's atmosphere and a garden greenhouse trap heat, preventing it from escaping and maintaining a warmer internal environment than the surrounding. The Earth's atmosphere and a greenhouse's glass walls both act as barriers that let in sunlight but inhibit the escape of heat (longwave radiation). Both systems rely on solar energy as the primary source of heat. In both cases, warming occurs due to the trapping of infrared radiation after solar radiation is absorbed and re-emitted. Differences: The Earth's atmosphere traps heat through the absorption and re-emission of infrared radiation by greenhouse gases, while glass physically traps air, preventing convection, which is a major heat loss mechanism. The Earth's atmosphere includes complex feedback systems, while a greenhouse is a simple system with limited feedback mechanisms.	4										
5	(a)	Global CO₂ monitoring through Mauna Loa Observatory and Cape Grim highlights the power of scientific collaboration. By standardising data collection protocols and sharing results internationally, scientists have established a robust record of atmospheric CO₂ levels. This collaboration ensures the reliability and comparability of data, advancing global climate research.	3										
	(b)	Increasingly sophisticated methods are used to monitor global CO₂ levels, and this information is used to design and motivate action for sustainability (e.g., through the Paris Agreement). This is an example of an application. However, the implementation of climate policy in many nations continues to be hampered by economic and political constraints. This is an example of a limitation.	4										

Question	Part	Author's response	Marks
6	(a)	Argo floats have enhanced understanding of ocean conditions by providing detailed, real-time data on temperature, salinity, and currents. For example, they revealed that ocean warming extends to depths of at least 2000 m, highlighting the oceans' role in mitigating surface warming.	2
	(b)	<i>Many answers possible. Examples include:</i> The collection of data on temperature and currents could improve models of ocean circulation and its effects on weather patterns, which would be useful in marine biology and meteorology. The ocean data collected could be used by policymakers to design strategies for climate adaptation, such as managing fisheries.	2
7	(a)	 Data points and line of best fit.	1 1
	(b) (i)	Increasing atmospheric temperatures have led to increased rates of thawing of land ice and permafrost.	1
	(ii)	Methane is a greenhouse gas able to absorb thermal IR radiation, reradiated from the surface of the Earth.	1
		Increased methane levels lead to greater absorption of thermal IR radiation.	1
		Thermal IR radiation is trapped for longer before escaping, which leads to a thermal imbalance, increasing the average global temperature in the Earth's troposphere.	1
	(iii)	Methane is present in the atmosphere at significantly lower concentrations compared to carbon dioxide.	1
	(c) (i)	Any one: • Mining • Production of fuels derived from fossil fuels • Intensive farming of livestock • Rice growing	1
	(ii)	Advantage: methane, as a greenhouse gas, is collected rather than being released into the troposphere.	1
		Disadvantage: the combustion of methane as a fuel source results in the emission of carbon dioxide, a greenhouse gas.	1

Question	Part	Author's response	Marks
8	(a)	The potential for “low emissions” marketing strategies for dairy products demonstrates how scientific knowledge about methane reduction aligns with societal and ethical priorities to combat climate change. Economic incentives, such as consumer demand for sustainable products, drive the acceptance and adoption of this innovation by dairy farmers. Additionally, cultural shifts toward environmental responsibility influence the appeal and marketability of these low-emission dairy products.	3
	(b)	The use of asparagopsis seaweed to reduce methane emissions in cattle feed demonstrates the application of scientific knowledge to address environmental challenges and promote sustainability. However, its reliance on a single licensed supplier in Victoria highlights a limitation, as scaling up production may face logistical, economic, or environmental challenges. This underscores the need for ongoing monitoring, risk assessment, and innovation to ensure the widespread and equitable adoption of this solution.	3
9	(a) (i)	$[H_3O^+] = 10^{-pH}$ $[H_3O^+] = 10^{-6.5}$ $[H_3O^+] = 3.16 \times 10^{-7} \text{ mol L}^{-1}$	1
		$[H_3O^+] = 10^{-pH}$ $[H_3O^+] = 10^{-4}$ $[H_3O^+] = 1 \times 10^{-4} \text{ mol L}^{-1}$	1
		Highest concentration of hydronium ions results from the lowest pH, a pH of 4.0.	1
	(ii)	Increase in acidity.	1
	(iii)	Each shift in pH value represents a 10-times change in concentration of hydronium ions.	2
	(b)	Any one: - The formation of acid rain from industrial activity. - The formation of acid rain from metal production. - The formation of acid rain from the oxides of sulfur and nitrogen formed during the combustion of fuels in motor vehicles.	1
10	(c)	Frogs eggs made from calcium carbonate will undergo reaction with hydrogen ions from acid rain leading to their dissolution.	1
	(a)	The global communication of scientific findings, such as Svante Odén's landmark paper and public outreach, raised international awareness of acid rain as a transboundary issue. Interdisciplinary and international collaboration among scientists, including Brynjulf Ottar and Waldemar Christofer Brøgger, enabled a comprehensive understanding of acid rain's causes and impacts. Joint policy actions like the Convention on Long-Range Transboundary Air Pollution demonstrated how effective communication of scientific research to policymakers can drive coordinated global solutions.	3
10	(b)	The regulations to reduce sulfur dioxide and nitrogen oxide emissions applied scientific research on acid rain's causes to mitigate its harmful effects on the environment and human infrastructure. The positive outcomes of these regulations, such as improved environmental health and reduced damage to structures, demonstrate the effective use of scientific knowledge to address a major problem. The need for international agreements like the Convention on Long-Range Transboundary Air Pollution highlights the limitations of local or national action in addressing the global nature of acid rain.	3

Question	Part	Author's response	Marks
11	(a) (i)	Slightly acidic	1
	(ii)	$\text{CO}_{2(g)} + \text{H}_2\text{O}_{(l)} \rightleftharpoons \text{H}_2\text{CO}_{3(aq)}$	2
	(b) (i)	$\text{Na}_2\text{CO}_{3(s)} + 2\text{H}^+_{(aq)} \rightleftharpoons \text{H}_2\text{O}_{(l)} + \text{CO}_{2(g)} + 2\text{Na}^+_{(aq)}$	2
	(ii)	$\text{pOH} = 14 - \text{pH}$ $= 14 - 10.5$ $= 3.5$ $[\text{OH}^-] = 10^{-\text{pOH}}$ $[\text{OH}^-] = 10^{-3.5}$ $[\text{OH}^-] = 3.16 \times 10^{-4} \text{ mol L}^{-1}$	1
			2
12	(a) (i)	$\text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^-$	2
	(ii)	An increase in hydrogen ion (H^+) concentration causes the pH of seawater to decrease, making it more acidic. This lower pH can disrupt chemical equilibria and affect marine life reliant on stable pH conditions.	2
	(iii)	$\text{pH} = -\log_{10}[\text{H}^+]$ $\text{pH} = -\log_{10}(1.7 \times 10^{-8})$ $\text{pH} = 7.77$	2
	(b) (i)	Decreased pH increases the concentration of H^+ ions. H^+ ions react with carbonate ions (CO_3^{2-}) to form bicarbonate ions (HCO_3^-). This reduces the availability of carbonate ions, making it harder for marine organisms to form calcium carbonate structures.	3
	(ii)	$\text{CaCO}_3 + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{H}_2\text{CO}_3$	2
	(iii)	The reaction dissolves calcium carbonate (CaCO_3), weakening the structural integrity of shells and exoskeletons. This compromises the organisms' protection and survival in acidic conditions.	2
	(c) (i)	Reduced calcium carbonate availability limits the ability of calcareous plankton to form their shells, leading to population decline. This can disrupt their role as a primary producer in marine ecosystems.	2
	(ii)	A decline in calcareous plankton impacts higher trophic levels, including small fish and larger predators, causing a cascading effect that disrupts the balance of the entire marine food web.	2
	(iii)	Ocean acidification lowers the availability of carbonate ions essential for organisms like corals, shellfish, and certain plankton to build their calcium carbonate structures. As these organisms struggle to survive, the ecosystems they support, such as coral reefs, face significant degradation. Coral reefs are biodiversity hotspots, providing habitat and food for thousands of marine species. Their decline disrupts the balance of marine ecosystems, leading to cascading effects on food webs. OR It threatens fisheries, food security, and livelihoods, especially in communities relying on marine resources for income and sustenance. Many coastal and island communities depend on fish and shellfish as a primary food source and income. Declines in fish populations due to the loss of reef habitats and key prey species like plankton can cause a reduction in fish stocks, impacting food security and economic stability. Additionally, reduced productivity in fisheries can lead to job losses, particularly in small-scale and subsistence fishing communities, which lack resources to adapt to these changes.	3

Question	Part	Author's response	Marks
12	(iv)	A viable strategy is reducing CO ₂ emissions by transitioning to renewable energy sources and adopting carbon capture technologies. Restoring seagrass and mangroves, which absorb CO ₂ , can also help mitigate local effects of acidification.	2
	(a) (i)	Covalent bond (triple).	1
13	(ii)	$\text{:N}\equiv\text{N:}$	2
	(b)	Air, which contains N ₂ and O ₂ gas, is drawn into the engines to burn the fuel. High temperatures encountered during the combustion of fuels in an aircraft engine breaks the strong covalent bonds, allowing nitrogen and oxygen to react to form nitric oxide.	1
		$\text{N}_{2(\text{g})} + \text{O}_{2(\text{g})} \rightarrow 2\text{NO}_{(\text{g})}$	1
		Nitric oxide oxidises further in the atmosphere, reacting with oxygen to form nitrogen dioxide.	1
		$2\text{NO}_{(\text{g})} + \text{O}_{2(\text{g})} \rightarrow 2\text{NO}_{2(\text{g})}$	1
	(c) (i)	Endothermic (photochemical)	1
	(ii)	Nitrogen dioxide photodissociates on absorption of ultraviolet radiation, forming nitric oxide and an oxygen radical.	1
		The oxygen radical reacts with oxygen forming ozone.	1
		$\text{NO}_{2(\text{g})} \xrightarrow{\text{UV}} \text{NO}_{(\text{g})} + \text{O}^{\bullet}$	1
		$\text{O}^{\bullet}_{(\text{g})} + \text{O}_{2(\text{g})} \rightarrow \text{O}_{3(\text{g})}$	1
	(d) (i)	Changes to the altitude and flight path result in different distances and times of flight, which result in the formation of more or less emissions of NO _x .	1
	(ii)	Carbon dioxide is a greenhouse gas.	1
		Increased concentration of atmospheric carbon dioxide has led to global warming. Any one (or other relevant consequences): Global warming has been linked to:	1
		• rising sea levels • extreme weather events.	1

Question	Part	Author's response	Marks
14	(a)	One of: Collaboration between Haagen-Smit and Arnold Beckman. - Haagen-Smit, a flavour chemist, adapted his equipment to analyse polluted air and identified that ozone was a major component of Los Angeles smog. He collaborated with Arnold Beckman, an instrument developer, who created tools like gas concentration recorders and air quality monitoring vans. - Partnership between scientists and engineers of different fields come together to solve problems - Haagen-Smit's chemical expertise allowed him to identify the components of smog, while Beckman's engineering skills led to the creation of instruments to measure and monitor air quality. By combining their knowledge and skills, they were able to better understand the causes of photochemical smog and advance air pollution research. Or Studies conducted in Jinan and Xi'an, which examined the health impacts of air pollution, such as increased mortality rates and links to respiratory diseases. - Result of collaborative efforts between researchers, healthcare professionals, and policymakers across different regions. - Collaboration between scientists to gather, analyse, and interpret data on smog episodes and health impacts. Engaging in global efforts to address air pollution as a shared environmental and health concern. - Studying similar issues in different regions, scientists can draw broader conclusions about global impact of air pollution, build more comprehensive understanding of the effects, and inform public health responses.	3
	(b)	Effectively communicating scientific findings ensures that both the public and policymakers are equipped with the knowledge they need to reduce air pollution, protect health, and create a sustainable future. Public awareness helps individuals take steps to reduce exposure, while policymakers rely on scientific data to implement regulations that lower pollution levels.	2
	(c)	- Provides clear and accessible information about air pollution. - Allows the public to make informed decisions, like limiting outdoor activities or taking precautions during high-pollution days to protect their health. - By simplifying complex data, the AQI empowers sensitive groups, such as children and those with respiratory conditions, to reduce exposure and avoid adverse health effects.	1 1 1
	(d)	Lack of comprehensive data on how prolonged and early-life exposure to pollutants influences the development of chronic diseases, such as asthma, cardiovascular issues, and other respiratory conditions, across different populations. Further research is necessary to better understand these impacts, enabling the development of targeted interventions and policies to reduce health risks for future generations.	1 1

Question	Part	Author's response	Marks
15	(a) (i)	Greater volumes of air containing pollutants are inhaled into the lungs during physical activity.	1
	(ii)	Any two: • Ozone affects respiratory function. • Individuals with existing respiratory illness are more susceptible to exposure to ozone. • Increased exposure to higher concentrations of ground-level ozone is detrimental to human health.	2
	(b) (i)	$\text{SO}_{3(g)} + \text{H}_2\text{O}_{(l)} \rightarrow \text{H}_2\text{SO}_{4(aq)}$	2
	(ii)	pH decreases	1
	(c)	7–8 am Disadvantage:	1
		Concentration of primary pollutants would increase due to peak hour traffic, increasing exposure.	1
		Advantage:	1
		Concentrations of secondary pollutants (such as ozone) are low, as little sunlight is available to generate photochemical reactions.	
		12 am –1 pm Disadvantage:	1
		Primary pollutants have had the opportunity to form secondary pollutants.	
		UV concentrations are high, leading to the formation of ozone and a peak in concentration (as long as sunlight is available).	
		Advantage:	1
		Primary pollutants may have been able to disperse depending on weather conditions.	
		8–9 pm Disadvantage:	1
		Evening peak-hour traffic would lead to increased concentrations of primary pollutants, increasing exposure.	
		Advantage:	2
		Without sunlight, ozone levels will decrease, limiting exposure.	
		Communication: spelling, sentence structure, and logical sequence.	

Question	Part	Author's response	Marks
16	(a) (i)	(1) Trigonal planar	1
	(2)	Oxygen has a higher electronegativity than carbon, with a stronger affinity for valence electrons.	1
		The difference in electronegativity between carbon and oxygen results in an uneven electron distribution, forming a polar bond ($O^{\delta-}$ and $C^{\delta+}$).	1
	(3)	Methanal molecules are small.	1
		Although the molecule is polar, methanal molecules experience only dipole–dipole interactions between the C=O bonds. These are weaker than the H-bonding that occurs in some other molecules, e.g., water.	1
		At room temperature, there is sufficient energy to overcome the interactions, therefore methanal is volatile (low boiling point), existing as a gas.	1
	(ii)	$NO_{2(g)} \xrightarrow{UV} NO_{(g)} + O^{\bullet}$	2
		$O^{\bullet} + O_{2(g)} \rightarrow O_{3(g)}$	2
	(b) (i)	To disperse and remove the pollutants.	1
	(ii)	Ozone is a respiratory irritant.	1
	(c) (i)	Addition	1
	(ii)	$ \begin{array}{c} H & & H \\ & & \\ H-C & = & C-H \\ & & \\ H & & H \end{array} $	2
	(iii)	Ozone, as an oxidising agent, breaks carbon–carbon double bonds present in the polymer.	1
		This leads to cracking and degradation of the function of the polymer.	1
	(iv)	Carbon–carbon double bonds are not present in the main chain, hence not as susceptible to degradation by ozone.	1
17	(a)	Scientists identified vehicle emissions as a major cause of air pollution, and engineer Eugene Houdry collaborated with industry by founding Oxy-Catalyst to develop catalytic converters as a solution.	1
		The introduction of three-way catalytic converters in the 1980s and continued improvements, such as the use of nanotechnology, enhanced efficiency and reduced costs.	1
		The partnership between scientists and industry enabled the creation and implementation of practical solutions, reducing vehicle emissions and addressing global environmental issues like air pollution.	1
	(b)	Beneficial effect: Catalytic converters significantly reduce harmful vehicle emissions, such as carbon monoxide, nitrogen oxides, and hydrocarbons, by converting them into less harmful gases like carbon dioxide, nitrogen, and water vapour, improving air quality and reducing environmental pollution.	1
		Limitation: Catalytic converters rely on platinum-group metals, which are rare and expensive to source, and their production can have environmental and economic impacts.	1

Question	Part	Author's response	Marks
17	(c)	High costs associated with manufacturing and installing the technology.	1
		The use of platinum-group metals in catalytic converters makes them expensive. For many low-income countries, the upfront cost of equipping vehicles with catalytic converters can be prohibitive.	1
		Less-wealthy countries may have limited financial resources for manufacturing, infrastructure, and enforcement of emissions standards.	1
	(d)	Studies linking vehicle emissions to air pollution highlighted the need for action, prompting communication between scientists and the public about the environmental and health risks.	1
		Effective communication between scientists, policymakers, and industries led to the development of catalytic converters as a technological solution to reduce harmful emissions.	1
18	(a)	Public awareness and scientific findings drove the introduction of emissions regulations, leading to widespread adoption of catalytic converters in vehicles during the 1970s and 1980s.	1
	(b)	The development of SCR technology demonstrates global collaboration, with the Engelhard Corporation in the US patenting the technology in 1957 and the Japanese IHI Corporation installing the first large-scale system in 1978. This international exchange of knowledge highlights how clear communication and cooperation between countries drive the refinement and implementation of scientific advancements.	4
		OR	
		Strict regulatory standards, such as the EURO 6 diesel emissions standards, exemplify collaboration between scientists, governments, and regulatory bodies to address environmental challenges. This partnership ensures that technological innovations like SCR are designed and deployed to meet societal and regulatory goals effectively.	
	(b)	SCR technology evolved from simple catalytic reactions to the use of advanced catalysts such as vanadium, titanium, and zeolites, which significantly enhanced its effectiveness and adaptability. This demonstrates how the development of complex scientific systems requires evidence and innovation from multiple disciplines, such as materials science and chemistry.	4
		OR	
	(c)	The introduction of nanotechnology into SCR systems boosted catalyst surface area, optimising the reaction process and improving efficiency. This highlights how advancements in technology can reveal new evidence and refine scientific processes, driving the development of more effective systems.	
	(c)	Stricter regulatory standards, such as the EURO 6 diesel emissions standards, have directly influenced the development and refinement of SCR technology. These regulations reflect societal and governmental priorities to reduce pollution, driving scientific advancements to meet environmental goals.	4
		OR	
		Advances in nanotechnology have significantly improved SCR systems by increasing catalyst surface area and optimising the reaction process. This cross-disciplinary influence demonstrates how developments in materials science directly enhance the efficiency and effectiveness of environmental technologies.	

Question	Part	Author's response	Marks																				
18	(d)	Application (any one of the following. Allocate one mark for identifying and two marks for explaining): - Recent innovation – SCR technology has been widely used in heavy trucks, cars, light commercial vehicles, industrial-scale boilers, and diesel ships, demonstrating its practical use in reducing harmful emissions across multiple sectors. - The application of SCR systems in diesel engines required design changes to integrate the technology, highlighting its real-world implementation to meet emission standards and improve air quality. - SCR technology has been applied to large diesel ships, helping to reduce NO_x emissions in the marine industry, showcasing its versatility and global application in diverse sectors to address environmental concerns.	3																				
		Limitation (any one of the following. Allocate one mark for identifying and two marks for explaining): - Susceptibility to catalyst poisoning. Impurities, such as sulfur compounds, deactivate the catalyst. This reduces its effectiveness. - Susceptibility to ammonia slip. If excess ammonia escapes unreacted into the environment, it will potentially cause secondary pollution. - SCR systems require high operating temperatures, which may reduce their effectiveness in cooler environments. Increased cost with running high temperatures. - High costs of vanadium-based catalysts and installation can be a barrier to adoption, especially for smaller facilities.	3																				
19	(a) (i)	Oxides of nitrogen are precursors to the formation of photochemical smog.	1																				
		Reducing their concentration reduces the formation of secondary pollutants such as ozone.	1																				
	(ii)	$2\text{NO}_{(g)} + \text{O}_{2(g)} \rightarrow 2\text{NO}_{2(g)}$	2																				
	(b) (i)	Oxidation	1																				
		The oxidation number of nitrogen increases from +4 in NO ₂ to +5 in NO ₃ ⁻ .	1																				
	(ii)	Incomplete combustion	1																				
	(iii)	Large surface area to expose pollutants to the catalyst material.	1																				
(iv)	$2\text{NO}_{(g)} + 2\text{CO}_{(g)} \rightarrow 2\text{CO}_{2(g)} + \text{N}_{2(g)}$	2																					
20	(a)	<table><tr><th>Element</th><th>Symbol</th><th>Atomic mass</th><th>m (g)</th><th>n (mol)</th></tr><tr><td>platinum</td><td>Pt</td><td>195.1</td><td>2.93</td><td>0.0150</td></tr><tr><td>palladium</td><td>Pd</td><td>106.4</td><td>3.46</td><td>0.0325</td></tr><tr><td>rhodium</td><td>Rh</td><td>102.9</td><td>8.61</td><td>0.0837</td></tr></table>	Element	Symbol	Atomic mass	m (g)	n (mol)	platinum	Pt	195.1	2.93	0.0150	palladium	Pd	106.4	3.46	0.0325	rhodium	Rh	102.9	8.61	0.0837	3
	Element	Symbol	Atomic mass	m (g)	n (mol)																		
platinum	Pt	195.1	2.93	0.0150																			
palladium	Pd	106.4	3.46	0.0325																			
rhodium	Rh	102.9	8.61	0.0837																			
	(b)	Nanoparticles offer greater surface area to catalyse the reaction, therefore less of these rare metals are required.	1																				

Question	Part	Author's response						Marks
21	(a)			Atomic mass	Concentration units			4
				g mol ⁻¹	mol L ⁻¹	g L ⁻¹	ppm	
		lead	Pb	207.2	9.7×10^{-7}	0.00020	0.20	
		cadmium	Cd	112.4	9.65×10^{-7}	0.000108	0.108	
		arsenic	As	74.92	6.7×10^{-7}	0.000050	0.050	
		mercury	Hg	200.6	9.0×10^{-7}	0.00018	0.18	
		zinc	Zn	65.38	6.1×10^{-5}	0.0040	4.0	
		selenium	Se	78.96	1.9×10^{-5}	0.0015	1.5	
		sodium	Na	22.99	6.05×10^{-4}	0.0139	13.9	
		calcium	Ca	40.08	2.07×10^{-4}	0.0083	8.3	
		magnesium	Mg	24.31	5.64×10^{-4}	0.0137	13.7	
	(b) (i)	Lethal level = 763 ppm = 763 mg L ⁻¹ = 763 × 55 mg in a 55 kg adult = 41965 mg Bottled water = 0.0500 ppm = 0.0500 mg L ⁻¹ $= \frac{41965}{0.0500}$ = 839300 L = 8.4 × 10 ⁵ L						1 2
	(ii)	Other elements may reach a concentration which is detrimental to human health.						1
22	(a)	$0.60 \text{ mol L}^{-1} \times (22.99 + 35.45) \text{ g mol}^{-1}$ = $0.60 \text{ mol L}^{-1} \times 58.44 \text{ g mol}^{-1}$ = 35.064 g L ⁻¹ = 35 g L ⁻¹ (2 sig. fig.) $35.064 \text{ g L}^{-1} \times 1000$ = 35 064 mg L ⁻¹ = 35 064 ppm = 35 000 ppm (2 sig. fig.)						1 1
	(b)	$m(\text{NaCl}) = 35.064 \text{ g L}^{-1} \times 1.35 \times 10^{21} \text{ L}$ = $4.734 \times 10^{22} \text{ g}$ = $4.7 \times 10^{22} \text{ g}$ (2 sig. fig.)						1
23	(a)	$0.995 \text{ ppm} = 0.995 \text{ mg L}^{-1}$ = 0.995 mg kg ⁻¹ = $0.995 \times 10^{-3} \text{ mg g}^{-1}$ = $0.995 \times 10^{-3} \times 150 \text{ mg}$ = 0.149 mg						1 2
	(b)	0.149 mg of mercury in 150 g of swordfish $\therefore 0.149 \text{ mg in } 75 \text{ kg}$ $= \frac{0.149}{75} \text{ mg kg}^{-1}$ = $1.99 \times 10^{-3} \text{ ppm}$						1 2
	(c)	Larger deep-sea fish contain higher levels of mercury, building from the consumption of smaller fish, hence reduced consumption is recommended. Young children and the unborn foetus of pregnant women are more susceptible to mercury exposure due to their small mass for absorption, leading to high concentrations of the element. Even less frequent consumption is recommended.						1 1

Question	Part	Author's response					Marks	
24	(a)	Quantity	Value in Standard Units	Scientific notation	Value using SI Prefix	Significant figures		
		Gold in the human body	0.0002 g	2×10^{-4} g	200 μ g (= 200×10^{-6} g)	1	1	
		Concentration of H^+ in bleach at a pH of 12.6	0.00000000000025 mol L ⁻¹	2.5×10^{-13} mol L ⁻¹	0.25 pmol L ⁻¹	2	1	
		Number of particles in a mole	602,214,076,000,000,000,000,000,000	$6.02214076 \times 10^{23}$	Value is unitless	9	1	
		Gold in the human body						
		0.0002 g						
		= $0.0002 \times 10^6 \mu$ g						
		= 200 μ g (which is 200×10^{-6} g)						
		Concentration of H^+ in bleach at pH of 12.6						
		0.25 pmol L ⁻¹						
25	(a)	The uncertainty surrounding the long-term, low-dose effects of BPA has led governments to adopt precautionary measures, erring on the side of caution to protect vulnerable populations, especially infants.					3	
		In response to both public concern and scientific uncertainty, governments in various regions, such as the EU, US, and Canada, have implemented bans on BPA in baby bottles and related products, prioritising the safety of infants while continuing to monitor and review scientific findings.						
		Possible effects on the endocrine system and infant health has pressured governments to take action, even in the absence of definitive scientific consensus.						
	(b)	Collaboration between researchers and government agencies allows for accurate risk assessment and monitoring to assess BPA exposure levels and identify potential health risks.					3	
		Biomonitoring data helps governments make evidence-based decisions, such as setting safety thresholds and implementing regulations to protect public health.						
		Continuous collaboration ensures that health risks are monitored and policies are adapted in response to new research and evolving exposure patterns.						
	(c)	Industry-funded studies may be influenced by financial interests, leading to conclusions that downplay potential health risks of BPA.					3	
		Industry studies may use methodologies that favour outcomes supporting BPA safety, potentially overlooking long-term, low-dose effects.						
		Industry-funded research may selectively report findings that support BPA safety, whereas academic or government studies tend to offer a more balanced assessment of the risks.						
	(d)	Long-term, low-dose effects of BPA are difficult to link directly to health issues due to the subtle and delayed nature of potential impacts.					3	
Controlled long-term studies on humans are ethically and logistically challenging, as researchers cannot safely expose people to BPA for extended periods.								
Individual differences in genetics, lifestyle, and health conditions make it hard to generalise findings, complicating the assessment of BPA's effects on human health.								
(e)	Plastic manufacturers would need to acknowledge the health risks of BPA and provide clear, transparent information to the public.					4		
	Manufacturers would shift focus to promoting BPA-free or safer alternatives, highlighting their efforts to reduce risks.							
	Public health agencies would update health guidelines, issue warnings, and advocate for stricter regulation of BPA, especially for vulnerable groups.							
Agencies would launch campaigns to educate the public on BPA risks and offer guidance on reducing exposure, while supporting policy changes for greater regulation.								

Question	Part	Author's response	Marks
26	(a) (i)	$m(\text{CO}_2) = 21.8 \times 10^3 \text{ g}$ $M(\text{CO}_2) = 44.01 \text{ g mol}^{-1}$ $n(\text{CO}_2) = \frac{m}{M}$ $n(\text{CO}_2) = \frac{21.8 \times 10^3}{44.01}$ $n(\text{CO}_2) = 495 \text{ mol}$ mole ratio $n(\text{CO}_2) : n(\text{C}_6\text{H}_{12}\text{O}_6) = 6 : 1$ $\frac{n(\text{C}_6\text{H}_{12}\text{O}_6)}{n(\text{CO}_2)} = \frac{1}{6}$ $\therefore n(\text{C}_6\text{H}_{12}\text{O}_6) = \frac{495}{6}$ $n(\text{C}_6\text{H}_{12}\text{O}_6) = 82.6 \text{ mol}$ $M(\text{C}_6\text{H}_{12}\text{O}_6) = 180.156 \text{ g mol}^{-1}$ $m(\text{C}_6\text{H}_{12}\text{O}_6) = n \times M$ $m(\text{C}_6\text{H}_{12}\text{O}_6) = 82.6 \times 180.156$ $m(\text{C}_6\text{H}_{12}\text{O}_6) = 14873 \text{ g}$ $m(\text{C}_6\text{H}_{12}\text{O}_6) = 14900 \text{ g}$ $m(\text{C}_6\text{H}_{12}\text{O}_6) = 14.9 \text{ kg (3 sig. fig.)}$	2
	(ii)	mole ratio $n(\text{CO}_2) : n(\text{O}_2) = 1 : 1$ $\therefore n(\text{O}_2) = 495 \text{ mol}$ $M(\text{O}_2) = 32.00 \text{ g mol}^{-1}$ $m(\text{O}_2) = n \times M$ $m(\text{O}_2) = 495 \times 32.00$ $m(\text{O}_2) = 15851 \text{ g}$ $m(\text{O}_2) = 15900 \text{ g (3 sig. fig.)}$	3
	(b) (i)	$\text{CO}_{2(\text{vehicle emission for one car})} = 4.7 \times 10^3 \text{ kg}$ $\text{CO}_{2(\text{absorbed by single tree})} = 21.8 \text{ kg}$ $\text{Total number of mature trees} = \frac{4700}{21.8}$ $= 216 \text{ mature trees}$	2
	(ii)	Through photosynthesis, trees offset considerable quantities emissions of carbon dioxide.	1

Question	Part	Author's response	Marks
27	(a) (i)	$\text{Zn}_{(s)} + \text{Cu}(\text{NO}_3)_{2(aq)} \rightarrow \text{Zn}(\text{NO}_3)_{2(aq)} + \text{Cu}_{(s)}$ Ratio 1:1	2 1
	(ii)	$n(\text{Zn}) = \frac{m}{M}$ $= \frac{2.00 \text{ g}}{65.38 \text{ g/mol}}$ $= 0.03 \text{ mol}$ $n(\text{Cu}(\text{NO}_3)_2) = C \times V$ $= 0.100 \text{ mol L}^{-1} \times 0.100 \text{ L}$ $= 0.0100 \text{ mol}$ Divide each by their coefficient $\frac{\text{Zn}}{0.03}$ $\frac{0.03}{1}$ $= 0.03$ $\frac{\text{Cu}(\text{NO}_3)_2}{0.01}$ $\frac{0.01}{1}$ $= 0.01$ $0.03 > 0.01$ Therefore, Zn is in excess at 0.03 mol and $\text{Cu}(\text{NO}_3)_2$ is limiting at 0.01 mol	2 1 1
	(iii)	Ratio $\text{Cu}(\text{NO}_3)_2 : \text{Cu}$ is 1 : 1 $\therefore n(\text{Cu}) = 0.0100$ (3 sig.fig.) mol	1 1
	(iv)	$m(\text{Cu}) = n \times M$ $= 0.0100 \text{ mol} \times 63.55 \text{ g}$ $= 0.636 \text{ g}$ (3 sig.fig.)	1 1
	(b) (i)	$\text{Mg}_{(s)} + 2\text{HCl}_{(aq)} \rightarrow \text{MgCl}_{2(aq)} + \text{H}_{2(g)}$	2
	(ii)	$n(\text{Mg}) = \frac{m}{M}$ $= \frac{1.20 \text{ g}}{24.31 \text{ g/mol}}$ $= 0.0494 \text{ mol}$ $n(\text{HCl}) = C \times V$ $= 0.500 \text{ mol L}^{-1} \times 0.050 \text{ L}$ $= 0.025 \text{ mol}$ Divide each by their coefficient $\frac{\text{Mg}}{0.0494}$ $\frac{0.0494}{1}$ $= 0.0494$ $\frac{\text{HCl}}{0.025}$ $\frac{0.025}{2}$ $= 0.0125$ $0.0494 > 0.0125$ Therefore, Mg is in excess at 0.0494 mol and HCl is limiting at 0.0125 mol	2 1 1
	(iii)	Mg is in excess at 0.0494 mol. $n(\text{Mg remaining after reaction is complete}) = 0.0494 - 1(0.0125)$ $= 0.0369 \text{ mol}$ $m(\text{Mg remaining after reaction is complete}) = n \times M$ $= 0.0369 \text{ mol} \times 24.31 \text{ g mol}^{-1}$ $= 0.897 \text{ g}$	1 1 1 1

Question	Part	Author's response	Marks								
28		$n(\text{PbS}) = \frac{m}{M}$ $= \frac{50\,000\text{ g}}{239.3\text{ g/mol}}$ $= 208.94\text{ mol}$ Divide each by their coefficient <table><tr><td>PbS</td><td>O₂</td></tr><tr><td>$\frac{208.94}{2}$</td><td>$\frac{468.75}{3}$</td></tr><tr><td>= 104.47</td><td>= 156.25</td></tr><tr><td colspan="2">104.47 < 156.25</td></tr></table> Therefore, PbS is limiting at 104.47 mol and O₂ is in excess at 156.25 mol To determine the moles of PbO that can be formed, we look at the mole ratio between the limiting reactant and PbO. PbS : PbO 2 : 2 1 : 1 Therefore, n(PbO formed) = 2 (104.47) mol Remember to include the coefficient = 208.94 mol m(PbO) = n × M = 208.94 mol × 223.2 g mol⁻¹ = 46 635.41 g = 47 kg (2 sig. fig.)	PbS	O₂	$\frac{208.94}{2}$	$\frac{468.75}{3}$	= 104.47	= 156.25	104.47 < 156.25		6
	PbS	O₂									
$\frac{208.94}{2}$	$\frac{468.75}{3}$										
= 104.47	= 156.25										
104.47 < 156.25											
29	(a)	$m(\text{O}_2) = 0.300\text{ g}$	2								
		$M(\text{O}_2) = 32.00\text{ g mol}^{-1}$									
		$n(\text{O}_2) = \frac{0.300}{32.00}$	2								
	$n(\text{O}_2) = 9.38 \times 10^{-3}\text{ mol}$										
(b)	$m(\text{N}_2) = 1.60\text{ g}$	2									
	$M(\text{N}_2) = 28.02\text{ g mol}^{-1}$										
	$n(\text{N}_2) = \frac{1.60}{28.02}$	1									
	$n(\text{N}_2) = 5.17 \times 10^{-2}\text{ mol}$										
	Mole ratio n(O ₂) : n(N ₂) = 1 : 1										
∴ O ₂ is the limiting reagent											
(b)	Mole ratio n(O ₂) : n(NO) = 1 : 2	2									
	$\frac{n(\text{NO})}{n(\text{O}_2)} = \frac{2}{1}$										
	$n(\text{NO}) = 2 \times 9.375 \times 10^{-3}$	2									
	$n(\text{NO}) = 1.875 \times 10^{-2}\text{ mol}$										
	$M(\text{NO}) = 30.01\text{ g mol}^{-1}$										
$m(\text{NO}) = 1.875 \times 10^{-2} \times 30.01$											
$m(\text{NO}) = 0.563\text{ g (3 sig. fig.)}$											

Question	Part	Author's response	Marks
30		Any three points: The Bio-Agtive system demonstrates “ <i>Development</i> ” by applying scientific innovation to address real-world problems, such as reducing carbon emissions from traditional fertilisers.	
	(a)	By using tractor exhaust to create a carbon-based fertiliser, the technology combines existing knowledge of diesel emissions, soil chemistry, and microbial activity to offer a potentially more sustainable solution. Scientific and technological advancements can drive progress, particularly in agriculture, by reducing environmental impacts and providing alternatives to conventional practices. Further research at Olds College to test its effectiveness and measure outcomes also reflects the ongoing refinement and progression of this technology.	3
	(b)	“Influence” is shown with the impact of rising fertiliser prices following Russia's invasion of Ukraine on the interest in the Bio-Agtive system. The economic and geopolitical event (fertiliser price spike) influenced farmers' willingness to consider alternative fertiliser technologies like Bio-Agtive. While farmers were previously hesitant to adopt an unproven product due to financial risks, the external economic pressures made the Bio-Agtive system a more appealing option.	1 1 1
	(c)	Application - The use of the Bio-Agtive system to produce a carbon-based fertiliser from diesel engine exhaust. - Demonstrates the application of scientific principles, particularly in chemistry and environmental science, to create a practical solution to reduce carbon emissions from traditional fertilisers. - By collecting exhaust from agricultural machinery and combining it with water to produce fertiliser, this technology is applied directly in farming practices to both enhance soil health and potentially reduce environmental impact. Limitation - Uncertainty about whether Bio-Agtive can fully replace traditional fertilisers. - Early research indicates that the Bio-Agtive system is not harmful to the soil, but it is still unclear whether it can completely replace traditional fertiliser or how long the carbon emissions it injects into the soil remain effective. - This uncertainty means that further research is needed to fully understand its long-term viability, crop yield outcomes, and environmental impact, which limits the widespread adoption of the product.	3 3
31	(a)	$c_{(\text{DCMU})} = 900 \text{ g L}^{-1}$ $\frac{\text{g}}{\text{L}} \div M = \frac{\text{mol}}{\text{L}}$ $= \frac{900}{233.1}$ $= 3.86 \text{ mol L}^{-1}$	2
	(b)	$c_1 \times V_1 = c_2 \times V_2$ $c_2 = \frac{c_1 \times V_1}{V_2}$ $c_2 = \frac{3.86 \times 40}{6000}$ $c_{(\text{diluted DCMU})} = 0.0257 \text{ mol L}^{-1} \text{ (3 sig. fig.)}$	3

Question	Part	Author's response	Marks
31	(c)	Convert 1.848 GL to litres, which gives us 1.848×10^9 L We know $V_1 = 20\,000$ L, $c_2 = 1.800$ mg L ⁻¹ , $V_2 = 1.848 \times 10^9$ L $c_1 V_1 = c_2 V_2$ $c_1 \times 20\,000$ L = 1.800 mg L ⁻¹ $\times$ 1.848×10^9 L $c_1 = \frac{1.800 \text{ mg L}^{-1} \times 1.848 \times 10^9 \text{ L}}{20\,000 \text{ L}}$ $c_1 = 166\,320$ mg L ⁻¹	2
	(a) (i)	Alkaline	1
	(ii)	Anhydrous sodium carbonate eliminates the need to account for water molecules in weighing the mass and during calculations.	1
	(iii)	Fewer impurities may affect the weighed mass or interact with the reagents, altering the desired concentration or products of the reaction.	1
	(iv)	End point	1
32	(b) (i)	$m(\text{NaOH}) = 4.002$ g $M(\text{NaOH}) = 39.998$ g mol ⁻¹ $n(\text{NaOH}) = \frac{4.002}{39.998}$ $n(\text{NaOH}) = 0.1001$ mol	2
	(ii)	$m(\text{H}_2\text{O}) = 7.601 - 4.002$ $m(\text{H}_2\text{O}) = 3.599$ g $M(\text{H}_2\text{O}) = 18.016$ g mol ⁻¹ $n(\text{H}_2\text{O}) = \frac{3.599}{18.016}$ $n(\text{H}_2\text{O}) = 0.1998$ mol	1 2
	(iii)	Ratio $n(\text{NaOH}) : n(\text{H}_2\text{O})$ = $0.1001 : 0.1998$ $\approx 1 : 2$ $\therefore \text{NaOH} \cdot 2\text{H}_2\text{O}$	2
	(iv)	The sodium hydroxide solid would have absorbed water. Fewer moles of sodium hydroxide would be present due to the mass of water. With fewer moles present, the final concentration of the sodium hydroxide solution would be lower than expected.	1 1
	(v)	Sodium carbonate does not absorb water from the air as readily as sodium hydroxide.	1

Question	Part	Author's response	Marks
33		Method 1	
		Using a beaker eliminates the need to deliver the solid solute to the flask.	1
		This technique does introduce the possibility of moles of solute being lost from residues left on the stirring rod.	1
		There is also the potential for some of the residual solution to remain adhered to the surface of the beaker.	1
		Method 2	
		Care must be taken to ensure that when transferring the solid solute from the watch glass none is lost.	1
34		Reweighing removes the potential of moles of dissolved solute remaining on the watch glass during rinsing.	1
		There is the potential for some residual solution to remain adhered to the surface of the funnel.	1
	(a)	Exemplifies SHE concept of Application. Precise and systematic scientific procedure, applied to monitor and control the acidity of oils, which is crucial for maintaining product quality and safety in the chemical and food industries.	1
		Demonstrates how scientific knowledge and methods are applied in practical, real-world contexts to optimise processes, improve efficiency, and meet industry standards, ensuring products remain suitable for consumers and commercial use.	1
	(b)	Slower Reaction Rates. Acid-catalysed esterification is slower, requiring longer reaction times, which increases production costs and reduces industrial efficiency.	
		Higher Costs and Conditions. Acid-catalysed reactions often require high temperatures and strong acids, leading to increased energy consumption, corrosion of equipment, and higher maintenance costs.	1
35		This exemplifies the concept of "Development". Scientific understanding of reaction mechanisms drives the improvement and selection of processes. Industries favour base-catalysed reactions because they are more efficient and cost-effective.	1
	(a)	White wine	1
	(b) (i)	Averaging the values reduces the effect of random error.	1
	(ii)	Higher degree of accuracy	1
		11.75 is closer to the group average of 11.80 and therefore can be considered more accurate than the average titre obtained for the original group.	1
	(c) (i)	Random error	1
36	(ii)	It is difficult to see the permanent colour change through the coloured suspension of orange juice.	1
	(d)	Carbon dioxide gas is being lost from the supersaturated solution.	1
	(a)	$V = \frac{(10.10 + 10.00 + 10.10)}{3}$ $= 10.07 \text{ mL}$	1
	(b)	$n(\text{NaOH}) = c \times V$ $= 0.2074 \text{ mol L}^{-1} \times 0.01007 \text{ L}$ $= 0.002089 \text{ mol}$	2

Question	Part	Author's response	Marks
36	(c)	$\frac{\text{H}_2\text{SO}_4}{\text{NaOH}} = \frac{1}{2}$ $\therefore n(\text{H}_2\text{SO}_4) = \frac{1}{2} \times 0.00209 \text{ mol}$ $= 0.00104 \text{ mol}$	2
	(d)	$c(\text{H}_2\text{SO}_4) = \frac{n}{V} = \frac{0.00104 \text{ mol}}{0.02 \text{ L}}$ $= 0.0522 \text{ mol L}^{-1}$	2
37	(a)	$c(\text{NaOH}) = 0.00200 \text{ mol L}^{-1}$ $V(\text{NaOH}) = 10.2 \text{ mL} = 0.0102 \text{ L}$ $n(\text{NaOH}) = c \times V$ $n(\text{NaOH}) = 0.00200 \times 0.0102$ $n(\text{NaOH}) = 2.04 \times 10^{-5} \text{ mol}$	2
	(b)	$\text{Mole ratio } n(\text{OH}^-) : n(\text{NH}_4^+) = 1 : 1$ $\therefore n(\text{NH}_4^+) = 2.04 \times 10^{-5} \text{ mol}$	1
	(c)	$c = \frac{n}{V}$ $c(\text{NH}_4^+) = \frac{2.04 \times 10^{-5}}{0.0200}$ $c(\text{NH}_4^+) = 1.02 \times 10^{-3} \text{ mol L}^{-1} \text{ (3 sig. fig.)}$	3
38	(a)	$c(\text{EDTA}) = 0.010 \text{ mol L}^{-1}$ $V(\text{EDTA}) = 30.0 \text{ mL} = 0.0300 \text{ L}$ $n(\text{EDTA}) = c \times V$ $n(\text{EDTA}) = 0.010 \times 0.0300$ $n(\text{EDTA}) = 3.0 \times 10^{-4} \text{ mol}$	2
	(b) (i)	$c(\text{Zn}^{2+}) = 0.00100 \text{ mol L}^{-1}$ $V(\text{Zn}^{2+}) = \frac{(52.90 + 52.80 + 52.70)}{3}$ $= 52.80 \text{ mL} = 0.0528 \text{ L}$ $n(\text{Zn}^{2+}) = c \times V$ $n(\text{EDTA}) = 0.0010 \times 0.0528$ $n(\text{EDTA}) = 5.3 \times 10^{-5} \text{ mol}$	3
	(ii)	$\text{Mole ratio } n(\text{Zn}^{2+}) : n(\text{EDTA}_{\text{excess}}) = 1 : 1$ $\therefore n(\text{EDTA}_{\text{excess}}) = 5.3 \times 10^{-5} \text{ mol}$	1
	(iii)	$n(\text{EDTA}_{\text{reacted}}) = n(\text{EDTA}_{\text{original}}) - n(\text{EDTA}_{\text{excess}})$ $n(\text{EDTA}_{\text{reacted}}) = 3.0 \times 10^{-4} - 5.28 \times 10^{-5}$ $n(\text{EDTA}_{\text{reacted}}) = 2.472 \times 10^{-4} \text{ mol}$ $n(\text{EDTA}_{\text{reacted}}) = 2.5 \times 10^{-4} \text{ mol}$	2
	(iv)	$\text{Mole ratio } n(\text{EDTA}_{\text{reacted}}) : n\text{Al}^{3+} = 1 : 1$ $\therefore n(\text{Al}^{3+}) = 2.5 \times 10^{-4} \text{ mol}$ $c = \frac{n}{V}$ $c(\text{Al}^{3+}) = \frac{2.472 \times 10^{-4}}{0.025}$ $c(\text{Al}^{3+}) = 9.9 \times 10^{-3} \text{ mol L}^{-1} \text{ (2 sig. fig.)}$	1 2

Question	Part	Author's response	Marks
38	(v)	$M(\text{Al}^{3+}) = 26.98 \text{ g mol}^{-1}$ $\frac{\text{mol}}{\text{L}} \times M \rightarrow \frac{\text{g}}{\text{L}} \times 10^3 \rightarrow \frac{\text{mg}}{\text{L}} = \text{ppm}$ $= 9.888 \times 10^{-3} \times 26.98 \times 10^3$ $= 266.7 \text{ ppm}$ $= 270 \text{ ppm}$	2
	(a)	$2\text{HCl}_{(\text{aq})} + \text{Na}_2\text{CO}_{3(\text{aq})} \rightarrow 2\text{NaCl}_{(\text{aq})} + \text{H}_2\text{O}_{(\text{l})} + \text{CO}_{2(\text{g})}$	2
39	(b)	$n(\text{Na}_2\text{CO}_3) = c \times V$ $= 0.0507 \text{ mol L}^{-1} \times 0.02035 \text{ L}$ $= 0.00103 \text{ mol}$	1 1
	(c)	$\frac{\text{HCl}}{\text{Na}_2\text{CO}_3} = \frac{2}{1}$ $n(\text{HCl reacted in titration}) = 2 \times 0.00103 \text{ mol}$ $= 0.00206 \text{ mol}$	1 1
	(d)	$n(\text{HCl originally added}) = c \times V$ $= 0.103 \text{ mol L}^{-1} \times 0.050 \text{ L}$ $= 0.00515 \text{ mol}$	1 1
	(e)	$n(\text{HCl reacted}) = 0.00515 \text{ mol} - 0.00206 \text{ mol}$ $= 0.00309 \text{ mol}$	1 1
	(f)	$\frac{\text{NH}_3}{\text{HCl}} = \frac{1}{1}$ $n(\text{NH}_3) = 0.00309 \text{ mol}$	1 1
	(g)	$c(\text{NH}_3) = \frac{n}{V}$ $= \frac{0.00309 \text{ mol}}{0.02000 \text{ L}}$ $= 0.1545 \text{ mol L}^{-1}$	1 1
	(h)	$\text{Molar mass NH}_3 \text{ is } 17.034 \text{ g mol}^{-1}$ $0.1545 \text{ mol L}^{-1} \times 17.034 \text{ g mol}^{-1}$ $= 2.63 \text{ g L}^{-1}$ $2.63 \text{ g L}^{-1} \times 10$ $= 0.263 \% \text{ w/v}$	1 1

Question	Part	Author's response	Marks
40	(a)	Mn +2 changes to Mn +3, indicating an increase and oxidation, hence this represents the reducing agent.	1 1
	(b)	$\text{Mn(OH)}_3 + 3\text{H}^+ \rightarrow \text{Mn}^{3+} + 3\text{H}_2\text{O}$	2
	(c) (i)	$c(\text{S}_2\text{O}_3^{2-}) = 0.0200 \text{ mol L}^{-1}$ $V(\text{S}_2\text{O}_3^{2-}) = 20.2 \text{ mL} = 0.0202 \text{ L}$ $n(\text{EDTA}) = c \times V$ $n(\text{S}_2\text{O}_3^{2-}) = 0.0200 \times 0.0202$ $n(\text{S}_2\text{O}_3^{2-}) = 4.04 \times 10^{-4} \text{ mol}$	2
	(ii)	Mole ratio $n(\text{S}_2\text{O}_3^{2-}) : n(\text{I}_2) = 2 : 1$ $\frac{n(\text{I}_2)}{n(\text{S}_2\text{O}_3^{2-})} = \frac{1}{2}$ $\therefore n(\text{I}_2) = \frac{4.04 \times 10^{-4}}{2}$ $\therefore n(\text{I}_2) = 2.02 \times 10^{-4} \text{ mol}$	2
	(iii)	Iodine formed from Equation 4 is reacted in Equation 5. $\therefore n(\text{I}_2) = 2.02 \times 10^{-4} \text{ mol}$	1
	(1)	Mole ratio $n(\text{S}_2\text{O}_3^{2-}) : n(\text{I}_2) : n(\text{Mn}^{3+}) : n(\text{Mn(OH)}_3) : n(\text{O}_2)$ $= 2:1, 1:2, 1:1, 1:4$ $\frac{n(\text{O}_2)}{n(\text{Mn(OH)}_3)} = \frac{1}{4}$ $\therefore n(\text{O}_2) = \frac{2.02 \times 10^{-4}}{4}$ $\therefore n(\text{O}_2) = 5.05 \times 10^{-5} \text{ mol}$	1 2
	(iv) (2)	$c = \frac{n}{V}$ $c(\text{O}_2) = \frac{5.05 \times 10^{-5}}{0.100}$ $c(\text{O}_2) = 5.05 \times 10^{-4} \text{ mol L}^{-1} \text{ (3 sig. fig.)}$	2
	(3)	$\frac{\text{mol}}{\text{L}} \times M = \frac{\text{g}}{\text{L}} \times 10^3 = \frac{\text{mg}}{\text{L}} = \text{ppm}$ $M(\text{O}_2) = 32.00 \text{ g mol}^{-1}$ $= 5.05 \times 10^{-4} \times 32.00 \times 1000$ $= 16.2 \text{ ppm}$	3
	(4)	2–8 ppm indicates moderately polluted water, therefore this water sample is polluted, as it is above that value.	1

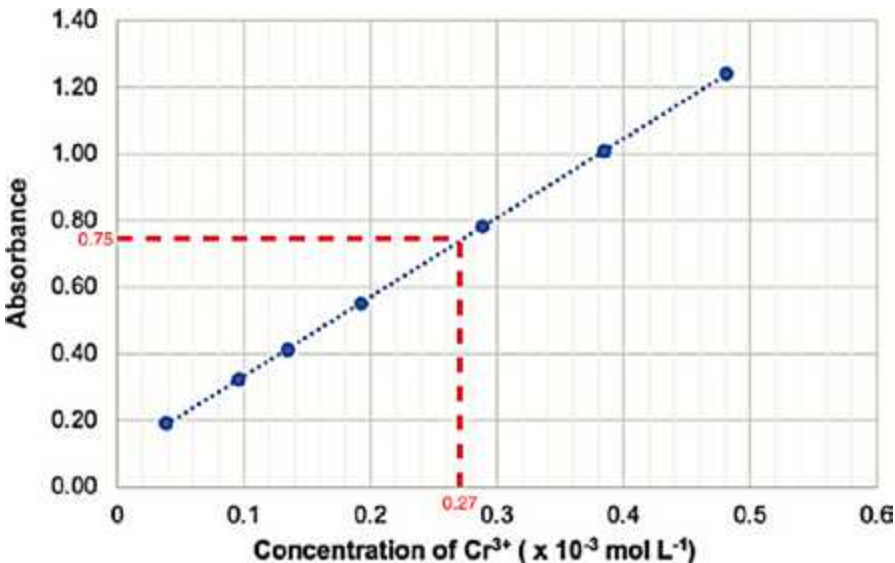
Question	Part	Author's response	Marks
41	(a)	Any well-explained point: - Ensures that scientists and public health authorities can monitor water quality for contaminants, such as harmful chemicals, bacteria, or heavy metals. - Allows for early detection and prevention. Continuous testing identifies issues promptly, enabling immediate corrective action to prevent public health risks. - Water testing ensures compliance with safety standards, providing the public with access to clean, safe, and affordable drinking water. This exemplifies the concept of "Application" because it demonstrates how scientific knowledge and testing methods are applied to solve real-world problems. Continuous water monitoring uses scientific advancements to safeguard public health, ensuring access to essential resources like safe drinking water, which is vital for society and well-being.	1 1 1
	(b)	Marketing and advertising create a perception that bottled water is cleaner or safer, appealing to cultural preferences. Social influence often outweighs scientific findings that tap water is equally safe in many regions. Bottled water companies, driven by profit, heavily promote their products, influencing public perception through branding and advertising. Consumers may accept these claims without questioning the scientific evidence due to trust in marketing messages.	1 1 1
	(c)	Limited testing across brands, production batches, or regions can lead to incomplete or biased conclusions about bottled water safety. Failing to test for a wide range of contaminants may overlook potential risks, reducing the reliability of findings. Data collected over short periods may miss long-term trends or cumulative health effects, weakening the overall conclusions.	1 1 1
	(d)	Conventions and verification maintain the integrity of scientific communication, ensuring that only accurate and reliable knowledge is shared within the scientific community and with the public. Before research findings are published in scientific journals, they are rigorously reviewed by other experts in the field to verify the accuracy, validity, and reliability of the methods, data, and conclusions. This process ensures that the research meets established scientific standards and eliminates errors or biases. The use of standardised conventions, such as clear methodologies, proper citations, and reproducibility of experiments, allows other scientists to replicate and verify the findings, reinforcing their credibility and reliability.	1 1 1
		Any two of the following points (or alternatives). The science must be clearly identified, and explicit links made to society (people). Application The development of chromatographic techniques like LC-MS and HPLC has enabled the analysis of over 1,000 metabolites in blood samples within just 15 minutes. This allows for the creation of individual metabolic profiles, tailoring treatments to patients' unique biochemistry and improving healthcare outcomes. Limitation The reliance on expensive and sophisticated equipment, such as LC-MS and HPLC, may limit access to these personalised medical approaches, particularly in underfunded healthcare systems or regions with limited resources. The complexity of interpreting metabolic profiles could lead to variability in clinical applications, making it challenging to generalise findings across diverse populations or ensure consistent results. The time, expertise, and infrastructure required for metabolomics research and its integration into clinical practice may hinder its widespread adoption.	2

Question	Part	Author's response	Marks
43	(a) (i)	$R_{fA} = \frac{3.4}{5} = 0.68$	2
		$R_{fB} = \frac{2.9}{5} = 0.57$	2
	(ii)	$TcO_4^- = A$ $TcO_2 = B$	2
	(b)	As the stationary phase is shorter, the duration of the separation is shorter, leading to a faster analysis.	1
		Although the components have moved different distances, the rate of movement remains constant.	1
		The R_f values will be the same (accounting for experimental error).	1
		Therefore the validity is still maintained.	1
44		Any one of the following points (or alternatives). The science must be clearly identified, and explicit links made to society (people). Development The development of MOMA technology required the adaptation of chromatographic techniques, such as GC-MS, for extreme environmental conditions on Mars (-90 °C to 20 °C). Also, engineers designed MOMA to be compact and robust, with redundant systems like multiple chromatographic columns. This demonstrates how science progresses by solving technological challenges. Application and Limitation MOMA allows for the first detailed organic analysis of Martian soil, providing valuable insights into the possibility of past life on Mars, which could significantly advance our understanding of the universe and life beyond Earth. The compact design and reliance on helium tanks highlight the limitations and challenges of adapting scientific equipment for extraterrestrial environments, such as weight and size constraints on spacecraft. Influence Public and cultural fascination with the search for extraterrestrial life has shaped scientific goals and influenced funding for missions like ExoMars. This societal interest ensures continued support for advancing technologies such as MOMA, highlighting how human aspirations can guide and propel scientific discovery. The discoveries made by MOMA, such as detecting organic molecules in Martian soil, have the potential to influence future space missions, the search for extraterrestrial life, and even our understanding of life's origins, showcasing the reciprocal impact of scientific exploration on broader areas of science and philosophy. Communication and Collaboration MOMA's success is the result of collaboration between scientists and engineers across various disciplines, such as chemistry, space exploration, and materials science, exemplifying how teamwork is essential in advancing scientific research.	2

Question	Part	Author's response	Marks
45	(a) (i)	Band C	1
		The component in band C has moved at the fastest rate.	1
		This indicates it was least strongly adsorbed to the polar stationary phase and most soluble in the mobile phase, therefore moving with it.	1
	(ii)	Increase the length of the column and, therefore, the stationary phase.	1
		Repeat the procedure altering the polarity of the solvent chosen.	
	(b)	Band C	1
The component in band C would move at the fastest rate, and therefore, the appear closest to the solvent front at the top of the chromatogram.		1	
As a ratio (of the distance the component travelled compared to the solvent) it would generate the largest value, which is closest to 1.		1	
46	(a)	Best aligns with the concept of "Application and Limitation". Any two of the following: Developing solutions and making discoveries: The application of GC×GC represents an innovative scientific approach to address the pressing issue of microplastic pollution. It provides a precise method to identify the type and origin of plastics. Action for sustainability:	1
		The creation of a global "plastic fingerprint" database supports efforts to reduce ocean pollution by informing sustainable practices and policies.	1
		Evaluating impacts: This technology allows scientists to assess the environmental impact of specific manufacturers and regions, fostering accountability and inspiring environmentally-conscious practices.	1
		Reliable predictions: By identifying pollution sources and trends, the database can help predict future hotspots of plastic pollution and guide proactive interventions.	1
		Potential impact: GC×GC technology can pinpoint the type and manufacturer of plastics, enabling targeted interventions to reduce pollution and hold responsible entities accountable. The high-resolution analysis of microplastics provides better data for understanding pollution patterns, aiding in global efforts to mitigate plastic pollution.	1
	(b)	Challenges: GC×GC instruments and expertise are expensive, which may limit their use to well-funded research institutions, leaving many regions without access to this technology. Establishing and maintaining a global "plastic fingerprint" database requires significant international collaboration, data sharing, and standardisation of methods. Also may require advanced training to interpret GC×GC data accurately.	1
			1
			1
			1
	47	(a)	Boat A
The majority of the peaks for boat A match the retention times, but do not for boat B.			1
The peaks demonstrate a lower relative abundance due to decomposition for boat A but remain at the same retention times.			1
(b)		Any one: The same oil may be used by other tankers. Peaks for components may have been lost as the hydrocarbons break down in the ocean or volatile components are lost.	1

Question	Part	Author's response	Marks
48	(a)	14.7 minutes (3 significant figures)	1
	(b) (i)	Methamphetamine contains an additional methyl group compared to amphetamine.	2
	(ii)	Methamphetamine is less polar than amphetamine.	1
		Methamphetamine has a larger retention time, as it was adsorbed more strongly to the stationary phase.	1
		Therefore, the stationary phase is likely to be non-polar.	1
49	(a) (i)	Ammonium and nitrate ions are soluble ions.	1
	(ii)	Anion exchange column	1
	(b)	The single negative charge of nitrate offers a lower charge-density compared to the double negative charge of the sulfate ions.	1
		Nitrate ions are less strongly adsorbed to the positively charged binding sites.	1
		Nitrates are more easily removed from binding sites. They travel at a faster rate along the column, hence a shorter retention time results.	1
	(c)	The high concentration of borate ions places a stress on the system at equilibrium.	1
		The position of equilibrium shifts to the right to counteract the change.	1
		Nitrate ions are exchanged from the surface of the resin, replaced with borate ions.	1
50	(a)	Be $1s^2 2s^2$ C $1s^2 2s^2 2p^2$ O $1s^2 2s^2 2p^4$ F $1s^2 2s^2 2p^5$ Na $1s^2 2s^2 2p^6 3s^1$ Al $1s^2 2s^2 2p^6 3s^2 3p^1$ Si $1s^2 2s^2 2p^6 3s^2 3p^2$ P $1s^2 2s^2 2p^6 3s^2 3p^3$ Ar $1s^2 2s^2 2p^6 3s^2 3p^6$ K $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$	10
	(b)	The element is located in the block of the periodic table indicated by the highest energy subshell occupied.	1
51	(a) (i)	They all end with an electron in the d-block, indicating that the highest energy subshell occupied is a <i>d</i> subshell.	1
	(ii)	Cu^{2+} (as sulfur usually takes a 2- charge to become sulfide, S^{2-}).	1
	(iii)	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^{10}$	2
	(iv)	Cu^+ : $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}$ (the 4s electron is removed first)	4
		Cu^{2+} : $1s^2 2s^2 2p^6 3s^2 3p^6 3d^9$	
	(b)	Atoms have greater stability if their subshells are half-filled because this creates a symmetry which makes the electron configurations shown more energetically stable than the alternative s^2 configurations	1
	(c) (i)	$2\text{Ag}_{(s)} + \text{H}_2\text{S}_{(g)} \rightarrow \text{Ag}_2\text{S}_{(s)} + \text{H}_{2(g)}$	2
	(ii)	H_2S or hydrogen sulfide	1

Question	Part	Author's response	Marks
52	(a) (i)	$= \frac{100}{13} \times 150$ $= 1153.8 \text{ mL}$ $= 1.1 \text{ L}$	2
	(ii)	Iodine is present in higher concentrations in other foods consumed daily.	1
	(b) (i)	$1s^2 2s^2 2p^6 3s^1$	2
	(ii)	$1s^2 2s^2 2p^6$	2
	(iii)	$1s^2 2s^2 2p^6 3s^2 3p^6$	2
	(iv)	In chloride and iodide, the final p subshell has been filled with the addition of one electron.	1
53	(a)	Electronics are imported from many regions around the world. They contain metals and raw materials extracted and refined from various regions of the world.	1
		Products that have become redundant in Australia become landfill or are exported back overseas for processing.	1
	(b)	Froth flotation, employed in metal production, can be used to collect the precious metals on the surface of bubbles.	1
54	(a) (i)	p	1
	(ii)	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^3$	2
	(b) (i)	Arsenic was present.	1
		The line emission spectra of arsenic is present in the spectra for the unknown sample.	1
	(ii)	Lead	1
	(c)	$606 \text{ ppb} = 606 \mu\text{g L}^{-1}$ $= 0.606 \text{ mg L}^{-1}$ $= 6.06 \times 10^{-4} \text{ mg g}^{-1}$ $= 6.06 \times 10^{-4} \times 1.02 \text{ mg}$ $= 6.18 \times 10^{-4} \text{ mg}$	1
			1
			1
55	(a) (i)	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^7$	2
	(ii)	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^3$	2
	(b)	Elemental (non-ionic) cobalt and chromium have electron configurations ending in $4s^2 3d^7$ and $4s^1 3d^5$, respectively.	2
		As they both end with an electron in a d subshell, they are both placed in the d-block.	
	(c) (i)	Increased concentration of chromium ions is associated with increased absorbance.	1

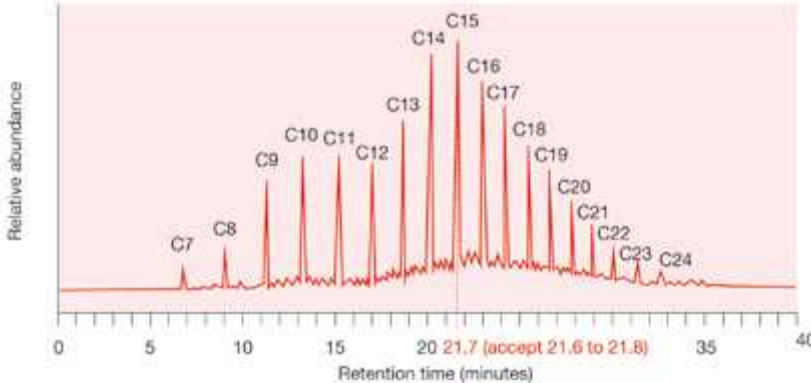
Question	Part	Author's response	Marks
55	(ii)	 Accept answers between $0.26\text{--}0.28 \times 10^{-3} \text{ mol L}^{-1}$.	1
	(iii)	$M(\text{Cr}) = 52.00 \text{ g mol}^{-1}$ $0.27 \times 10^{-3} \text{ mol L}^{-1} \times 52.00 \text{ g mol}^{-1} = 14.04 \times 10^{-3} \text{ g L}^{-1}$ $14.04 \times 10^{-3} \text{ g L}^{-1} \times 1000 = 14.04 \text{ mg L}^{-1}$ $14.04 \text{ mg L}^{-1} = 14.04 \text{ ppm}$	2
	(1)	Systematic error	1
	(2)	Line-of-best-fit does not pass through the origin	1
	(iv)	<i>Many responses possible. Examples include:</i> Failure to correctly calibrate the apparatus with a blank solution (3) Incorrect technique when diluting standard solutions Contamination of standard solutions Incorrect selection of wavelength (or an insufficiently specific set of wavelengths)	1
	(v)	The wavelength of chromium selected for detection is unique to chromium. The transitions in manganese do not match the detected wavelength, and therefore they are unable to absorb radiation incident from the lamp at this wavelength.	2
	(vi)	Any two: A lamp emitting a wavelength specific to an electron transition in the manganese ion would be used. A new calibration curve would be created using standard solutions of manganese. A detector specific to the manganese wavelength would be used.	2

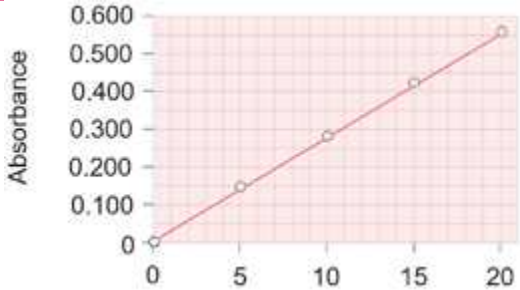
Question	Part	Author's response	Marks
56	(a)		3
	(b) (i)	Chemist B	1
	(ii)	(1) Chemist A	1
		(2) $265 \mu\text{g}/100 \text{ mL} = 0.265 \text{ mg}/100 \text{ mL} = 2.65 \text{ mg L}^{-1} = 2.65 \text{ ppm}$ The limit is 3 ppm so the water is safe to drink.	1
	(c) (i)	Breaks the sample down into individual atoms.	1
	(ii)	Allows only the specific wavelength being investigated to reach the detector.	1
57	(a) (i)	p	1
	(ii)	$1s^2 2s^2 2p^6 3s^2 3p^2$	2
	(iii)	Covalent network	1
	(iv)	Strong primary covalent bonds exist between silicon and oxygen atoms in the extended network producing a hard material.	1
		A large amount of energy is required to overcome the bonds, thus ensuring a high melting point.	1
	(b) (i)	$\text{SiO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SiO}_3 + \text{H}_2\text{O}$	2
	(ii)	Acidic oxide	1
	(c) (i)	$0.326 \mu\text{g mL}^{-1} = 326 \mu\text{g L}^{-1}$ $= 326 \text{ ppb}$	2
	(ii)	Metal	1
	(iii)	$1s^2 2s^2 2p^6 3s^2 3p^6$	2
	(iv)	(1) A low degree of scatter around the line of best fit.	
		(2) Systematic error. Graph does not pass through origin (0,0).	1 1

Summary test 1 solutions: Monitoring the environment

Question	Part	Author's response	Marks
1	(a) (i)	$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$	2
	(ii)	Any one: Combustion of fossil fuels in internal combustion engines for transport. Combustion of fossil fuels during the production of electricity in power stations. Combustion of fossil fuels to create heat for industrial processes. Chemical manufacturing processes (e.g., production of glass and ceramic). Deforestation and land-clearing.	1
	(iii)	Carbon dioxide is a greenhouse gas.	1
		Increased levels of carbon dioxide in the atmosphere leads to an increase in the infrared thermal radiation that is absorbed from the surface of the Earth.	1
		This creates a thermal imbalance between the radiation lost and absorbed from the lower atmosphere, resulting in an increased average temperature in the Earth's troposphere.	1
	(b)	$= 0.927 \times 4.18 \times 10^9 \times 10^3$ $= 3.87 \times 10^{12} \text{ kg}$	2
	(c) (i)	Any four: - The concentration of dissolved carbon dioxide in the oceans has increased and is predicted to show further increase. - This increase is exponential. - pH decreases accordingly as the concentration of dissolved carbon dioxide increases. - Carbon dioxide dissolves in water to form carbonic acid. - Carbonic acid partially ionises, increasing the concentration of H^+, thus decreasing the pH. $\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3$ $\text{H}_2\text{CO}_3 \rightarrow \text{HCO}_3^- + \text{H}^+$	4
	(ii)	Highest concentration H^+ is represented by the lowest pH. $[\text{H}^+] = 10^{-7.85}$ $= 1.41 \times 10^{-8} \text{ mol L}^{-1}$	1 2
	(iii)	Increased ocean acidity corresponds to an increase the concentration of H^+ ions. Increasing the concentration of H^+ results in the formation of hydrogen carbonate ions. The formation of hydrogen carbonate reduces the available concentration of carbonate ions. (Note: <i>simplified description, equilibrium is covered in Topic 2.</i>)	1 1

Question	Part	Author's response	Marks
1	(d)	Any two of the following points (or alternatives). The science must be clearly identified, and explicit links made to society (people). Influence: Environmental Mining practices to obtain raw materials for renewable energy infrastructure contribute significantly to atmospheric emissions of carbon dioxide. Energy requirements, processing, and transportation of products also contribute. Elevated concentrations of atmospheric carbon dioxide have led to global warming and climate change. Climate change impacts humans and native ecosystems. Mining practices also significantly impact upon native plant and animal species and their associated ecosystem in the location of the mine site. Researchers have mapped mine sites for renewable materials and important regions of natural biodiversity to influence planning for sustainability. Economic Australia has a substantial body of natural resources required for renewable energy production. Mined materials are a valuable export for Australia, with significant economic contribution. Economic decisions may not consider impact on biodiversity. Researchers have mapped mine sites for renewable materials and important regions of natural biodiversity to influence economic decisions. Social/Political Social pressures from the community with regards to environmental concerns of impact upon ecosystems and biodiversity may influence political decisions on where mining takes place and the extent of mining allowed. The findings outlined from researchers mapping of mine sites for renewable materials and important regions of natural biodiversity, may influence social understanding and subsequent political decisions.	4
2	(a) (i)	Any one: High temperatures are experienced during the combustion of fuels in the engine. Nitrogen and oxygen are both present in air in the air-fuel mixture.	1
	(ii)	$2\text{NO}_{(g)} + \text{O}_{2(g)} \rightarrow 2\text{NO}_{2(g)}$	2
	(b) (i)	Any one: The reaction is photochemical, requiring the absorption of UV light. The absorption of UV light provides the energy required to achieve the activation energy.	1
	(ii)	$\text{NO}_{2(g)} \xrightarrow{\text{UV}} \text{NO}_{(g)} + \text{O}_{(g)}$ $\text{O}_{(g)} + \text{O}_{2(g)} \rightarrow \text{O}_{3(g)}$	2 2
	(iii)	Human exposure to ozone may cause eye irritation and respiratory distress.	1
		3 significant figures should be used in the following answers.	–
	(c) (i)	Yellow	1
	(ii)	$n(\text{NaOH}) = 0.100 \times 9.16 \times 10^{-3}$ $= 9.16 \times 10^{-4}$ $= 9.16 \times 10^{-4} \text{ mol}$	2
	(iii)	mole ratio $n(\text{NaOH}) : n(\text{HNO}_3)$ 1:1 $\therefore n(\text{HNO}_3) = 9.16 \times 10^{-4} \text{ mol}$	1

Question	Part	Author's response	Marks
2	(iv)	mole ratio $n(\text{HNO}_3) : n(\text{NO}_2)$ $2:2 = 1:1$ $\therefore n(\text{NO}_2) = 9.16 \times 10^{-4} \text{ mol}$	1
	(v)	$C(\text{NO}_2) = \frac{9.16 \times 10^{-4}}{5.00}$ $= 1.832 \times 10^{-4} \text{ mol L}^{-1}$ $= 1.832 \times 10^{-4} \times 46.01 \text{ g L}^{-1}$ $= 1.832 \times 10^{-4} \times 46.01 \times 10^3 \text{ mg L}^{-1}$ $= 8.43 \text{ ppm (3 sig. fig.)}$	2 2
3	(a) (i)	Octane	1
	(ii)	 21.7 (+/- 0.1) min (3 sig. fig.)	1 1
	(iii)	As carbon chain length increases, the retention time increases.	1
	(iv)	Non-polar The non-polar alkanes adsorb to a non-polar stationary phase. (If a polar stationary phase were to be used, the alkanes would not adsorb and therefore would not separate).	1 1
	(v)	Any one: • Shorter chain alkanes present are volatile and may be lost when temperatures rise. • Longer chain alkanes are decomposed, breaking down to volatile products which are lost.	1
	(b) (i)	Positive	1
	(ii)	Phosphate Phosphate ions have a 3- charge compared to 1- for nitrate. Overall, they have a higher negative charge density, resulting in stronger electrostatic attraction to the zeolite surface. They would be more difficult to remove from the surface and shift across the stationary phase. This therefore results in a longer retention time.	1 1 1

Question	Part	Author's response	Marks
	(a) (i)	d	1
	(ii)	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^5$	2
	(iii)	+6	2
	(b) (i)	Absorbance	1
	(ii)	 Axes correctly scaled, axes labelled, labels include units, data points plotted correctly, line of best fit drawn straight (not join-the-dots).	1
			1
			1
			1
			1
			1
	(iii)	Low degree of scatter.	1
	(iv)	The wavelength of copper selected for detection is unique to copper.	1
		The transitions in chromium and arsenic do not match the detected wavelength, and therefore they are unable to absorb radiation incident from the lamp at this wavelength.	1
4	(c)	Acid rain increases the mobilisation of cations, including toxic species.	1
	(d)	Any two of the following points (or alternatives). The science must be clearly identified, and explicit links made to society (people). Development The transition from CCA-treated timber to steel posts exemplifies the development of materials through the integration of evidence from multiple fields, including material science and environmental studies, to improve the durability and sustainability of vineyard infrastructure. Application and Limitation The search for alternatives to CCA posts reflects the application of scientific understanding to develop more sustainable and durable materials, such as steel, which reduces breakage rates and waste. However, the high cost and the need for custom parts limit the widespread adoption of steel posts in the viticulture industry. The environmental impact of stockpiled and landfill-bound CCA-treated posts highlights the limitation of current solutions. This drives innovation to find alternatives that balance cost, sustainability, and practicality. Influence Environmental concerns about the long-term effects of CCA-treated timber, including potential soil contamination and waste management challenges, influence the development of alternative materials. This reflects how societal values and ecological awareness drive changes in industrial practices. Economic pressures within the viticulture industry influence the development of alternatives to CCA-treated posts. While steel posts offer sustainability benefits, their higher cost and logistical challenges impact their acceptance, demonstrating how economic considerations shape the adoption of scientific advancements.	4

Question	Part	Author's response	Marks
4		Communication and Collaboration	
	(d)	Collaboration between the viticulture industry, material scientists, and environmental researchers is essential in the search for alternatives to CCA-treated posts. These partnerships ensure that new solutions, like steel posts, address practical concerns, environmental impacts, and industry-specific needs, demonstrating how effective teamwork drives scientific and technological progress. Communication plays a critical role in promoting the adoption of alternatives to CCA-treated posts. Clear dissemination of research findings about the environmental risks of CCA-treated timber and the benefits of steel posts can influence vineyard operators and policymakers, encouraging informed decisions that prioritise sustainability and innovation.	
5	(a)	$1s^2 2s^2 2p^6 3s^2 3p^2$	2
	(b) (i)	$M(\text{SiCl}_4) = (1 \times 28.09) + (4 \times 35.45) = 169.89 \text{ g mol}^{-1}$ $n(\text{SiCl}_4) = \frac{225}{169.89} = 1.32 \text{ mol}$	1
		$M(\text{Mg}) = 24.31 \text{ g mol}^{-1}$ $N(\text{Mg}) = \frac{225}{24.31} = 9.26 \text{ mol}$	1
	(ii)	$n(\text{SiCl}_4) : n(\text{Mg}) = 1:2$ For SiCl_4 , $\frac{1.32}{1} = 1.32$	1
		For Mg , $\frac{9.26}{2} = 4.63$ $1.32 < 4.63 \therefore \text{SiCl}_4$ is the limiting reagent. Mg is in excess.	1
	(iii)	$n(\text{SiCl}_4) : n(\text{Si}) = 1:1$	1
		$n(\text{SiCl}_4) = 1.32 \text{ mol} \therefore n(\text{Si}) = 1.32 \text{ mol}$	1
		$m(\text{Si}) = n \times M = 1.32 \times 28.09 = 37.1 \text{ g}$	1
	(c) (i)	Silicon-based technologies, like the newly developed polarisation multiplexer, have advanced high-speed data communications, enabling improvements in telecommunication networks. This provides enhanced connectivity for collaborative research and development.	2
	(ii)	Society's growing demand for data-intensive applications, such as streaming, cloud computing, and IoT, has driven the need for faster and more efficient communication technologies. This demand directly influenced the development of the polarisation multiplexer, which operates at higher frequencies to enable ultra-fast 6G wireless communications, meeting the increasing need for high-speed data transfer.	2
	(iii)	International collaboration combines diverse expertise, resources, and perspectives, accelerating the development of advanced technologies like 6G. The partnership between the University of Adelaide and Osaka University highlights how pooling knowledge and skills fosters innovation, enables refinement of complex systems, and ensures that new technologies are robust and globally applicable.	2

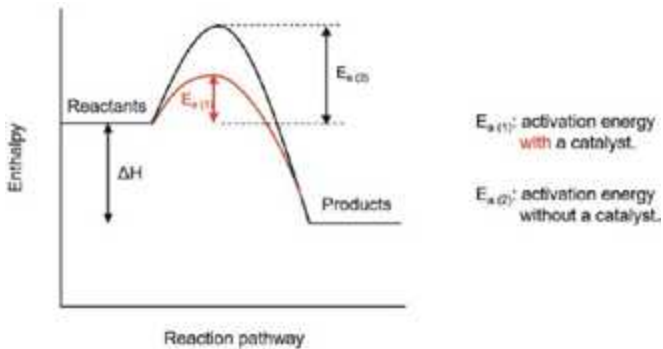
Question	Part	Author's response	Marks
5	(iv)	<i>Many responses possible. Examples include:</i> The enhanced data collection capabilities of 6G networks could facilitate mass surveillance, raising concerns about privacy violations and misuse of personal data. Faster data speeds and higher connectivity in 6G networks may increase vulnerability to cyberattacks and large-scale data breaches. Users may face challenges in understanding and controlling how their data is collected and used, leading to potential violations of consent and data ownership. The rapid advancement of 6G technology could outpace the development of privacy laws and regulations, creating gaps in accountability.	2
	(v)	<i>Many responses possible. Examples include:</i> Enable remote collaboration through enhanced video conferencing and virtual reality workspaces. Facilitate faster access to large datasets and cloud computing resources. Support the automation of workflows with real-time communication between IoT devices. Expand access to interactive and immersive educational tools, e.g., VR and AR. Improve real-time communication between educators and students in remote or hybrid learning environments. Allow faster sharing of large-scale research data and resources globally. Enhance social connectivity through ultra-realistic virtual interactions and metaverse platforms. Support high-quality communication globally, connecting distant communities.	2
	(vi)	<i>Many responses possible. Examples include:</i> Increased energy demand from 6G infrastructure, including base stations and data centres, could increase carbon emissions. The transition to 6G will generate electronic waste as older devices and equipment are phased out, creating recycling and disposal challenges. Manufacturing 6G hardware relies on rare earth elements and other resources, straining finite natural reserves and contributing to environmental damage. Building new infrastructure, such as towers and cables, may disrupt ecosystems and alter urban or rural landscapes. Data centre expansion to handle 6G traffic could lead to increased energy and water use.	2

Topic 2 solutions: Managing chemical processes

Question	Part	Author's response	Marks
1	(a)	Application and Limitation Novel reactors such as spinning disc reactors (SDRs) and oscillatory baffled reactors (OBRs) address limitations of conventional reactors by enhancing mass and heat transfer. These designs increase reaction rates and product selectivity while minimising energy and waste. This showcases how scientific innovation addresses practical constraints in chemical processes. <i>OR</i> Influence on Society By reducing energy consumption and waste production, these reactors contribute to global sustainability goals. Industries adopting such technologies can mitigate environmental impact, supporting society's push toward greener processes This is helping to address societal concerns about resource depletion.	4
	(b)	Development SDRs and OBRs embody advancements in reactor design, utilising thin films and oscillatory motion to intensify mixing and control reaction conditions. These technological developments represent a refinement of existing models for chemical kinetics and thermodynamics to achieve enhanced efficiency. Influence The adoption of these novel reactors reduces industrial energy consumption and waste. This demonstrates how scientific advancements can align industrial practices with societal goals, such as minimising environmental impact and promoting resource conservation.	3

Question	Part	Author's response	Marks
2	(a)	Activation energy is the minimum amount of energy that reacting particles must collide with for a chemical reaction to occur.	1
	(b)	The energy of a collision between molecules increases with temperature because temperature is a measure of the average kinetic energy of the particles. A higher temperature indicates that the particles are moving faster, leading to more frequent and more energetic collisions.	2
	(c)	For a collision between molecules to result in a chemical reaction, the colliding particles must have energy equal to or greater than the activation energy, and the particles must collide with the correct orientation.	2
	(d)	The units for reaction rate depend on the quantity being measured in the method. For example, if the volume of gas produced is measured, the rate will be expressed as volume per time, e.g., cm^3/s . If the mass of a substance is measured, the rate could be in g/s , while if concentration is measured, the rate might be given in $\text{mol}\cdot\text{L}^{-1}\cdot\text{s}^{-1}$.	3
3	(a)	If the surface area of CaCO_3 is increased, exposing more particles, and altering the surface area to volume ratio. The frequency of collisions between HCl and CaCO_3 increases as more particles of CaCO_3 are exposed. The increased collision frequency results in a higher number of successful collisions per unit time between HCl and CaCO_3 . Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction.	3
	(b)	If the concentration of HCl is reduced there are less H^+ ions in the system available to react with CaCO_3 and the frequency of collisions is decreased. Less collisions occur and as a result less successful collisions occur between H^+ ions and CaCO_3 . Therefore, less successful collisions occur per unit time resulting in a decrease in the rate of reaction.	3
	(c)	At $t=5$ seconds there is a greater concentration of reactants than at $t=50$ seconds when more of the reactants have been converted into carbon dioxide gas. The greater concentration leads to an increased frequency of collisions between HCl and CaCO_3 . More collisions occur between reacting particles and as a result a larger number of successful collisions occur. Therefore, a larger number of successful collisions occur per unit time at $t=5$ seconds resulting in a higher instantaneous rate of reaction.	4
	(d)	A mass of CaCO_3 is added to a conical flask. A specific volume of HCl is poured into a conical flask. The time taken for the CaCO_3 to completely react and no longer being visible is measured using a timer.	3

Question	Part	Author's response	Marks
4	(a)	Development MOF-based catalysts represent a significant advancement in water splitting by optimising efficiency. These catalysts provide abundant active sites and facilitate rapid charge transfer, reducing the activation energy required for hydrogen generation. These developments showcase the role of catalytic technology in advancing the hydrogen economy as part of a sustainable future.	3
	(b)	Influence Efficient hydrogen production from renewable sources reduces greenhouse gas emissions, promoting a transition to clean energy. Catalysts reduce dependence on fossil fuels and significantly lower greenhouse gas emissions, aligning with global efforts to combat climate change. However, challenges remain that limit their widespread implementation. The high production costs of MOF-based materials make large-scale adoption economically challenging (e.g., high costs of metal precursors and synthesis techniques). Additionally, the long-term durability of these catalysts under real-world operating conditions must be addressed to ensure their reliability.	4
5	(a)	Lactase provides an alternative pathway with a lower E_a for the lactose to digest in the human gut. This results in a larger proportion of collisions between reacting particles reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring. Therefore, a larger number of successful collisions occur per unit time increasing the rate of digestion of lactose.	3
	(b)	If the temperature of the milk is increased this results in the average kinetic energy of all particles in the milk increasing and exhibiting more thermal energy. Therefore, there is a larger proportion of collisions between reacting particles in the milk reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring between these particles. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of formation by products in the milk.	3

Question	Part	Author's response	Marks
6	(a)	$2\text{Mg} + \text{O}_2 \rightarrow 2\text{MgO}$	2
	(b)	The surface area of magnesium is increased when using a powder instead of strips, exposing more particles, and altering the surface area to volume ratio. The frequency of collisions between magnesium and oxygen increases as more particles of magnesium are exposed. More collisions occur and as a result a larger number of successful collisions occur between magnesium and oxygen. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction.	3
	(c)	The fuse releases a large amount of energy that is provided to the system, this results in the average kinetic energy of the magnesium and oxygen increasing and exhibiting more thermal energy. Therefore, there is a larger proportion of collisions between magnesium and oxygen reaching or exceeding the Activation Energy. There is an increased frequency of successful collisions occurring between the particles. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction	3
	(d)	The reaction between magnesium and oxygen is exothermic and the energy produced is transferred to unreacted magnesium and oxygen.	2
	(e)	 $E_{a(f)}$: activation energy with a catalyst. $E_{a(d)}$: activation energy without a catalyst.	3
7	(a)	Application and Limitation The bicarbonate buffer system demonstrates how chemical equilibrium principles are applied in physiology to maintain blood pH within a narrow range. This application is critical for homeostasis, but limitations arise when buffer capacity is exceeded. This can lead to disorders such as acidosis or alkalosis.	3
	(b)	Development Medical professionals use equilibrium principles to analyse blood gas levels and design interventions. For example, in acidosis, increasing ventilation expels more CO_2, shifting the bicarbonate buffer system to counteract the pH drop. Influence Understanding these mechanisms has improved medical treatments and outcomes for acid-base disorders, addressing societal health challenges. This knowledge exemplifies how scientific understanding can directly impact and improve human well-being.	4

Question	Part	Author's response	Marks																				
8	(a)	$K_c = \frac{[\text{CH}_3\text{COOCH}_3] \cdot [\text{H}_2\text{O}]}{[\text{CH}_3\text{OH}] \cdot [\text{CH}_3\text{COOH}]}$	1																				
	(b)	<table><tr><td></td><td>CH₃OH</td><td>CH₃COOH</td><td>CH₃COOCH₃</td><td>H₂O</td></tr><tr><td>Initial moles</td><td>1.2</td><td>1.2</td><td>0.00</td><td>0.00</td></tr><tr><td>Change in moles</td><td></td><td></td><td></td><td></td></tr><tr><td>Equilibrium moles</td><td></td><td></td><td>0.50</td><td></td></tr></table>		CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O	Initial moles	1.2	1.2	0.00	0.00	Change in moles					Equilibrium moles			0.50		3
			CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O																	
		Initial moles	1.2	1.2	0.00	0.00																	
		Change in moles																					
		Equilibrium moles			0.50																		
		<table><tr><td></td><td>CH₃OH</td><td>CH₃COOH</td><td>CH₃COOCH₃</td><td>H₂O</td></tr><tr><td>Initial moles</td><td>1.2</td><td>1.2</td><td>0.00</td><td>0.00</td></tr><tr><td>Change in moles</td><td></td><td></td><td>+0.50</td><td></td></tr><tr><td>Equilibrium moles</td><td></td><td></td><td>0.50</td><td></td></tr></table>		CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O	Initial moles	1.2	1.2	0.00	0.00	Change in moles			+0.50		Equilibrium moles			0.50		
			CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O																	
		Initial moles	1.2	1.2	0.00	0.00																	
		Change in moles			+0.50																		
		Equilibrium moles			0.50																		
		<table><tr><td></td><td>CH₃OH</td><td>CH₃COOH</td><td>CH₃COOCH₃</td><td>H₂O</td></tr><tr><td>Initial moles</td><td>1.2</td><td>1.2</td><td>0.00</td><td>0.00</td></tr><tr><td>Change in moles</td><td>-0.50</td><td>-0.50</td><td>+0.50</td><td>+0.50</td></tr><tr><td>Equilibrium moles</td><td></td><td></td><td>0.50</td><td></td></tr></table>		CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O	Initial moles	1.2	1.2	0.00	0.00	Change in moles	-0.50	-0.50	+0.50	+0.50	Equilibrium moles			0.50		
			CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O																	
		Initial moles	1.2	1.2	0.00	0.00																	
		Change in moles	-0.50	-0.50	+0.50	+0.50																	
		Equilibrium moles			0.50																		
		<table><tr><td></td><td>CH₃OH</td><td>CH₃COOH</td><td>CH₃COOCH₃</td><td>H₂O</td></tr><tr><td>Initial moles</td><td>1.2</td><td>1.2</td><td>0.00</td><td>0.00</td></tr><tr><td>Change in moles</td><td>-0.50</td><td>-0.50</td><td>+0.50</td><td>+0.50</td></tr><tr><td>Equilibrium moles</td><td>0.70</td><td>0.70</td><td>0.50</td><td>0.50</td></tr></table>		CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O	Initial moles	1.2	1.2	0.00	0.00	Change in moles	-0.50	-0.50	+0.50	+0.50	Equilibrium moles	0.70	0.70	0.50	0.50	
			CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O																	
		Initial moles	1.2	1.2	0.00	0.00																	
		Change in moles	-0.50	-0.50	+0.50	+0.50																	
Equilibrium moles	0.70	0.70	0.50	0.50																			
v = 200 mL = 0.200 L																							
<table><tr><td></td><td>CH₃OH</td><td>CH₃COOH</td><td>CH₃COOCH₃</td><td>H₂O</td></tr><tr><td>Equilibrium moles</td><td>0.70</td><td>0.70</td><td>0.50</td><td>0.50</td></tr><tr><td>Concentration at equilibrium (mol L⁻¹)</td><td>$\frac{0.70}{0.200}$ = 3.5 mol L⁻¹</td><td>$\frac{0.70}{0.200}$ = 3.5 mol L⁻¹</td><td>$\frac{0.50}{0.200}$ = 2.5 mol L⁻¹</td><td>$\frac{0.50}{0.200}$ = 2.5 mol L⁻¹</td></tr></table>		CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O	Equilibrium moles	0.70	0.70	0.50	0.50	Concentration at equilibrium (mol L ⁻¹)	$\frac{0.70}{0.200}$ = 3.5 mol L ⁻¹	$\frac{0.70}{0.200}$ = 3.5 mol L ⁻¹	$\frac{0.50}{0.200}$ = 2.5 mol L ⁻¹	$\frac{0.50}{0.200}$ = 2.5 mol L ⁻¹								
	CH ₃ OH	CH ₃ COOH	CH ₃ COOCH ₃	H ₂ O																			
Equilibrium moles	0.70	0.70	0.50	0.50																			
Concentration at equilibrium (mol L ⁻¹)	$\frac{0.70}{0.200}$ = 3.5 mol L ⁻¹	$\frac{0.70}{0.200}$ = 3.5 mol L ⁻¹	$\frac{0.50}{0.200}$ = 2.5 mol L ⁻¹	$\frac{0.50}{0.200}$ = 2.5 mol L ⁻¹																			
(c)	$K_c = \frac{[\text{CH}_3\text{COOCH}_3] \cdot [\text{H}_2\text{O}]}{[\text{CH}_3\text{OH}] \cdot [\text{CH}_3\text{COOH}]}$ $\therefore K_c = \frac{2.5 \times 2.5}{3.5 \times 3.5}$ $\therefore K_c = 0.5102$ $\therefore K_c = 0.51 \text{ (2sf)}$	2																					

Question	Part	Author's response	Marks																																																																																				
9	(a)	<table><tr><td></td><td>H₂</td><td>I₂</td><td>HI</td></tr><tr><td>Initial moles</td><td>0.5</td><td>0.3</td><td>0.00</td></tr><tr><td>Change in moles</td><td></td><td></td><td></td></tr><tr><td>Equilibrium moles</td><td></td><td></td><td>0.2</td></tr><tr><td></td><td></td><td></td><td></td></tr><tr><td>Initial moles</td><td>0.5</td><td>0.3</td><td>0.00</td></tr><tr><td>Change in moles</td><td></td><td></td><td>+0.20</td></tr><tr><td>Equilibrium moles</td><td></td><td></td><td>0.2</td></tr><tr><td></td><td></td><td></td><td></td></tr><tr><td>Initial moles</td><td>0.5</td><td>0.3</td><td>0.00</td></tr><tr><td>Change in moles</td><td>-0.10</td><td>-0.10</td><td>+0.20</td></tr><tr><td>Equilibrium moles</td><td></td><td></td><td>0.20</td></tr><tr><td></td><td></td><td></td><td></td></tr><tr><td>Initial moles</td><td>0.5</td><td>0.3</td><td>0.00</td></tr><tr><td>Change in moles</td><td>-0.10</td><td>-0.10</td><td>+0.20</td></tr><tr><td>Equilibrium moles</td><td>0.40</td><td>0.20</td><td>0.20</td></tr><tr><td colspan="4">v = 100 mL = 0.100 L</td></tr><tr><td></td><td></td><td></td><td></td></tr><tr><td></td><td>H₂</td><td>I₂</td><td>HI</td></tr><tr><td>Equilibrium moles</td><td>0.40</td><td>0.20</td><td>0.20</td></tr><tr><td>Concentration at equilibrium (mol L⁻¹)</td><td>$\frac{0.40}{0.100}$ = 4 mol L⁻¹</td><td>$\frac{0.20}{0.100}$ = 2 mol L⁻¹</td><td>$\frac{0.20}{0.100}$ = 2 mol L⁻¹</td></tr></table>		H ₂	I ₂	HI	Initial moles	0.5	0.3	0.00	Change in moles				Equilibrium moles			0.2					Initial moles	0.5	0.3	0.00	Change in moles			+0.20	Equilibrium moles			0.2					Initial moles	0.5	0.3	0.00	Change in moles	-0.10	-0.10	+0.20	Equilibrium moles			0.20					Initial moles	0.5	0.3	0.00	Change in moles	-0.10	-0.10	+0.20	Equilibrium moles	0.40	0.20	0.20	v = 100 mL = 0.100 L									H ₂	I ₂	HI	Equilibrium moles	0.40	0.20	0.20	Concentration at equilibrium (mol L ⁻¹)	$\frac{0.40}{0.100}$ = 4 mol L ⁻¹	$\frac{0.20}{0.100}$ = 2 mol L ⁻¹	$\frac{0.20}{0.100}$ = 2 mol L ⁻¹	3
			H ₂	I ₂	HI																																																																																		
		Initial moles	0.5	0.3	0.00																																																																																		
		Change in moles																																																																																					
		Equilibrium moles			0.2																																																																																		
		Initial moles	0.5	0.3	0.00																																																																																		
		Change in moles			+0.20																																																																																		
		Equilibrium moles			0.2																																																																																		
Initial moles	0.5	0.3	0.00																																																																																				
Change in moles	-0.10	-0.10	+0.20																																																																																				
Equilibrium moles			0.20																																																																																				
Initial moles	0.5	0.3	0.00																																																																																				
Change in moles	-0.10	-0.10	+0.20																																																																																				
Equilibrium moles	0.40	0.20	0.20																																																																																				
v = 100 mL = 0.100 L																																																																																							
	H ₂	I ₂	HI																																																																																				
Equilibrium moles	0.40	0.20	0.20																																																																																				
Concentration at equilibrium (mol L ⁻¹)	$\frac{0.40}{0.100}$ = 4 mol L ⁻¹	$\frac{0.20}{0.100}$ = 2 mol L ⁻¹	$\frac{0.20}{0.100}$ = 2 mol L ⁻¹																																																																																				
(b)	$K_c = \frac{[\text{HI}]^2}{[\text{H}]_2 \cdot [\text{I}]_2}$ $\therefore K_c = \frac{(2)^2}{4 \times 2}$ $\therefore K_c = \frac{4}{8}$ $\therefore K_c = 0.5$	3																																																																																					
(c)	A decrease in the volume to 50 mL leads to an increase in the pressure of the system at equilibrium. According to Le Châtelier's principle the system will counteract the introduced change placed on the equilibrium mixture by attempting to decrease the pressure. The decrease in pressure is achieved by shifting to the side of the equation which results in the formation of the least moles of gaseous particles until equilibrium is re-established. In this reaction the right hand side has 2 moles of gas whilst the left hand side has 1 mole of gas. Therefore, the position of equilibrium would shift to the left in the backward direction as this creates the least moles of gas. Therefore, decreasing the concentration of HI and increasing the concentrations of H₂ and I₂.	3																																																																																					

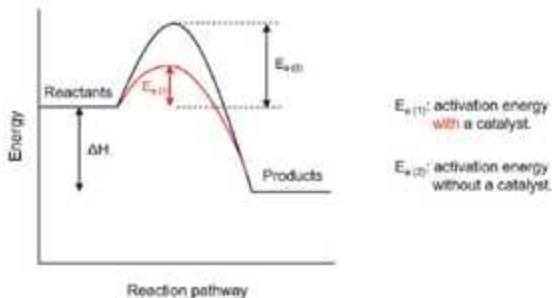
Question	Part	Author's response	Marks
9	(d)	The enthalpy given for this reaction is negative, indicating that the forward reaction is exothermic and the backward reaction is endothermic. According to Le Châtelier's principle, the endothermic reaction is favoured when the temperature of the reaction mixture is increased. This will result in the backward reaction being favoured in order to absorb the additional energy, shifting the position of equilibrium in the backward direction until equilibrium is re-established. Therefore, increasing the concentrations of H_2 and I_2 and decreasing the concentration of HI.	3
	(e)	No change to K_c value NOTE: The K_c value is only affected by changes to temperature	1
10	(a)	Development The catalyst developed by the Tokyo Institute of Technology represents a technological breakthrough in ammonia production. By enabling ammonia synthesis at ambient temperatures and pressures, it minimizes energy consumption compared to the Haber process. This demonstrates how advancements in catalyst technology can address inefficiencies in traditional methods. OR Application and Limitation The new catalyst addresses the environmental and energy limitations of the Haber process, such as high energy inputs and significant CO_2 emissions. However, the success of this technology depends on the availability of raw materials (e.g., titanium dioxide and ruthenium nanoparticles) and its scalability for widespread industrial use.	3
	(b)	Influence Ammonia-based fertilisers are critical for sustaining global food production, especially as the global population grows. This new catalyst ensures that ammonia can be produced efficiently and sustainably, meeting increasing demand without exacerbating environmental harm. Application and Limitation By enabling ammonia production at lower temperatures and pressures, the catalyst reduces reliance on fossil fuels and minimizes greenhouse gas emissions. This aligns with societal goals of reducing climate change impacts. However, challenges such as integrating the catalyst into existing infrastructure and ensuring the cost-effectiveness of the process must be addressed.	4

Question	Part	Author's response	Marks
11	(a)	Development Flow chemistry represents a technological advancement over traditional batch processing. By continuously flowing reactants through interconnected reactors, this method enables precise control over reaction conditions, such as temperature, pressure, and residence time, improving efficiency and product quality. This demonstrates how scientific models and theories are applied to create innovative technologies for drug synthesis. OR: Application and Limitation The ability to optimize react on conditions and minimize unwanted by-products illustrates the practical application of flow chemistry in reducing waste and improving yield. However, limitations include the complexity of integrating this technology into existing production systems and the high cost of specialized equipment.	3
	(b)	Two of: Influence Flow chemistry accelerates drug discovery and development, reducing manufacturing time and costs. This ensures quicker access to essential medicines, improving public health outcomes. Additionally, the minimisation of waste and energy use contributes to environmental sustainability. Development The precise control over reaction conditions in flow chemistry supports the synthesis of complex pharmaceutical compounds with high quality and yield. This enhances the efficiency of manufacturing processes and reduces the risk of variability in drug production. Application and Limitation While flow chemistry offers significant benefits, challenges such as the high cost of implementation, technical expertise required, and the integration of this technology into existing systems must be addressed. Overcoming these barriers is essential to ensure that the pharmaceutical industry can fully realise the potential of flow chemistry.	4

Question	Part	Author's response	Marks
12	(a)	Manure, straw or H ₂ O	1
	(b)	$K_c = \frac{[\text{CH}_3\text{OH}]}{[\text{CO}] \cdot [\text{H}_2]^2}$	1
	(c)	The enthalpy given for this reaction is negative, indicating that the forward reaction is exothermic. According to Le Châtelier's principle, the exothermic reaction is favoured when the temperature of the reaction mixture is decreased. This will result in the forward reaction being favoured in order to release energy, shifting the position of equilibrium in the forward direction until equilibrium is re-established. Therefore, favouring the production of methanol.	3
	(d)	A high reaction temperature increases the average kinetic energy of reacting particles, leading to an increase in the rate of the reaction. However, a high reaction temperature would favour the backward reaction according to Le Châtelier's principle, decreasing the yield of methanol. Therefore, it is evident that by increasing the rate of reaction through an increase in temperature, this would result in a reduction of yield of methanol due to equilibrium principles. Therefore, using a higher temperature is a compromise for industry.	3
	(e)	If a catalyst is used, this would provide an alternative reaction pathway for the reacting particles with a lower Activation Energy. Therefore, a larger number of successful collisions occur per unit time resulting in an increase in the rate of reaction. Therefore, the system would reach a state of equilibrium faster. The catalyst does not alter the methanol yield at equilibrium as it only affects the rate of reaching equilibrium..	3

Summary test 2 solutions: Managing chemical processes

Question	Part	Author's response	Marks																				
1	(a) (i)	The dependent variable is the concentration of N ₂ O (mol L ⁻¹).	1																				
	(a) (ii)	$\text{Rate} = \frac{\Delta [\text{N}_2\text{O}]}{\Delta T} = \frac{[0.55 - 0.37]}{[60 - 100]} = \frac{0.18}{-40} = -0.0045 \text{ mol L}^{-1} \text{ s}^{-1}$	3																				
	(a) (iii)	At the start, the concentration of N ₂ O is highest. A higher concentration leads to an increased frequency of collisions between reacting particles. More successful collisions per unit time result in a faster rate of decomposition initially.	3																				
	(b) (i)	$\text{Rate} = \frac{[\text{PCl}_3][\text{Cl}_2]}{[\text{PCl}_5]}$	1																				
	(b) (ii)	The equilibrium constant K _c increases from 1.8 × 10 ⁻³ to 1.5 × 10 ⁻² as the temperature increases from 250°C to 350°C.	3																				
	(1)	According to Le Châtelier's principle, if K _c increases with an increase in temperature, the reaction favours the forward direction at higher temperatures. The equilibrium constant K _c increases with temperature, indicating that the forward reaction is endothermic.																					
	(b) (iii)	$Q_c = \frac{[0.0336].[0.0336]}{[0.0120]}$ $Q_c = 0.0941$ As Q _c (0.0941) > K _c (0.0018), the reaction is not at equilibrium. The system will shift to the left.	3																				
	(b) (iii)	v = 2 L <table><tr><td></td><td>PCl₅</td><td>PCl₃</td><td>Cl₂</td></tr><tr><td>Initial moles</td><td>0.250</td><td></td><td></td></tr><tr><td>Change in moles</td><td>-0.130</td><td>+0.130</td><td>+0.130</td></tr><tr><td>Equilibrium moles</td><td>0.120</td><td>0.130</td><td>0.130</td></tr><tr><td>Equilibrium conc (mol L⁻¹).</td><td></td><td></td><td>0.0650</td></tr></table>		PCl ₅	PCl ₃	Cl ₂	Initial moles	0.250			Change in moles	-0.130	+0.130	+0.130	Equilibrium moles	0.120	0.130	0.130	Equilibrium conc (mol L ⁻¹).			0.0650	4
		PCl ₅	PCl ₃	Cl ₂																			
	Initial moles	0.250																					
Change in moles	-0.130	+0.130	+0.130																				
Equilibrium moles	0.120	0.130	0.130																				
Equilibrium conc (mol L ⁻¹).			0.0650																				
(2)	$[\text{PCl}_5] = \frac{0.120}{2.0} = 0.060 \text{ mol L}^{-1}$ $[\text{PCl}_3] = \frac{0.130}{2.0} = 0.065 \text{ mol L}^{-1}$ $[\text{Cl}_2] = \frac{0.130}{2.0} = 0.065 \text{ mol L}^{-1}$ $Q_c = \frac{(0.065)(0.065)}{0.060}$ $K_c = 0.0704$	2																					
(b) (iii)	(3) There is no effect on K _c , as equilibrium constants depend only on temperature.	1																					

Question	Part	Author's response	Marks
2	(a)	A triple covalent bond exists between nitrogen atoms within the nitrogen molecule. A triple covalent bond is very strong and requires large amounts of thermal energy to break this bond. A chemical reaction can only occur once this triple covalent bond within the nitrogen molecule is broken, the thermal energy required means the temperature provided to the reaction needs to be high.	3
	(b)	Temperature The enthalpy given for this reaction is negative, indicating that the forward reaction is exothermic. According to Le Châtelier's principle, the exothermic reaction is favoured when the temperature of the reaction mixture is decreased. This will result in the forward reaction being favoured in order to release energy, shifting the position of equilibrium in the forward direction until equilibrium is re-established. In this reaction the left hand side has 4 moles of gas whilst the right hand side has 2 moles of gas. According to Le Châtelier's principle, the production of the least moles of gas is favoured when the pressure is increased. Therefore, the use of low temperature and high pressure would favour the production of ammonia.	4
	(c) (i)	Water or O ₂	1
	(c) (ii)	The process operates at high temperatures (approximately 900°C) to ensure the reaction occurs at an appreciable rate. At lower temperatures, the rate of reaction is too slow, leading to higher production times and costs. The process uses moderate pressures (1–10 atm) instead of very high pressures. High pressures would require robust, expensive reaction vessels and significantly increase energy costs. A platinum-rhodium catalyst is used to lower the activation energy, enabling the reaction to proceed at lower pressures and temperatures without significantly compromising yield.	3
	(d) (i)	The catalyst provides an alternative pathway with lower activation energy. More particles achieve sufficient energy for successful collisions. This results in a greater rate of reaction per unit time	3
	(d) (ii)		4

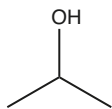
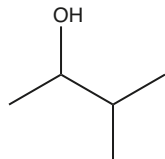
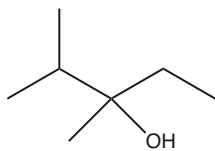
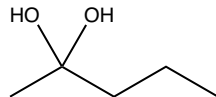
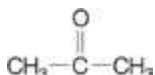
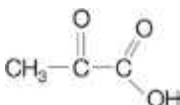
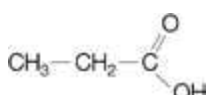
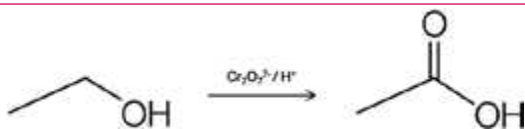
Question	Part	Author's response	Marks
2		Two of: Efficient catalysts lower the activation energy of the reaction, allowing it to proceed at lower temperatures. This reduces the amount of energy required, typically generated by burning fossil fuels, thereby decreasing CO ₂ emissions. OR (d) (iii) Lower energy demands lead to a reduction in the combustion of fossil fuels. This directly lowers the release of greenhouse gases like CO ₂ and other pollutants into the atmosphere. OR By improving the reaction's selectivity for nitric oxide, advanced catalysts minimise the formation of by-products such as NO _x NO _x contributes to air pollution and acid rain.	4
	(d) (iv)	The forward reaction is exothermic, meaning lower temperatures favour the production of nitric oxide (NONONO) according to Le Châtelier's Principle. By operating at lower temperatures, the equilibrium shifts to the right, increasing the yield of nitric oxide. While high temperatures are needed for the reaction rate, advanced catalysts enable the reaction to proceed at lower temperatures without compromising yield, making the process more efficient and cost-effective.	3
3	(a)	The reaction involves a decrease in the number of gas moles (from 3 to 2). According to Le Châtelier's Principle, an increase in pressure shifts the equilibrium to the side with fewer gas moles. This increases the yield of SO ₃ , as the forward reaction is favoured.	3
	(b)	The oxidation of sulfur dioxide is exothermic and slow due to a high activation energy. The vanadium oxide catalyst provides an alternative pathway with lower activation energy, increasing the rate of reaction. This allows the reaction to proceed at moderate temperatures, improving efficiency.	2
	(c)	Concentrating sulfuric acid helps improve the yield by absorbing sulfur trioxide more efficiently. Higher yields reduce production costs and increase the overall profitability of sulfuric acid manufacturing.	2
4	(a)	The conversion of N ₂ and H ₂ to ammonia is only ~15% per pass. Recycling unreacted gases minimizes waste, ensuring nearly complete usage of raw materials. This increases overall yield, reduces costs, and enhances process efficiency.	2
	(b)	Recycling increases the concentrations of the reactants, N ₂ and H ₂ According to Le Châtelier's Principle, increasing reactant concentrations shifts the equilibrium towards the products, favouring ammonia formation. This increases the overall yield.	3
	(c)	Inert gases, such as argon or methane, do not react and accumulate in the system. Their presence dilutes reactants, reducing the frequency of successful collisions between N ₂ and H ₂ . This lowers the efficiency of ammonia production.	2

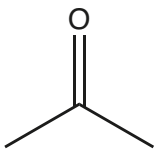
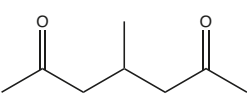
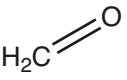
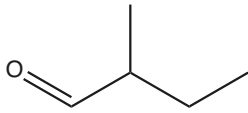
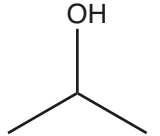
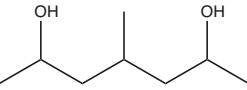
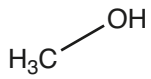
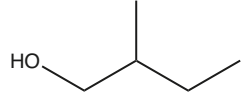
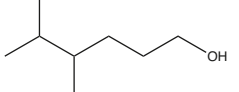
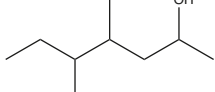
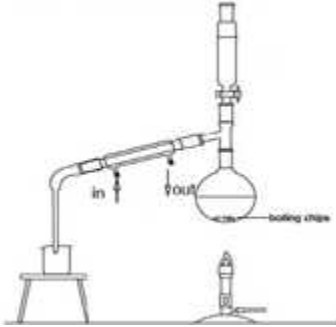
Question	Part	Author's response	Marks
5	(a)	Doubling the initial concentration of acetone, doubles the number of acetone molecules available to collide with iodine. This increases the rate of reaction proportionally, as the reaction is second-order with respect to acetone.	2
	(b)	Doubling iodine has no effect on the reaction rate, as iodine is zero-order in this reaction. The rate is independent of iodine concentration because it is not involved in the rate-determining step.	2
	(c)	Increasing temperature raises the average kinetic energy of molecules. A greater proportion of molecules have sufficient energy to overcome the activation energy barrier. This leads to more frequent successful collisions per unit time, increasing the reaction rate.	3
6	(a)	Influence Society's need for a safer alternative to salicylic acid due to its stomach-irritating side effects drove Felix Hoffmann to seek improvements. The public demand for pain-relief medication that could be widely tolerated influenced research priorities. OR Application Scientists at the time had advanced understanding of organic reactions, such as acetylation, which enabled Hoffmann to chemically modify salicylic acid into acetylsalicylic acid (aspirin). This highlights how scientific knowledge is applied to solve real-world problems.	2
	(b)	During World War I, aspirin was extensively used to manage pain and fever in soldiers, demonstrating its effectiveness in treating common wartime ailments. Its ability to provide rapid and reliable relief under challenging conditions solidified its reputation as a dependable medication. The large-scale use of aspirin by military forces highlighted its practicality and effectiveness, leading to increased confidence in its therapeutic benefits.	3
	(c)	Ongoing research demonstrated aspirin's ability to reduce the risk of heart attacks by preventing blood clot formation. Later studies suggested its role in reducing the risk of certain cancers. These discoveries added to the understanding of aspirin's benefits and highlighted its broader therapeutic applications.	3
	(d)	Aspirin's development demonstrates how scientific research addresses the limitations of existing drugs. Salicylic acid, while effective as a pain reliever, caused severe stomach irritation, making it less suitable for widespread use. Researchers identified this limitation as a key barrier to its acceptance as a practical medication.	3

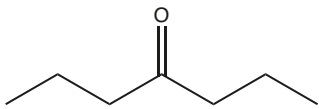
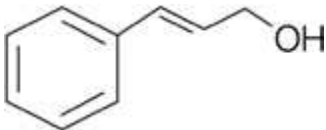
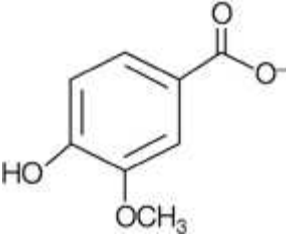
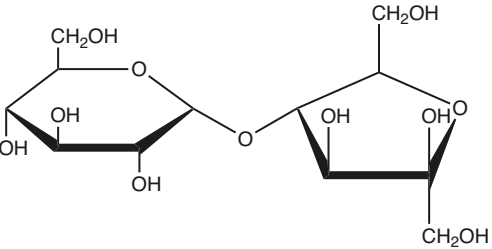
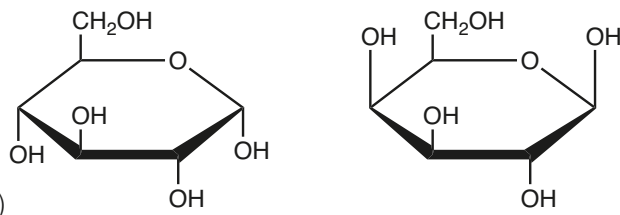
Topic 3 solutions: Organic and biological chemistry

Question	Part	Author's response						Marks
1	(a)	Name	Molecular formula	Empirical formula	Complete structural formula	Condensed structural formula	Skeletal structure	
		butane	C ₄ H ₁₀	C ₂ H ₅		CH ₃ -CH ₂ -CH ₂ -CH ₃		
		2-methylpentane	C ₆ H ₁₄	C ₃ H ₇		CH ₃ -CH(CH ₃)-CH ₂ -CH ₂ -CH ₃		
		2-methyl-3-hexene	C ₇ H ₁₄	CH ₂		CH ₃ -CH ₂ -CH=CH-CH(CH ₃)-CH ₃		
		3-ethyl-3-methylhexane	C ₉ H ₂₀	C ₉ H ₂₀		CH ₃ -CH ₂ -C(CH ₃)(CH ₂ -CH ₃)-CH ₂ -CH ₂ -CH ₃		
		2,3-dimethyl-2-butene	C ₆ H ₁₂	CH ₂		CH ₃ -C(CH ₃)=C(CH ₃)-CH ₃		
	(b) (i)	methylhex-3-yne (numbering the methyl is not required as it will always be on the second carbon in the chain)						2
	(ii)	methylpropene						2
	(iii)	penta-1,3-diene						2
	(c) (i)							2
	(ii)							2
(d)	Compound		Correct name		Structural formula			
	3-ethylbutane		3-methylpentane		$H_3C-CH_2-\underset{\substack{ \\ CH_3}}{CH}-CH_2-CH_3$		4	
	1-methyl-4-propylhexane		4-ethyloctane		$H_3C-CH_2-CH_2-\underset{\substack{ \\ CH_2 \\ \\ CH_3}}{CH}-CH_2-CH_2-CH_2-CH_3$		4	
	3-methyl-3-butene		2-methylbut-1-ene		$H_3C-CH_2-\underset{\substack{ \\ CH_3}}{C}=CH_2$		4	

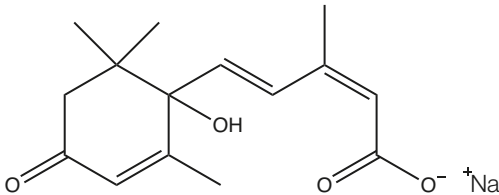
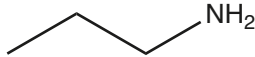
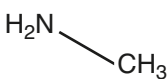
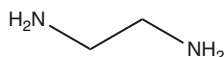
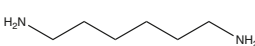
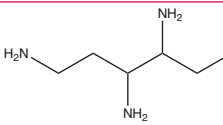
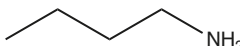
Question	Part	Author's response	Marks
2	(a)	1 Propane (lowest b.p.) < 2 diethyl ether < 3 ethanol (highest b.p.)	3
		The boiling points of covalent molecular substances are determined by their molecular weight and the strength of the intermolecular forces between the molecules. These compounds have similar molecular weights.	1
		Plus any two of:	2
	(b)	— Ethanol molecules can form hydrogen bonds with each other; ethanol will have a high boiling point.	
		— Diethyl ether molecules are slightly polar, and will experience dipole-dipole interactions; diethyl ether will have a moderate boiling point.	
		— Propane molecules experience only dispersion forces; propane will have a low boiling point.	
		Butan-1-ol molecules can form hydrogen bonds with each other, while pentane molecules are only attracted to one another by dispersion forces.	1
	(c)	Hydrogen bonds are much stronger than dispersion forces.	1
		It takes significantly more energy to overcome the hydrogen bonds, so a higher temperature is necessary for butan-1-ol to boil.	1
		Ethanol will have the greatest solubility in water.	1
	(d)	The hydroxyl functional group (–OH) present in ethanol can form hydrogen bonds with water.	1
		The other compounds are unable to form hydrogen bonds with water.	1
3	(e) (i)	Alcohols contain the hydroxyl functional group (–OH).	1
		Hydroxyl functional groups can form hydrogen bonds with water, increasing the solubility of the overall molecule.	1
	(ii)	Hydrocarbon chains are non-polar and do not form strong intermolecular bonds with polar water molecules.	1
		As the length of the hydrocarbon chain increases, the non-polar aspect of the molecule comes to dominate and the effect of hydroxyl group(s) on solubility diminishes.	1
		Ethanol is the most soluble, followed by butan-1-ol, then hexan-1-ol as the least soluble.	1
		All molecules have a polar hydroxyl functional group, which can form hydrogen bonds with polar water, making it soluble. However, solubility of the molecule decreases as the length of the non-polar carbon chain increases.	1
	(f)	Ethanol is a small, polar molecule. Polar water molecules can adequately surround ethanol and form hydrogen bonds with the polar hydroxyl group; ethanol is readily soluble in water. Butan-1-ol has a longer non-polar carbon chain so it is more non-polar; solubility decreases compared to ethanol. Hexan-1-ol has the longest non-polar carbon chain of the three, therefore is the least soluble in water.	1
	(a) (i)	3,4-dimethylheptan-3-ol	2
	(ii)	4-methylhexan-2-ol	2
	(iii)	3,3-dimethylpentane-2,2-diol	2
	(iv)	2-methylpropane-1,2,3-triol	2
	(b) (i)	tertiary	1
	(ii)	secondary	1
	(iii)	secondary	1
	(iv)	Left to right – primary, tertiary, primary	1

Question	Part	Author's response				Marks			
3	(c)	a	propan-2-ol		b	3-methylbutan-1-ol	2 2		
									
		c	2,3-dimethylpentan-3-ol		d	pentane-2,2-diol		2 2	
									
4	(a)	(i)			(ii)		(iii)		2 each
	(b) (i)	(1)	ethanol					2	
		(2)	propane-1,2,3-triol					2	
		(3)	2-methyl-butan-1-ol					2	
	(ii)							2	
	(iii)	2-methylbutan-1-ol has a polar hydroxyl group, which can form hydrogen bonds with polar water.						1	
		However, it also has a long non-polar carbon chain which makes it harder for the water molecules to surround it and fully dissolve it.						1	
		Propane-1,2,3-triol, with its three polar hydroxyl groups, has multiple sites for hydrogen bonding to occur with polar water molecules; it is therefore more soluble.						1	
	(iv)	Primary alcohol						1	
	(c) (i)			Compound D		Compound E		1 each correct box	
		Molecular formula		C ₅ H ₁₀ O ₅		C ₉ H ₁₇ O			
		Empirical formula		CH ₂ O		C ₉ H ₁₇ O			
		Functional groups present		Aldehyde Hydroxyl		Alkene Hydroxyl			
(ii)	Option 1: Test for alkenes								
	Place each compound in a separate test tube. Add several drops of bromine water to each test tube and shake.						1		
	Test tube that immediately decolourises from red-brown to colourless contains Compound E. An addition reaction occurs between the bromine water and the alkene functional group. Alkenes immediately decolourise bromine water when shaken.						2		
	Test tube containing Compound D will remain red-brown.						1		
	Option 2: Test for aldehydes (covered in Subtopic 3.3)						1		
	Place each compound in a separate test tube. Add several drops of Tollens' reagent to each test tube and shake.						2		
	Test tube that forms a black precipitate and then a silver mirror on the test tube contains Compound D, which has the aldehyde functional group. Test tube Containing Compound D will remain colourless.						1		

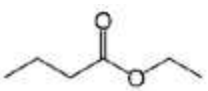
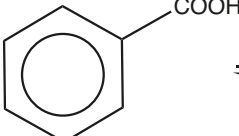
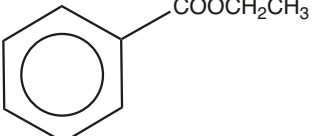
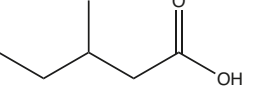
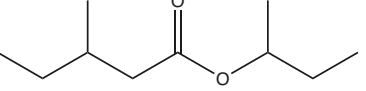
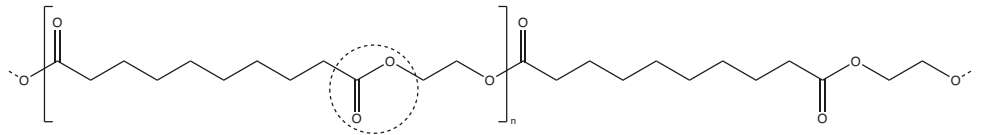
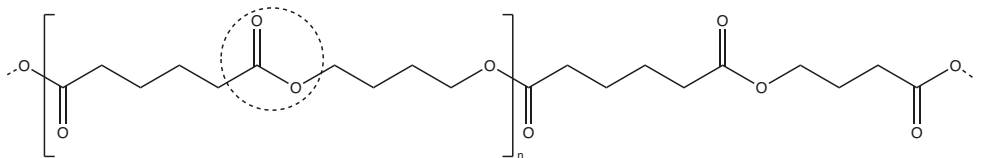
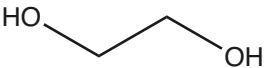
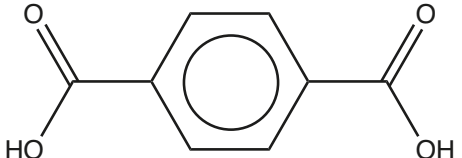
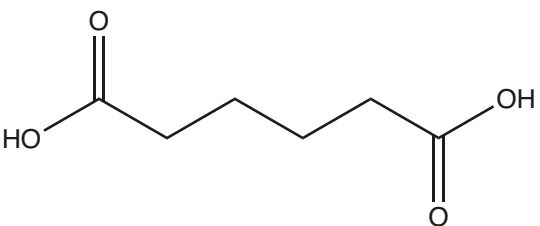
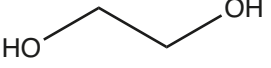
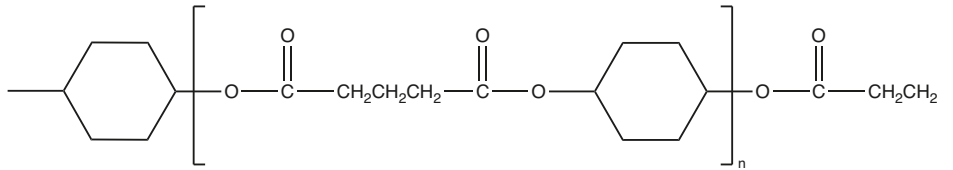
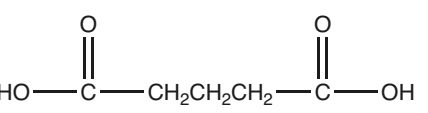
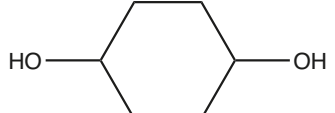
Question	Part	Author's response	Marks
5		$\begin{array}{c} \text{H} \\ \\ \text{H}-\text{C}-\text{C}=\text{O} \\ \quad \\ \text{H} \quad \text{H} \end{array} \quad \text{or} \quad \text{CH}_3\text{CHO}$	
6	(a)	i) 2-ethyl-3-methylpentanal	2
		ii) 2-methylbutanal	2
		iii) ethanedial	2
		iv) 3-methylpentan-2-one	2
		v) butan-2,3-dione	2
		vi) 3,3-dimethylbutan-2-one	2
	(b)	i) 	6
		ii) 	
		iii) 	
		iv) 	
	(c)	Tollen's test (using ammoniacal silver nitrate)	1
		Add a small amount of Tollen's reagent to separate test tubes containing a sample of both compounds and heat.	1
6	(d)	The terminal carbonyl group present in compound iii) will oxidise resulting in the reduction silver diamine ion, producing a silver mirror on the inside of the reaction vessel.	1
		Compound ii) contains two ketone (non-terminal carbonyl) groups which do not oxidise and therefore will produce no observable reaction.	1
	(e)	i) 	6
		ii) 	
		iii) 	
		iv) 	
	(f)	v) 	6
		vi) 	
6	(g)	i) A: addition funnel or dropper funnel, B: Liebig condenser	1+1
		ii)	1
			2
		iii) $\text{Cr}_2\text{O}_7^{2-} + 14\text{H}^+ + 6\text{e}^- \rightarrow 2\text{Cr}^{3+} + 7\text{H}_2\text{O}$	1
		iv) carboxyl	

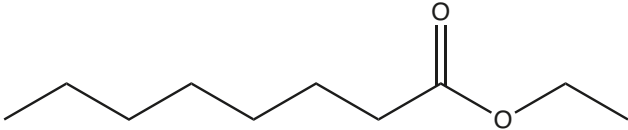
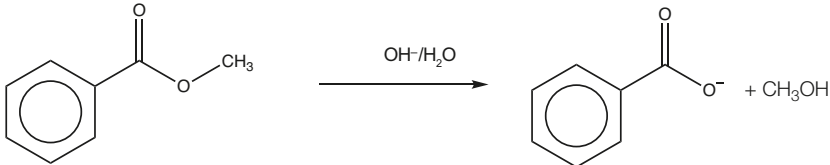
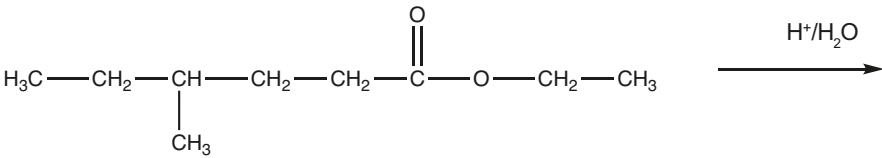
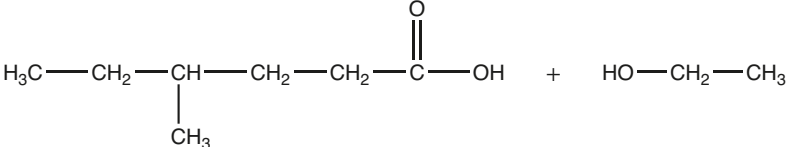
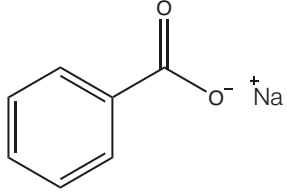
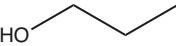
Question	Part	Author's response	Marks
6	i)	 heptan-4-one	1
		3-methyl hexanal	2
	(f) ii)	e.g., (Heptan-2-one, heptan-3-one and heptan-4-one are all isomers of the aldehyde shown).	
	iii)	In its ionic form the carboxylate anion contains a full negative charge.	1
		The negative charge on the oxygen atom is able to form strong ion-dipole bonds with water.	1
		This allows water molecules to successfully surround and separate the carboxylate salt facilitating its solubility.	1
6	(g) (i)		2
	(ii)	Alkene	1
	(iii)		2
7	(a)	Polyhydroxy ketone	1
	(b)	Molecules with the same molecular formulae, but differing structural formula containing different functional groups.	1
		Changes to structural formulae results in changes to chemical properties.	1
	(c)		2
	(d)	Condensation	1
7	(e)	Addition of Tollens' reagent.	1
		The straight-chain glucose has a terminal carbonyl group which can be oxidised by Tollens' reagent resulting in the formation of a silver mirror on the inside of the reaction vessel.	1
			1
	(f)	(i) $C_{12}H_{22}O_{11}$  (ii)	2
			2+2

Question	Part	Author's response	Marks
8	(a)		1
	(b)		2
	(c)	Polysaccharide	1
9	(a)	Ethane-1,2-dioic acid	1
	(b)	$C_2O_4H_2$	1
	(i)	$RCOOH + OH^- \rightarrow H_2O + RCOO^-$	1
		The oxalic acid (a solid) at room temperature with react with sodium hydroxide solution to produce a soluble carboxylate salt.	1
		The resulting solution will be miscible.	1
		(ii) $2RCOOH + CO_3^{2-} \rightarrow H_2O + 2RCOO^- + CO_2$	1
		The oxalic acid (a solid) at room temperature with react with sodium carbonate solution to produce a soluble carboxylate salt.	1
		The resulting solution will be miscible and produce effervescence due to the carbon dioxide produced.	1
	(i)	1. Methanoic acid	2
		2. Butanoic acid	2
	(ii)	3. Propane-1,3-dioic acid	2
		1.	2
	(d)	2.	2
		3.	2

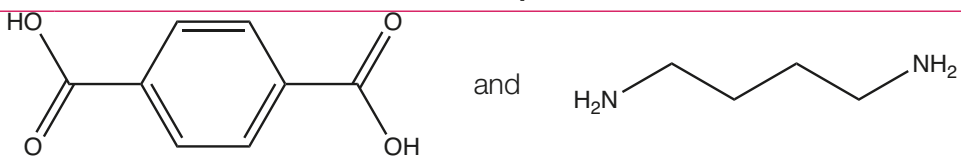
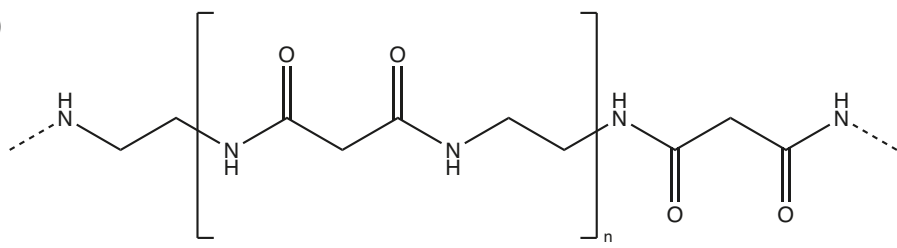
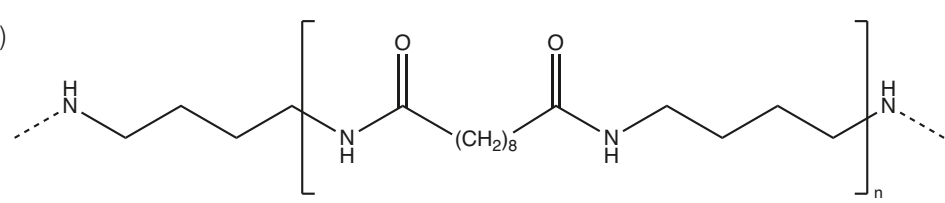
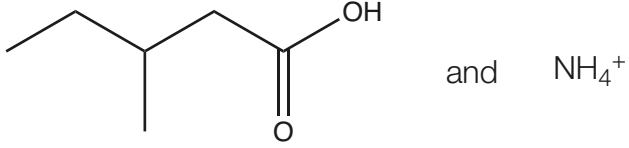
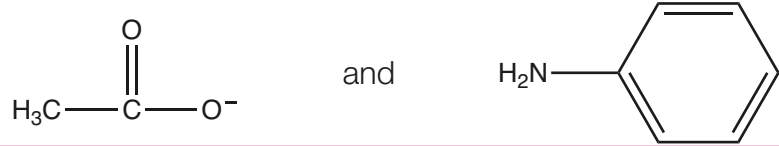
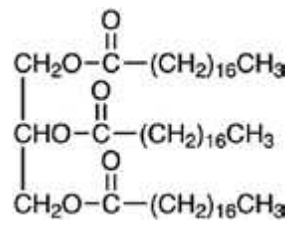
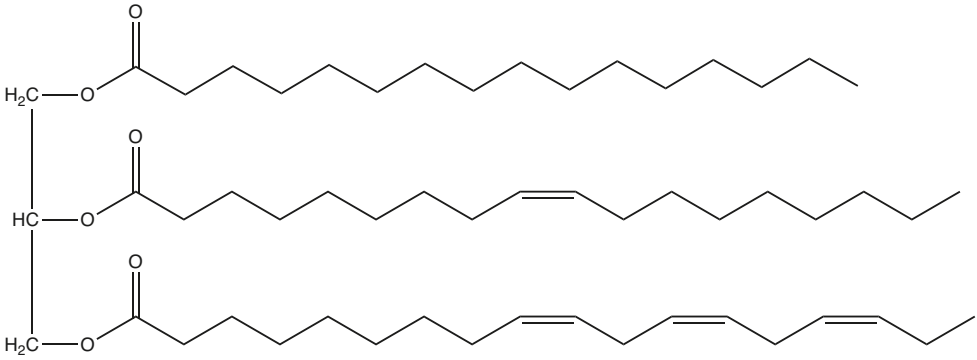
Question	Part	Author's response	Marks												
10	(a)	$C_{15}H_{20}O_4$	1												
	(b)	Carbonyl, hydroxyl, carboxyl and alkene. Any three are acceptable.	1 + 1 + 1												
	(c)	<table><thead><tr><th>Absciscic acid tested with...</th><th>Observations</th></tr></thead><tbody><tr><td>Bromine water (Br_2)</td><td>Orange to colourless colour change</td></tr><tr><td>Acidified dichromate ($Cr_2O_7^{2-}/H^+$)</td><td>No observable changes seen</td></tr><tr><td>Tollens' reagent</td><td>No observable change seen</td></tr><tr><td>Sodium bicarbonate solution ($NaHCO_3$)</td><td>Effervescence</td></tr></tbody></table>	Absciscic acid tested with...	Observations	Bromine water (Br_2)	Orange to colourless colour change	Acidified dichromate ($Cr_2O_7^{2-}/H^+$)	No observable changes seen	Tollens' reagent	No observable change seen	Sodium bicarbonate solution ($NaHCO_3$)	Effervescence	1 1 1 1 1		
		Absciscic acid tested with...	Observations												
		Bromine water (Br_2)	Orange to colourless colour change												
		Acidified dichromate ($Cr_2O_7^{2-}/H^+$)	No observable changes seen												
		Tollens' reagent	No observable change seen												
	Sodium bicarbonate solution ($NaHCO_3$)	Effervescence													
	(i)		2												
	(d)	(ii) In its ionic form the carboxylate anion contains a full negative charge. The negative charge on the oxygen atom is able to form strong ion-dipole bonds with water. This allows water molecules to successfully surround and separate the carboxylate salt facilitating its solubility. Absciscic acid can only form weaker hydrogen and dipole-dipole associations with water which are not significant enough to allow it to be soluble.	1 1 1												
11		Ketogenic diets have been used in children with severe epilepsy since the 1990s.	1												
		A fatty acid, decanoic acid, directly binds to a molecule that is found on the surface of brain cells and is known to be involved in spreading electrical impulses between different neurons.	1												
		Through research at the University of London scientists are developing a ketogenic diet high in decanoic fatty acid following a wide range of evidence from many sources and across disciplines.	1												
		The development of new dietary regimes is revealing new evidence that may modify previous general ketogenic diets.	1												
12	(a)	<table><tbody><tr><td>(i)</td><td>Secondary</td><td>(ii)</td><td>Primary and Secondary</td><td>(iii)</td><td>Primary</td></tr><tr><td>(iv)</td><td>Tertiary</td><td>(v)</td><td>Secondary</td><td>(vi)</td><td>Secondary</td></tr></tbody></table>	(i)	Secondary	(ii)	Primary and Secondary	(iii)	Primary	(iv)	Tertiary	(v)	Secondary	(vi)	Secondary	1 1 1 1 1 1
		(i)	Secondary	(ii)	Primary and Secondary	(iii)	Primary								
		(iv)	Tertiary	(v)	Secondary	(vi)	Secondary								
	(b)	(i)		(ii)		(iii)		2 2							
		(iv)		(v)		(vi)		2 2 2 2							

Question	Part	Author's response	Marks
13	(a)		2
	(i)		2
	(b)		2
	(ii)		2
14	(a)	(i)	3
		Ester: ethyl ethanoate	3
		Alcohol: ethanol	
		Carboxylic acid: ethanoic acid	
		(ii)	
		Ester: methyl butanoate	
		Alcohol: methanol	
		Carboxylic acid: butanoic acid	
	(a)	(iii)	3
		Ester: propyl methanoate	3
		Alcohol: propanol	
		Carboxylic acid: methanoic acid	
		(iv)	
		Ester: ethyl propanoate	
		Alcohol: ethanol	
		Carboxylic acid: propanoic acid	
	(a)	(v)	3
		Ester: methyl propanoate	3
		Alcohol: methanol	
		Carboxylic acid: propanoic acid	
		(vi)	
		Ester: ethyl 4-methylpentanoate	
		Alcohol: ethanol	
		Carboxylic acid: 4-methylpentanoic acid	
(b)	(i)	methyl hexanoate	2
			2
	(iii)	butyl butanoate	2
			2
(b)	(ii)	2-methylpropyl propanoate	2
			2
	(iv)	propyl octanoate	2
			2

Question	Part	Author's response	Marks
14	(i)	$\text{CH}_3\text{CH}_2\text{CH}_2\text{COOH} + \text{CH}_3\text{CH}_2\text{OH} \rightleftharpoons$ 	2
	(ii)	$\text{H}_3\text{C}-\overset{\text{O}}{\parallel}{\text{C}}-\text{OH} + \text{H}_3\text{C}-\underset{\text{CH}_3}{\underset{ }{\text{CH}}}-\text{OH} \rightleftharpoons \text{H}_3\text{C}-\overset{\text{O}}{\parallel}{\text{C}}-\text{O}-\underset{\text{H}}{\underset{ }{\text{C}}}(\text{CH}_3)_2$	2
	(c)	(iii) $\text{CH}_3\text{CH}_2\text{OH} +$  $\rightleftharpoons$ 	2
	(iv)	 $+ \text{CH}_3\text{CH}_2\text{CH}(\text{CH}_3)\text{OH} \rightleftharpoons$ 	2
15	(a)		4
	(b)		4
16	(a)	 and 	2 2
	(b)	 and 	2 2
	(c)	(i)  (ii)  and 	1 2 2

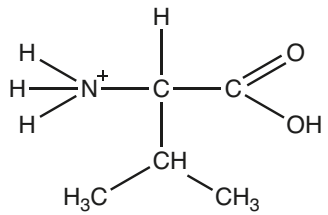
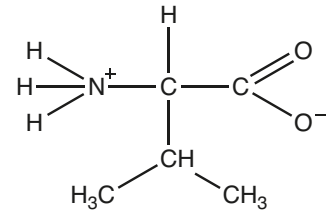
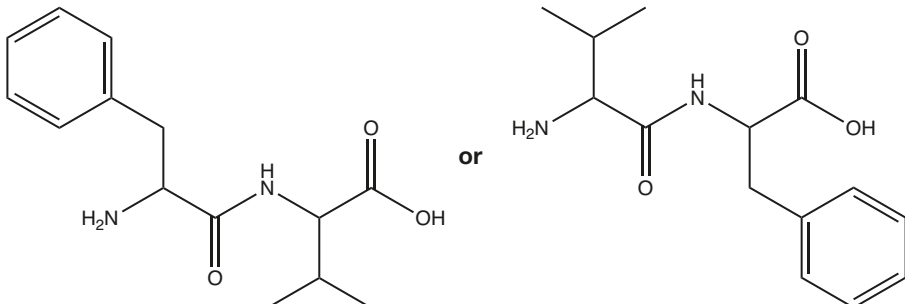
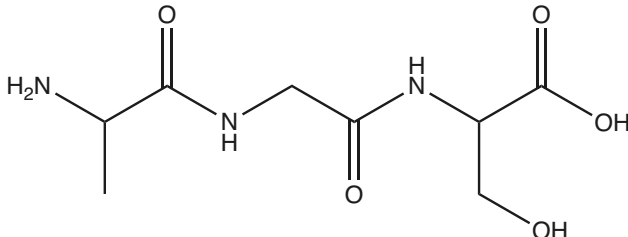
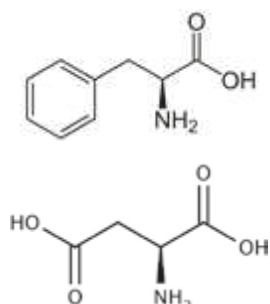
Question	Part	Author's response	Marks
17	(a)	Octanoic acid	2
	(i)		2
	(ii)	ethyl octanoate	2
	(iii)	Acts as a catalyst, providing an alternate reaction pathway of lower activation energy, increasing the rate of reaction.	1
	(iv)	Reflux allows the reaction to take place at the highest temperatures with minimal loss of reactants.	1
	(b)	Increases kinetic energy of particles, allowing more particles to possess the necessary activation energy.	1
		This leads to a greater number of successful collisions per unit time, thus increases rate of reaction.	1
		(v) Esterification is an example of an equilibrium reaction.	1
		Adding excess ethanol increases the concentration of reactants.	1
		This stresses the reaction system, and in accordance to Le Chatelier's principle the system will adjust to oppose the change.	1
		This favours the forward reaction, increasing the yield of the ester produced.	
18	(a)		2 2
	(i)		2
	(b)		2
	(ii)	4-methylhexanoic acid and ethanol	2
	(c) (i)	  Carboxylate salt Alcohol	2 2
	(ii)	In its ionic form the carboxylate anion contains a full negative charge. The negative charge on the oxygen atom is able to form strong ion-dipole interactions with water. This allows water molecules to successfully surround and separate the carboxylate salt facilitating its solubility. The original ester can only form weaker dipole-dipole associations with water which are not significant enough to allow it to be soluble.	1 1 1

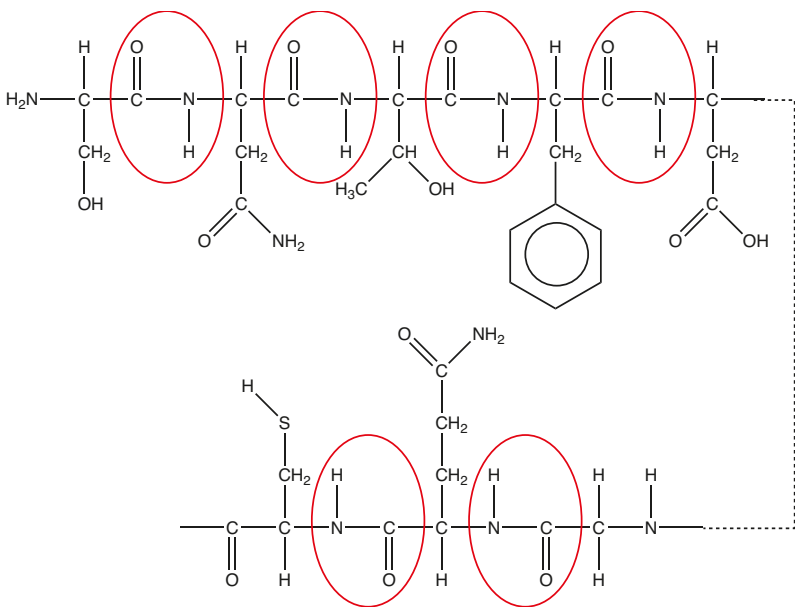
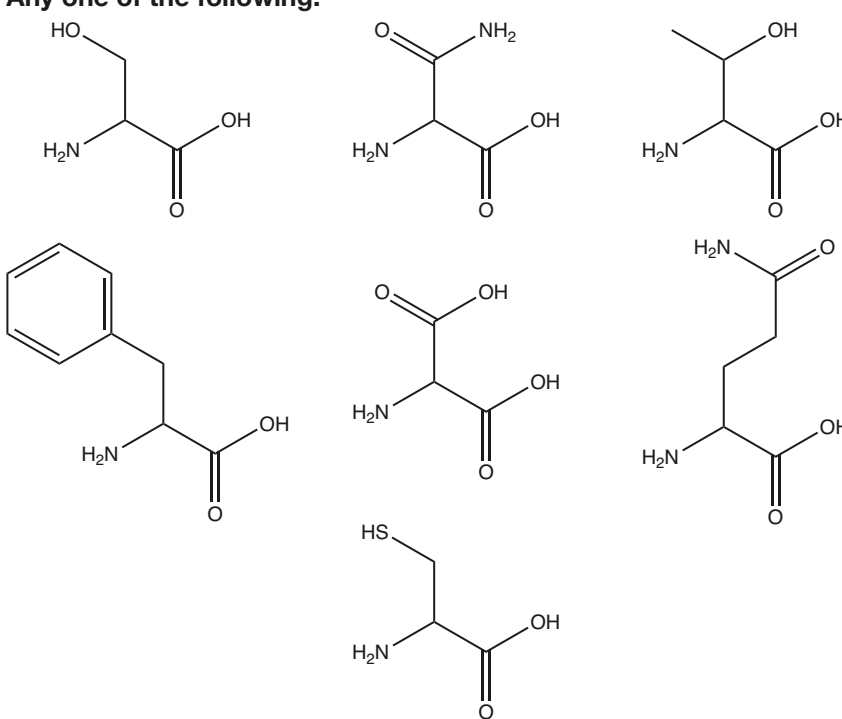
Question	Part	Author's response	Marks
19	(a)	(i) Butan-1-amine and propanoic acid	2
		(ii) Pentanoic acid and propan-2-amine	2
		(iii)	2
		(iv)	2
	(b)	(i)	2
		(ii)	2
		(iii)	2
		(iv)	2
20	(a)	Tertiary	1
	(b)	Secondary	1
	(c)	Tertiary	1
	(d)	Secondary	1
	(e)	Primary	1
21		Niacinamide contains a polar amide group.	1
		The N-H group is capable of forming strong hydrogen bonds with adjacent polar water molecules, and the carbonyl group will form dipole-dipole interactions with water molecules.	1
		These interactions allow water molecules to surround and separate niacinamide providing its water soluble and skin absorbing properties.	1

Question	Part	Author's response	Marks
22	(a)		2 2
	(b)		2 2
	i)		2 2
	ii)		
23	(a)		2 2
	(b)		2 2
	(c)		2 2
24			2
25			2

Question	Part	Author's response	Marks
26	(a)	$\text{HO}-\overset{\text{O}}{\parallel}\text{C}-(\text{CH}_2)_{12}\text{CH}_3$	2
		$\text{HO}-\overset{\text{O}}{\parallel}\text{C}-(\text{CH}_2)_{14}\text{CH}_3$	2
		$\text{HO}-\overset{\text{O}}{\parallel}\text{C}-(\text{CH}_2)_7\text{CH}=\text{CH}(\text{CH}_2)_7\text{CH}_3$	2
	(b)	$\text{CH}_3(\text{CH}_2)_{13}\text{CH}_2-\overset{\text{O}}{\parallel}\text{C}-\text{O}^-$	2
27		$n_{(\text{iodine})} = \frac{m}{M}$	1
		$n = \frac{85}{253.81}$	
		$n = 0.33 \text{ mol}$	
		$n_{(\text{ricinoleic acid})} = \frac{100}{298.46}$	
27		$n = 0.34 \text{ mol}$	1
		If 0.33 mol of iodine reacts with 0.34 of ricinoleic acid, and x mol of iodine reacts with 1 mol of ricinoleic acid then:	
		$\frac{x}{1} = \frac{0.33}{0.34}$	
		$x = \frac{0.33}{0.34} \times 1$	
27		$x = 1 \text{ mol}$	1
		1 mole of iodine are needed for every 1 mole of ricinoleic acid. Therefore, ricinoleic acid has 1 carbon-carbon double bond.	

Question	Part	Author's response	Marks
28	(a)	(i) Oleic acid: $C_{18}H_{34}O_2$ (ii) Linoleic acid: $C_{18}H_{32}O_2$	1 1
	(b)		2
	(c)	$ \begin{array}{c} \text{H}_2\text{C} - \text{O} - \text{C}(=\text{O}) - (\text{CH}_2)_7 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH}_3 \\ \\ \text{HC} - \text{O} - \text{C}(=\text{O}) - (\text{CH}_2)_7 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH}_3 \\ \\ \text{H}_2\text{C} - \text{O} - \text{C}(=\text{O}) - (\text{CH}_2)_7 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH} = \text{CH} - \text{CH}_2 - \text{CH}_3 \end{array} $	2
	(d)	Hydrogen, H_2	1
	(e)	High temperature	1
		High pressure	1
		Nickel catalyst	1
	(f)	Flaxseed oil is a unsaturated triglyceride which is a liquid at room temperature, whereas margarine is a saturated triglyceride which is a solid at room temperature.	
	(g)	The melting points of edible fats and oils are dependent on the strengths of the intermolecular forces between triglyceride molecules.	
		Edible saturated triglycerides such as margarine are solid at room temperature due to the greater proportion of triglyceride molecules with saturated carbon chains.	1
		Shorter distance separates triglycerides with saturated carbon chains which increases the strength of the dispersion forces between molecules.	1
		The lower melting point of the oils that make up margarine, are attributed to the greater proportion of triglyceride molecules with unsaturated carbon chains.	1
29		Each double bond introduces a "kink" to the chain increasing the distance between hydrocarbon chain decreasing the strength of attractive forces between them.	1
		Scientific knowledge, understanding, and inquiry is enabling scientists to develop a possible solution for disorders of the central nervous system.	1
		Scientists application of core-shell nanoscopic carriers for the treatment of such disorders may have advantageous applications due to their size, ease of preparation, ease of sterilization and the possibility of surface modification.	1

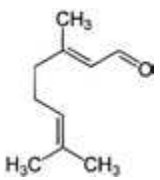
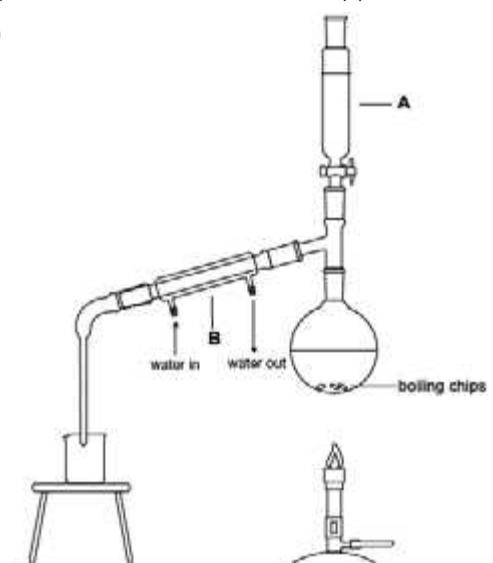
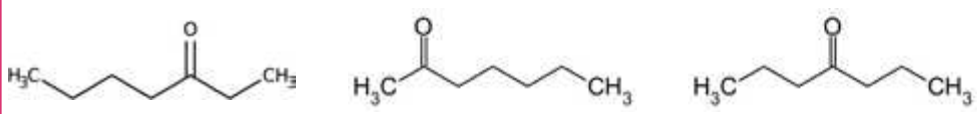
Question	Part	Author's response	Marks
30	(a)	carboxyl	1
	(b)	amino	1
	(i)		2
	(c)	(ii) 	2
	(d)	Both molecules contain a polar amine and carboxyl group, capable of forming hydrogen bonds (N-H and O-H) and dipole-dipole bonds (C=O) with adjacent water molecules. Asparagine contains an amide on its side chain, in comparison to leucine which has only a hydrocarbon side chain. This additional polar functional group allows asparagine to form hydrogen bonds (N-H) and dipole-dipole bonds (C=O) with adjacent water molecules. This significant secondary bonding with water facilitates the molecule's solubility, in comparison to leucine.	1 1 1 1
31	(a)		2
	(b)	 Note: the amino acids are shown connected in the order alanine-glycine-serine, but any order is acceptable.	2
	(c)		2 2

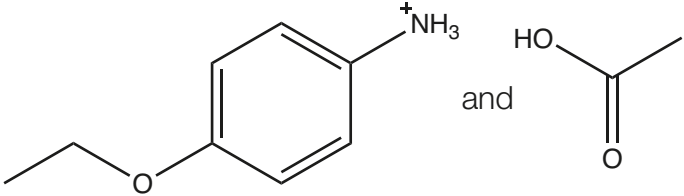
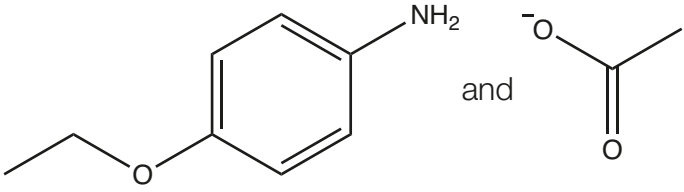
Question	Part	Author's response	Marks
		Any one of:  (a)	1
32	(b)	Any one of the following: 	

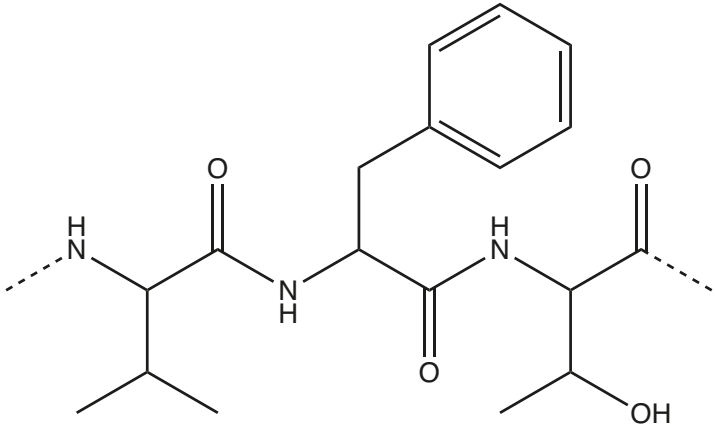
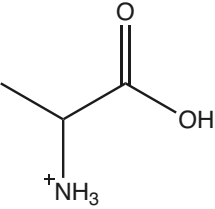
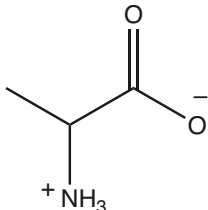
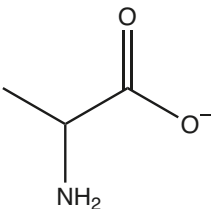
Question	Part	Author's response	Marks
32	(c)		1
	(d)	Proteins are sensitive to fluctuations in temperature and pH. Fluctuations can cause them to denature (unravel) and not be able to carry out their biological function. R groups with basic side become protonated when the pH of the environment is below 7. In most cases, attractive forces are replaced by repulsive forces which leads to the unfolding and denaturation of the protein. This impacts the protein's functionality.	1 1 1 1

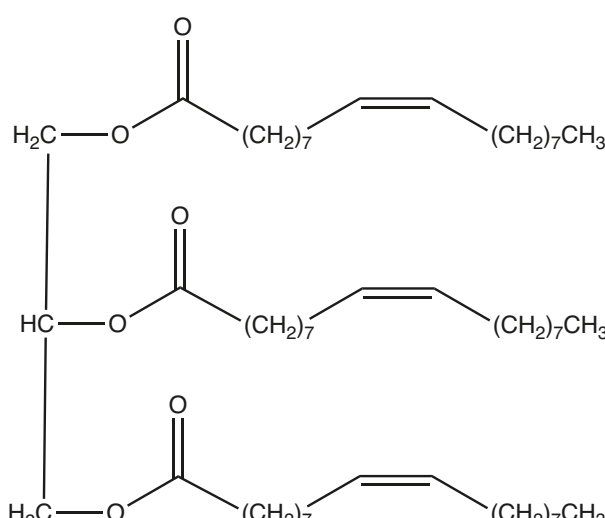
Summary test 3 solutions:

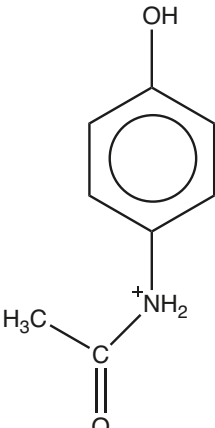
Organic and biological chemistry

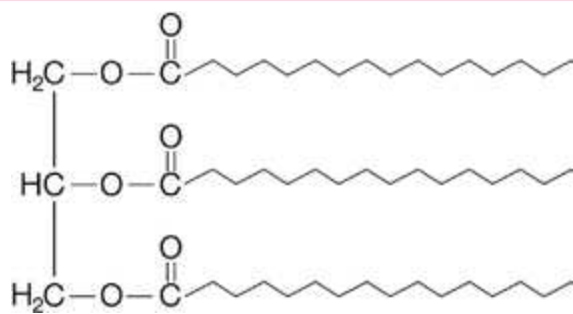
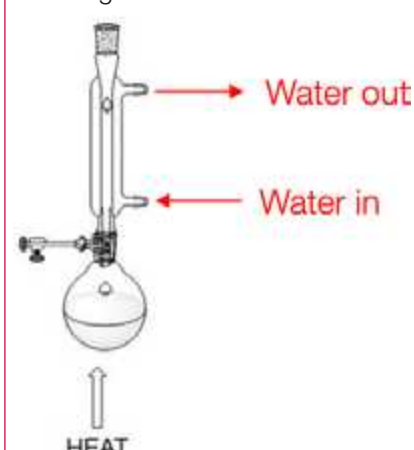
Question	Part	Author's response	Marks										
1	(a)	$C_{10}H_{18}O$	2										
	(b)		2										
	(c)	i) $C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$	2										
		ii) 1) Primary	1										
		2) Secondary	1										
		iii)											
		<table><tr><th>Compound</th><th>Organic product</th></tr><tr><td>$CH_3CH_2CH(OH)CH_3$</td><td>$CH_3CH_2COCH_3$</td></tr><tr><td>$CH_3CH_2COCH_3$</td><td>NR</td></tr><tr><td>$CH_3CH_2CH_2OH$</td><td>CH_3CH_2CHO</td></tr><tr><td>$CH_3CH_2CH_2CHO$</td><td>$CH_3CH_2CH_2COOH$</td></tr></table>	Compound	Organic product	$CH_3CH_2CH(OH)CH_3$	$CH_3CH_2COCH_3$	$CH_3CH_2COCH_3$	NR	$CH_3CH_2CH_2OH$	CH_3CH_2CHO	$CH_3CH_2CH_2CHO$	$CH_3CH_2CH_2COOH$	1 1 1 1
		Compound	Organic product										
		$CH_3CH_2CH(OH)CH_3$	$CH_3CH_2COCH_3$										
		$CH_3CH_2COCH_3$	NR										
$CH_3CH_2CH_2OH$		CH_3CH_2CHO											
$CH_3CH_2CH_2CHO$		$CH_3CH_2CH_2COOH$											
(iv) A is an addition funnel or dropper funnel and B is a Liebig Condenser	1+1												
(v)		1											
(vi) $Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$	2												
(vii) Carboxyl	1												
(d)	(i) 3-methylhexanal (ii) heptan-3-one or heptan-2-one or heptan-4-one 	2 2											

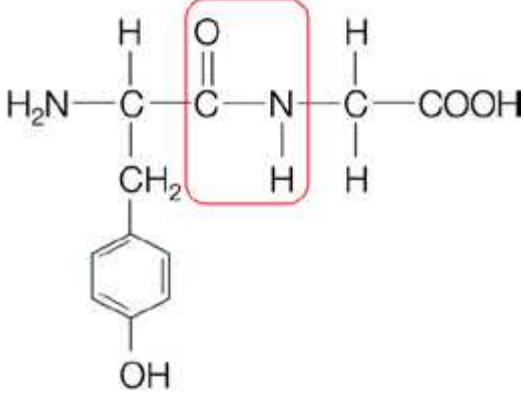
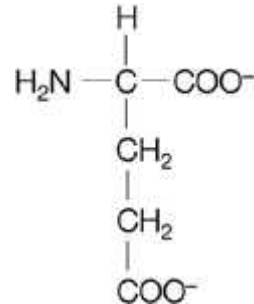
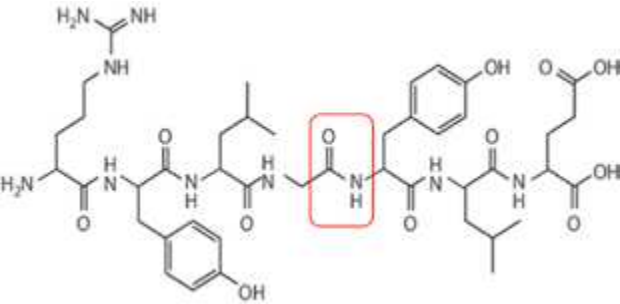
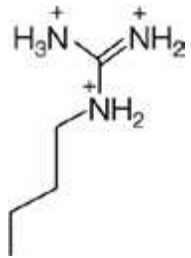
Question	Part	Author's response	Marks
2	(a)	Any two of: Carboxyl Ester Aromatic ring	1+1
	(b)	Compound A contains a carboxyl group.	1
		Addition of sodium carbonate to separate samples of A and B would induce an acid/carbonate reaction in the test tube containing compound A.	1
		Carbon dioxide would be observed in the form of effervescence indicating this reaction.	1
	(c)	Compound B contains a polar amide group. The N-H group is capable of forming strong hydrogen bonds with adjacent polar water molecules, and the carbonyl group will form dipole-dipole interactions with water molecules. These interactions allow water molecules to surround and partially separate Compound B resulting in its partial solubility.	1 1 1
	(d)		2 2
	(e)		2 2
3	(a)	$C_6H_{12}O_4$	2
	(b)	Example of a polyhydroxyaldehyde.	1
	(c)	(i) two compounds with the same molecular formula, but differing structural formulae.	1
		(ii) secondary	1
		(iii) Compound A contains an aldehyde (terminal carbonyl group). Compound B, does not.	1
		Tollen's test will result in the formation of a silver mirror on the inside of the reaction vessel containing Compound A. This is due to the oxidation of the carbonyl group.	1 1

Question	Part	Author's response	Marks
4	(a)	Amino and carboxyl	2
	(b)	Threonine	1
	(c)	 Note: The amino acids are shown connected in the order valine, phenylalanine, threonine, but any order is acceptable.	2
	(d)	(i)  (ii)  (iii) 	2
	(e)	(i) 1. hydrogen 2. hydrogen 3. dispersion 4. covalent (ii) Ionic and secondary bonding types are disrupted by changes to pH. An increase in pH (basic conditions) will change -NH_2 to -NH_3^+. Any change to functional groups will disrupt specific 3D shape. Shape determines function therefore the functionality of the protein will likely be impaired.	1 1 1 1 1 1 1 1

Question	Part	Author's response	Marks
5	(a)	Propane-1,2,3-triol	2
	(b)	(i) 1. 	2
	(ii)	Water	1
	(iii)	Plant	1
	(iv)	A: hydrogen, B: high pressure/temp, C: Nickel catalyst	3
	(c)	(i) $n = \frac{m}{M}$ $n = \frac{0.1}{876.16}$ $n = 1.14 \times 10^{-4} \text{ mol}$	1
		(ii) molar ratio of 1:5 (given the presence of 5 double bonds)	1
		$n = 1.14 \times 10^{-4} \text{ mol} \times 5$	1
		$n = 5.71 \times 10^{-4} \text{ mol}$	1
		(iii) $v = \frac{n}{c}$ $v = \frac{5.71 \times 10^{-4}}{0.01}$ $v = 0.0571 \text{ L}$ $v = 57.1 \text{ mL}$	1

Question	Part	Author's response	Marks
6	(a)	Hydroxyl, aromatic ring and amide.	1
	(i)		2
	(b)	(ii) The protonated form of acetaminophen contains a full positive charge. This results in the molecule being converted to its ionic form. The full positive charge on the nitrogen atom is able to form strong ion-dipole bonds with water. This allows water molecules to successfully surround and separate acetaminophen facilitating its solubility.	1 1 1 1
	(c)	The evidence presented in the article regarding the non-treatment of fever to help fight the COVID-19 demonstrates collaboration between scientists from around the world. Daniel Davis from the University of Manchester and Mark Peters from the UCL Great Ormond Street Institute of Child Health in London both support that "by increasing your body temperature, you may be slowing down the ability to a virus to multiple".	1+1
		In addition to looking at treating COVID-19 without fever reducing medicine, current medications are also being investigated regarding their efficacy and safety. UK's National Institute for Health and Care Excellence review of the evidence related to Ibuprofen's use in the treatment of COVID-19 is an example of communication and collaboration. The review and verification of results is important for science as a global enterprise.	1+1
	(a) (i)	C_9H_7NO	1
	(ii)	amine/amino, tertiary	2
	(iii)	Hydroxyl and amine functional groups are polar and can form hydrogen bonds with polar water.	1
		However, molecule contains large, non-polar rings that do not form interactions with polar water.	1
		Hydrogen bonding is limited; hence, molecule is only slightly soluble in cold water.	1
7	(b) (i)	Compound B	1
		Contains carbon=carbon double bond	1
	(ii)	Place each compound in a separate test tube. Add bromine water and shake. Compound B will immediately decolourise from red-brown.	1 1
		Br_2 reacts with alkene functional group and breaks the $C=C$ double bond in an addition reaction.	1
		Compound C will remain red-brown.	1
	(c) (i)	Oxidation	1
	(ii)	Orange to green	1

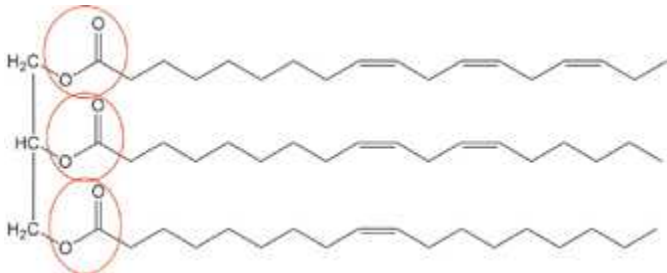
Question	Part	Author's response	Marks
7	(iii)	Solid at room temperature.	1
		Saturated fatty acid. Long hydrocarbon tail. Molecules can pack neatly with strong dispersion forces holding them together.	1
		Takes more thermal energy to overcome these interactions; higher melting point; solid at room temperature.	1
	(iv)		2
	(1)	ester	1
	(2)	 Name: ethanol	2 diagram 1 name
	(3)	Apparatus 2	1
	(v) (4)	See diagram. 	1
	(5)	Acts as a catalyst.	1
		Increases rate of reaction.	1
		Provides an alternate pathway where activation energy is lower and an environment where particles can orientate themselves correctly.	1
	(6)	Heat under reflux.	1

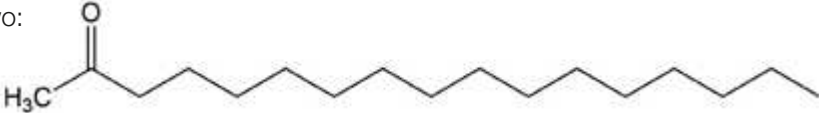
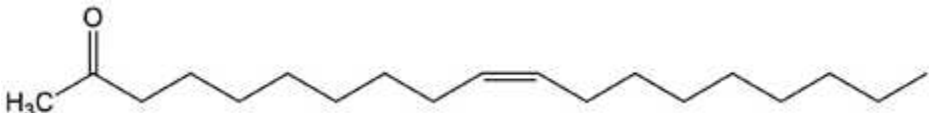
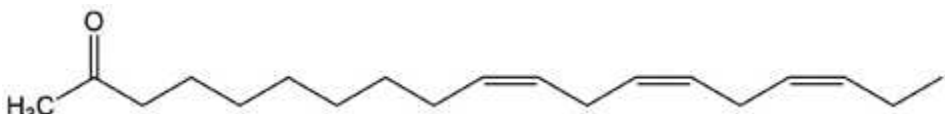
Question	Part	Author's response	Marks
8	(a) (i)		2 diagram 1 peptide link
	(ii) (A)	In neutral form, glutamic acid has polar functional groups and is able to form hydrogen bonds with polar water. In zwitterion form, glutamic acid is ionic and is able to form stronger ion-dipole interactions with polar water. Ion-dipole interactions are stronger than hydrogen bonds, therefore the glutamic acid zwitterion is more soluble than the neutral form.	1 1 1
	(B)		2
	(b) (i)	One example shown below. 	1
	(ii)		2
	(iii)	Lactic acid bacteria will decrease the pH of the protein and increase the concentration of H⁺. As shown above, the side chain with amino functional groups becomes protonated. The intermolecular forces of hydrogen bonding have changed to ion-dipole interactions. This changes the structure of the protein. Structure relates to function.	1 1 1 1
	(c) (i)	A carbohydrate is a polyhydroxy aldehyde or polyhydroxy ketone, or a compound that hydrolyses to polyhydroxy aldehydes or polyhydroxy ketones.	2

Question	Part	Author's response	Marks
8	(ii)	Lactose contains many polar hydroxyl groups, making lactose a very polar molecule.	1
		Multiple sites for hydrogen bonding to occur between lactose and polar water molecules.	1
	(iii)	Isomers	1
9	(a) (i)	amino and amide	1
	(ii)	primary	1
	(iii)	ethanol	1
	(b)	Any three points: <i>Develop solutions and make discoveries:</i> If Tamiflu proves effective in humans, it could expand treatment options beyond hearing aids and implants, offering a preventative measure rather than reactive solutions. By identifying Tamiflu as a candidate for treatment, researchers demonstrate how existing drugs might be repurposed to tackle emerging health challenges, saving time and resources compared to developing entirely new therapies. <i>Economic impact:</i> Reducing the need for costly hearing aids and implants could lessen the financial burden on healthcare systems and individuals. <i>Social / cultural impact:</i> Improving access to preventative treatments may enhance the quality of life for those affected by noise-induced hearing loss, fostering inclusivity in workplaces and social environments. <i>Environmental impact:</i> If Tamiflu reduces reliance on disposable hearing aids, it could minimise the environmental footprint associated with manufacturing and disposing of electronic devices. Limitations: Translating animal research to humans requires careful evaluation. Unexpected side effects or limited effectiveness in humans must be assessed through rigorous trials, reflecting the importance of monitoring and evaluation of risks when applying scientific knowledge. Limitation of insufficient data in drawing conclusions about human applications. Public debate and interest in potential treatments may influence the research direction, emphasising the need for transparency and careful communication of the findings to avoid premature conclusions.	3
	(c) (i)	2 –	1
	(ii)	+ 2	1

Topic 4 solutions: Managing resources

Question	Part	Author's Response	Marks
1	(a)	The development of third- and fourth-generation biofuels involves inputs from biology, chemistry, and engineering. For example: Biology: Understanding algae and microorganisms for photosynthesis efficiency. Chemistry: Developing processes like transesterification for biodiesel production. Engineering: Designing scalable algal farms and systems for biofuel production. A multidisciplinary approach is necessary because producing biofuels involves addressing biological growth, chemical extraction of biofuels, and engineering challenges for large-scale production and distribution.	3
		Social factors: Public perception of biofuels as "green" alternatives can promote their acceptance.	3
		Economic factors: High production costs for biofuels may limit adoption, although subsidies and incentives can make them competitive.	
		Cultural factors: Nations with high carbon emissions, such as Australia, may feel pressure to adopt biofuels to meet international climate goals, especially for industries like aviation.	3
	(c)	Beneficial: Biofuels reduce carbon emissions and are compatible with existing aviation infrastructure.	
		Unexpected consequences: Large-scale production of biofuels may compete with agriculture for food production or result in habitat destruction. Monitoring/Evaluation: Use emissions monitoring systems to track reductions in CO ₂ / Monitor changes in land use and food supply.	
2	(a) (i)	$6\text{CO}_{2(g)} + 6\text{H}_2\text{O}_{(l)} \xrightarrow{\text{energy}} \text{C}_6\text{H}_{12}\text{O}_{6(s)} + 6\text{O}_{2(g)}$	2
	(ii)	Endothermic	1
		Photosynthesis requires the absorption of energy from sunlight.	1
	(b) (i)	Any one: Glucose is used during respiration.	1
		Glucose is used to form lipids (oils). Glucose, a monosaccharide, is being converted into more complex carbohydrates as biomass.	1
	(ii) (1)	Longer growth periods generate more lipids (oil) in the biomass, the raw material to produce biodiesel.	1
	(2)	Longer growth periods allow for greater opportunities for algae to remove carbon dioxide through photosynthesis.	1
		Carbon dioxide converted during growth offsets carbon dioxide produced during the combustion of biodiesel. Carbon dioxide is a greenhouse gas which contributes to global warming.	1

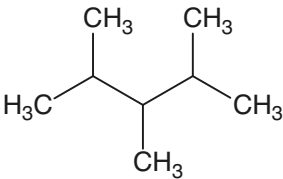
Question	Part	Author's Response	Marks
2	(c)	Any 6 of (at least one advantage and disadvantage for each fuel): Biodiesel – Advantages Sources for the raw materials to produce biodiesel are plentiful and can easily be grown. Renewable fuel source. Less net emission of carbon dioxide. Biodiesel – Disadvantages Competition for cropping land. Limited production and distribution infrastructure. Diesel – Advantages Well-established fuel including extraction, processing and infrastructure. Diesel – Disadvantages Non-renewable fuel source. Release of sulfur pollutants during combustion.	6
3	(a) (i)	Any two:	1
		Triglyceride (oil)	
		Methanol	
		Water	1
		Acid	
		Sodium hydroxide	
	(ii)	Generation of atmospheric pollutants, oxides of nitrogen and sulfur, (which can lead to photochemical smog and acid rain) as well as carbon dioxide, (which can lead to global warming).	1
	(iii)	Rate of reaction is increased.	1
		A catalyst provides an alternative energy pathway with a lower activation energy.	1
		A greater proportion of reactant collisions are successful in reaching or exceeding the activation energy, resulting in more productive collisions per unit time.	1
	(b) (i)	propan(e)-1,2,3-triol	2
	(ii)	Glycerol contains three polar hydroxyl functional groups.	1
		This provides multiple opportunities for polar water molecules to form hydrogen bonds with glycerol.	1
		The glycerol molecule is relatively small and can be surrounded by water molecules during hydrogen bonding.	1
	(iii)	Methanol has fewer opportunities for hydrogen bonding between molecules and has a smaller molecular mass, resulting in weaker dispersion forces.	1
		Less energy is required to overcome these interactions, therefore resulting in a lower boiling point.	1
	(c) (i)		1

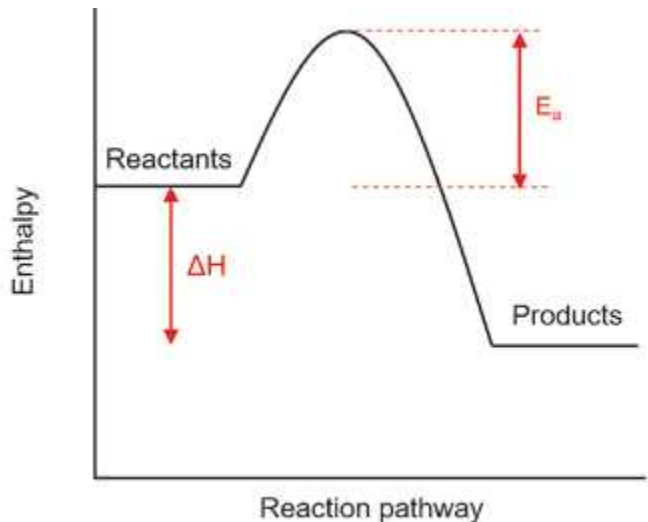
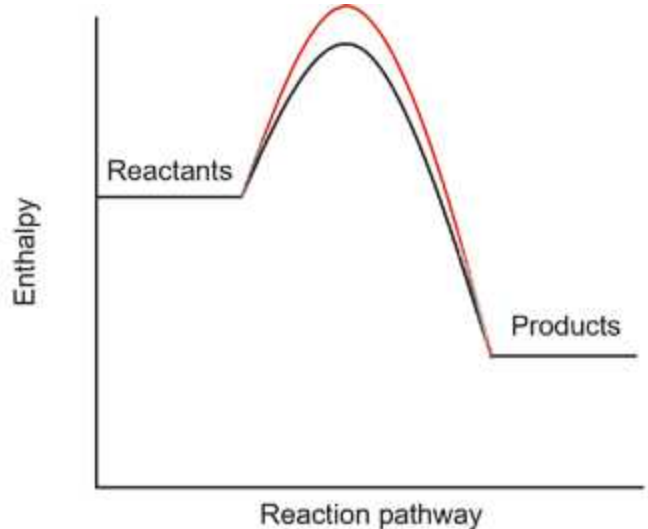
Question	Part	Author's Response	Marks
3	(ii)	Coconut oil has a higher melting point. The triglyceride shown in coconut oil is saturated, while the triglyceride shown in soybean oil is unsaturated (contains C=C). This results in a more regular structure for molecules in coconut oil. Molecules can pack more closely in coconut oil compared to the irregular structure of molecules in soybean oil. Stronger dispersion forces are experienced with closer interactions, requiring more energy to overcome.	3
	(iii)	Any two: 	2
			2
			2
	(iv)	Any one: Renewable source of triglyceride. Easily farmed in short growth periods.	1
	(v)	Any one: Cost and difficulty of processing. Access to technology.	1
4	(a)	$\text{C}_3\text{H}_{8(g)} + 5\text{O}_{2(g)} \rightarrow 3\text{CO}_{2(g)} + 4\text{H}_2\text{O}_{(l)}$	2
	(b)	$\text{CH}_3\text{OH}_{(l)} + \frac{3}{2}\text{O}_{2(g)} \rightarrow \text{CO}_{2(g)} + 2\text{H}_2\text{O}_{(l)}$	2
	(c)	$\text{C}_{19}\text{H}_{38}\text{O}_{2(l)} + \frac{55}{2}\text{O}_{2(g)} \rightarrow 19\text{CO}_{2(g)} + 19\text{H}_2\text{O}_{(l)}$	2
5	(a) (i)	Hexadecane is a relatively large non-polar molecule. Dispersion forces are experienced between non-polar molecules. At room temperature (25 °C), there is sufficient energy to overcome the forces holding the molecules in fixed positions in a solid, allowing them to flow as a liquid.	2
	(ii)	$\text{C}_{17}\text{H}_{34}\text{O}_2$	2
	(iii)	$\text{C}_{16}\text{H}_{34(l)} + \frac{49}{2}\text{O}_{2(g)} \rightarrow 16\text{CO}_{2(g)} + 17\text{H}_2\text{O}_{(l)} \quad \Delta H = -10701 \text{ kJ mol}^{-1}$	4
	(iv)	Although methyl hexadecanoate contains an ester group with oxygen atoms present in the molecule, it also contains an additional carbon atom in the methyl group. Overall, the same number of molecules of oxygen are required to achieve the stoichiometric ratio.	1
		$\text{C}_{17}\text{H}_{34(l)} + \frac{49}{2}\text{O}_{2(g)} \rightarrow 17\text{CO}_{2(g)} + 17\text{H}_2\text{O}_{(l)}$ Equation not required for full marks.	1
	(v)	Concentration of oxygen in the air is relatively fixed.	1
		It is more difficult to achieve the stoichiometric ratio required for complete combustion with fuels containing a higher number of carbon atoms in the molecule.	1
	(b)	Carbon monoxide displaces oxygen from the blood, as haemoglobin forms carboxyhaemoglobin. Carbon monoxide is delivered to the cells in the human body instead of oxygen. In low concentrations, carbon monoxide exposure leads to dizziness and fatigue. In high concentrations, exposure can lead to loss of consciousness and death.	1 1 1

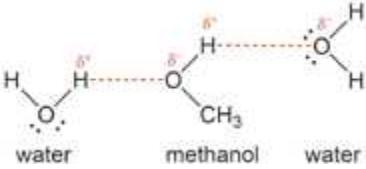
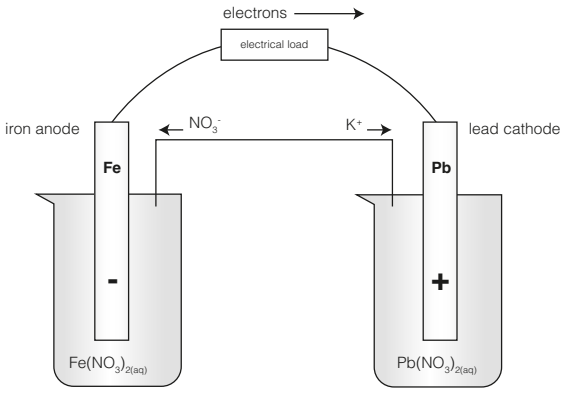
Question	Part	Author's Response	Marks
5	(c) (i)	Particle size of soot is large enough to be trapped in a particulate filter.	1
	(ii)	Climate change	
		Soot released locally in the atmosphere leads to greater absorption of solar radiation.	1
		Black carbon in soot absorbs all wavelengths, resulting in warming in the lower atmosphere.	1
		Soot landing on reflective bodies such as areas of ice and snow reduces reflectivity (albedo).	1
		This results in in less solar radiation being reflected from the Earth's surface, increasing warming.	1
	Human health		
	As a fine particulate pollutant, soot enters the lungs and lodges in the alveoli. This leads to reduced respiratory function and increases the risk of respiratory and coronary disease.	1	
	Compounds on the surface of carbon structures (polycyclic aromatic hydrocarbons). enter the bloodstream. PAH's are known carcinogens.	1	
6	(a) (i)	$n = \frac{m}{M}$ $n = \frac{50,000}{M_{270.442}}$ $n = 184.85 \text{ mol}$	2 1
		$\Delta H = -10,100 \text{ kJ/mol}$ $n = 184.85 \text{ mol}$ $Q = n \times \Delta H$ $Q = -1,867,385 \text{ kJ}$ $Q = 1.87 \times 10^6 \text{ kJ}$	2 2
	(b)	$Q_{\text{petrodiesel}} = Q_{\text{biodiesel}} \times (1+0.09)$ $Q_{\text{petrodiesel}} = 1,867,385 \times 1.09$ $Q_{\text{petrodiesel}} = 2,035,450.65 \text{ kJ}$ $\Delta Q = Q_{\text{petrodiesel}} - Q_{\text{biodiesel}}$ $\Delta Q = 2,035,451 - 1,867,385$ $\Delta Q = 168,066 \text{ kJ}$ $\Delta Q = 1.68 \times 10^5 \text{ kJ}$	1 1
		$Q_{\text{petrodiesel}} = 2,035,450.65 \text{ kJ}$ $Q_{\text{biodiesel}} = 1,867,385 \text{ kJ}$ $Q_{\text{usable, biodiesel}} = Q_{\text{biodiesel}} \times \text{efficiency}$ $Q_{\text{usable, biodiesel}} = 1,867,385 \times 0.35$ $Q_{\text{usable, biodiesel}} = 653,584.75 \text{ kJ}$ $Q_{\text{usable, biodiesel}} = Q_{\text{biodiesel}} \times \text{efficiency}$ $Q_{\text{usable, biodiesel}} = 2,035,451 \times 0.40$ $Q_{\text{usable, biodiesel}} = 814,180.4 \text{ kJ}$	3
	(c)		

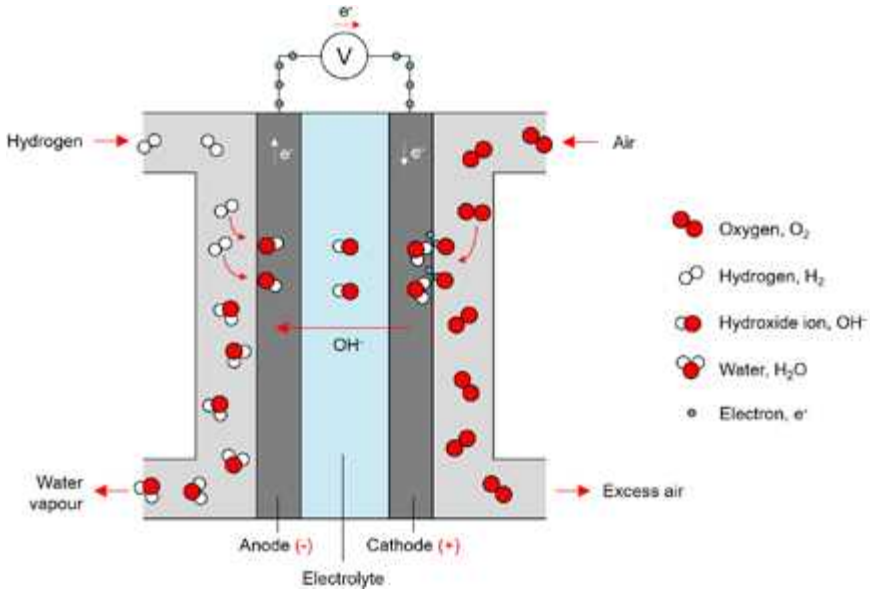
Question	Part	Author's Response	Marks
7	(a) (i)	$m(\text{C}_{\text{complete combustion}}) = 5.00 \times 10^6 \text{ g}$ $= 5000 \text{ g}$ $n = \frac{m}{M}$ $n(\text{C}_{\text{complete}}) = \frac{5.00 \times 10^6}{12.01}$ $= 4.16 \times 10^5 \text{ mol}$ $Q = n \times \Delta H$ $Q(\text{C}_{\text{complete}}) = 4.16 \times 10^5 \times 393$ $= Q(\text{C}_{\text{complete}}) = 164 \text{ GJ kJ}$	2
	(ii)	$m(\text{C}_{\text{complete combustion}}) = 5.00 \times 10^6 \times 0.8 (80\%) = 4.00 \times 10^6$ $m(\text{C}_{\text{incomplete combustion}}) = 5.00 \times 10^6 \times 0.2 (20\%) = 1.00 \times 10^6 \text{ g}$ $n = \frac{m}{M}$ $n(\text{C}_{\text{complete}}) = \frac{4.00 \times 10^6}{12.01}$ $= 3.33 \times 10^5 \text{ mol}$ $n(\text{C}_{\text{incomplete}}) = \frac{1.00 \times 10^6}{12.01}$ $= 8.33 \times 10^5 \text{ mol}$ $Q = n \times \Delta H$ $Q(\text{C}_{\text{incomplete}}) = 3.33 \times 10^5 \times 393$ $= 1.31 \times 10^8 \text{ kJ}$ $Q(\text{C}_{\text{complete}}) = 8.33 \times 10^5 \times \frac{232}{2}$ $= 9.66 \times 10^6 \text{ kJ}$ $Q(\text{C}_{\text{total}}) = 1.41 \times 10^8 \text{ kJ}$	2
	(b) (i)	CO (+2), CO ₂ (+4) Increase in oxidation number represents oxidation ∴ reducing agent (reducer/reductant).	2 1
	(ii)	$m(\text{Fe}) = 959 \times 10^6 \times 10^6 \text{ g}$ $M(\text{Fe}) = 55.85 \text{ g mol}^{-1}$ $n(\text{Fe}) = \frac{m}{M}$ $n(\text{Fe}) = \frac{959 \times 10^6 \times 10^6}{55.85}$ $n(\text{Fe}) = 1.717 \times 10^{10} \text{ mol}$ $\text{mole ratio } n(\text{Fe}) : n(\text{CO}_2) = 2 : 3$ $\frac{n(\text{CO}_2)}{n(\text{Fe})} = \frac{3}{2}$ $\therefore n(\text{CO}_2) = \frac{3 \times 1.717 \times 10^{10}}{2}$ $n(\text{CO}_2) = 2.576 \times 10^{10} \text{ mol}$ $M(\text{CO}_2) = 44.01 \text{ g mol}^{-1}$ $m(\text{CO}_2) = n \times M$ $m(\text{CO}_2) = 2.576 \times 10^{10} \times 44.01$ $m(\text{CO}_2) = 1.134 \times 10^{15} \text{ g}$ $m(\text{CO}_2) = 1.134 \times 10^{12} \text{ kg (3 sig. fig.)}$	2 1
			2

Question	Part	Author's Response	Marks
7	(c) (i)	After entering the lungs on the surface of carbon, PAHs (polycyclic aromatic hydrocarbons) can be absorbed into the bloodstream. PAHs are known carcinogens.	1 1
	(ii)	0.150 ppm = 0.150 mg in 1L = 0.150 × 8 mg = 1.20 mg	2
8	(a) (i)	$m(\text{CH}_3\text{OH}) = 5.00 \times 0.05 \text{ g}$ $M(\text{CH}_3\text{OH}) = 32.04 \text{ g mol}^{-1}$ $n(\text{CH}_3\text{OH}) = \frac{5.00 \times 0.05}{32.04} \text{ mol}$ $n(\text{CH}_3\text{OH}) = 7.803 \times 10^{-3} \text{ mol}$ $m(\text{C}_2\text{H}_5\text{OH}) = 5 \times 0.95 \text{ g}$ $M(\text{C}_2\text{H}_5\text{OH}) = 46.07 \text{ g mol}^{-1}$ $n(\text{C}_2\text{H}_5\text{OH}) = \frac{5.00 \times 0.95}{46.07} \text{ mol}$ $n(\text{C}_2\text{H}_5\text{OH}) = 1.031 \times 10^{-1} \text{ mol}^{-1}$ $n_{(\text{Total})} = 7.803 \times 10^{-3} + 1.031 \times 10^{-1} \text{ mol}^{-1}$ $n_{(\text{Total})} = 0.1109 \text{ mol}$	2 2 1
	(ii)	$Q = n \times \Delta H$ $Q(\text{CH}_3\text{OH}) = 7.803 \times 10^{-3} \times 715.0$ $= 5.579 \text{ kJ}$ $Q(\text{C}_2\text{H}_5\text{OH}) = 1.031 \times 10^{-1} \times 1371$ $= 141.4 \text{ kJ}$ $Q_{(\text{Total})} = 146.9 \text{ kJ}$ $Q = m \times c \times \Delta T \text{ (J)}$ $\Delta T = \frac{Q}{m \times c}$ $\Delta T = \frac{146.9 \times 10^{-3}}{500 \times 4.18}$ $\Delta T = 70.30^\circ\text{C}$ $T_{\text{final}} = 21.0 + 70.3 = 91.3^\circ\text{C}$	2 2 2
	(b)	Heat is lost to the cooking utensils and the surroundings.	1
		The combustion is incomplete.	1

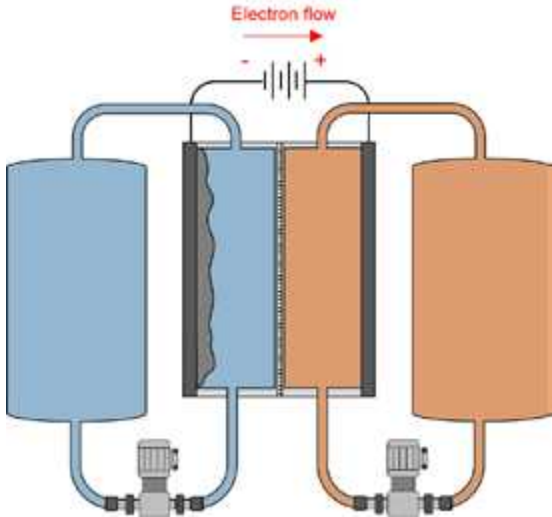
Question	Part	Author's Response	Marks
9	(a) (i)		2
	(ii)	$\text{C}_6\text{H}_{14(l)} + 19/2 \text{O}_{2(g)} \rightarrow 6\text{CO}_{2(g)} + 7\text{H}_2\text{O}_{(l)} \quad \Delta H = -4163 \text{ kJ mol}^{-1}$	4
	(b) (i)	2,2,4-trimethylpentane $\Delta m = m_{\text{initial}} - m_{\text{final}}$ $= 136.20 - 135.76$ $= 0.440 \text{ g}$ $M(\text{C}_8\text{H}_{18}) = (8 \times 12.01) + (18 \times 1.008)$ $M(\text{C}_8\text{H}_{18}) = 114.23 \text{ g mol}^{-1}$ $n = \frac{m}{M}$ $= \frac{0.44}{114.23} = 3.85 \times 10^{-3} \text{ mol}$	1
		(1) Heptane $\Delta m = m_{\text{initial}} - m_{\text{final}}$ $= 134.70 - 134.27$ $= 0.430 \text{ g}$ $M(\text{C}_7\text{H}_{16}) = (7 \times 12.01) + (16 \times 1.008)$ $M(\text{C}_7\text{H}_{16}) = 100.21 \text{ g mol}^{-1}$ $n = \frac{m}{M}$ $= \frac{0.43}{100.21} = 4.29 \times 10^{-3} \text{ mol}$	2
		2,2,4-trimethylpentane $\Delta H(\text{C}_8\text{H}_{18}) = \frac{m \times c \times \Delta T}{1000 \times n} \text{ (kJ mol}^{-1}\text{)}$ $\Delta H(\text{C}_8\text{H}_{18}) = \frac{100 \times 4.18 \times 20}{1000 \times 3.852 \times 10^{-3}}$ $= -2170 \text{ kJ mol}^{-1}$	2
		Heptane $\Delta H(\text{C}_7\text{H}_{16}) = \frac{m \times c \times \Delta T}{1000 \times n} \text{ (kJ mol}^{-1}\text{)}$ $\Delta H(\text{C}_7\text{H}_{16}) = \frac{100 \times 4.18 \times 20}{1000 \times 4.291 \times 10^{-3}}$ $= -1950 \text{ kJ mol}^{-1}$	1
		Combustion occurs in pure oxygen. This leads to complete combustion of the fuels compared to incomplete combustion in air with a component of oxygen. The bomb calorimeter is extremely well insulated. Very little thermal energy can escape; the majority enters the water surrounding the bomb and is measured as the temperature rises.	2
	(c) (i)	Exothermic	1

Question	Part	Author's Response	Marks
9	(ii)		2
	(iii)		1

Question	Part	Author's Response	Marks
10	(a) (i)	$\text{CH}_3\text{OH}_{(l)} + \frac{3}{2} \text{O}_{2(g)} \rightarrow \text{CO}_{2(g)} + 2\text{H}_2\text{O}_{(l)} \quad \Delta H = -715 \text{ kJ mol}^{-1}$	4
	(ii)	$\frac{\text{kJ}}{\text{mol}} \div \text{M} \frac{\text{kJ}}{\text{g}} \times \rho \frac{\text{kJ}}{\text{L}}$	2
		$= \frac{715}{32.04} = 22.32 \text{ kJ g}^{-1}$	2
		$= \frac{715}{32.04} \times 792 = 17670 \text{ kJ L}^{-1}$	
	(iii)	 Methanol is a relatively small molecule containing a polar hydroxyl functional group. Polar water molecules have the ability to hydrogen bond to the hydroxyl group and surround the molecule.	1 1 1
	(b) (i)	$\frac{\text{kJ}}{\text{L}} \div \rho \frac{\text{kJ}}{\text{g}} \times \text{M} \frac{\text{kJ}}{\text{mol}}$ $= \frac{23\,475}{789} = 29.75 \text{ kJ g}^{-1}$ $= \frac{23\,475}{789} \times 46.07 = -1371 \text{ kJ mol}^{-1}$	2 2
	(ii)	Per litre, ethanol and ethanol blends produce less energy when compared to petrol.	1
	(iii)	This would mean a greater volume of fuel would have to be stored during transport or the vehicle would have to refuel more frequently. Bioethanol blends contain ethanol derived from renewable sources such as plants. During their growth, the plants used for bioethanol production absorb and offset a proportion of the carbon dioxide produced by their combustion, contributing less to global warming.	1 1 1 1
11	(a)	 Anode: Iron (Fe) Charge: Negative (-) Cathode: Lead (Pb) Charge: Positive (+) Salt bridge: Contains KNO_3 Electron flow in the wire: From anode (Fe) to cathode (Pb). Ion flow in the salt bridge: K^+ ions move toward the cathode. NO_3^- ions move toward the anode.	1 1 1 1 1

Question	Part	Author's Response	Marks
11	(b)	Iron (Fe) is oxidised because it has higher reactivity than lead.	1
	(c)	$\text{Fe}_{(s)} \rightarrow \text{Fe}^{2+}_{(aq)} + 2e^{-}$	2
	(d)	$\text{Pb}^{2+}_{(aq)} + 2e^{-} \rightarrow \text{Pb}_{(s)}$	2
	(e)	$\text{Fe}_{(s)} + \text{Pb}^{2+}_{(aq)} \rightarrow \text{Fe}^{2+}_{(aq)} + \text{Pb}_{(s)}$	3
12	(a)	Many answers possible. Examples include: Environmental: MFCs reduce pollution by generating energy while treating wastewater. However, scaling up MFCs could face challenges like ensuring minimal disruption to ecosystems. Economic: MFCs can reduce energy costs in wastewater treatment plants. However, the high initial cost of setting up MFC technology may limit adoption in developing economies.	4
	(b)	MFCs currently produce low power and current, which limits their use in large-scale energy production. Future applications will likely focus on: - Powering small biosensors for environmental monitoring. - Generating electricity in niche areas like remote wastewater treatment plants.	2
	(c)	Bird et al. (2022) conducted a meta-analysis of pilot-scale MFC systems, standardising data across different studies. This research highlights how communication and collaboration among scientists allow for: - Identification of operational trends and performance improvements. - Development of scalable solutions to transition MFCs from research to practical, full-scale applications.	2
13	(a) (i)	Chemical energy to electrical energy	2
	(ii)		2
	(b) (i)	Oxidation Oxidation is represented by a loss of electrons (electrons appear on the right) or an increase in oxidation number (hydrogen increases from 0 to +1).	1 1
	(ii)	Anode	1

Question	Part	Author's Response	Marks
13	(iii)	The water produced can be used by astronauts.	1
	(c)	Any four: (must include comparison) Fuel cells provide continuous energy as long as fuel and oxygen are supplied, unlike galvanic cells, which have a fixed capacity. Fuel cells are more efficient in converting chemical energy to electrical energy than galvanic cells, which often lose more energy as heat. Fuel cells produce water as a useful by-product for astronauts, whereas galvanic cells do not provide such beneficial outputs. Fuel cells are lightweight and compact, making them ideal for space flight, unlike galvanic cells, which can be bulkier for the same energy output. Fuel cells' reactants can be replenished, unlike galvanic cells, which are single-use or require total replacement.	4
	(d) (i)	$\text{CO}_{2(g)} + 2\text{KOH}_{(aq)} \rightarrow \text{K}_2\text{CO}_{3(aq)} + \text{H}_2\text{O}_{(l)}$	2
	(ii)	The carbon dioxide produced is an acidic oxide.	1
	(ii)	Acidic carbon dioxide undergoes a reaction with alkaline potassium hydroxide in the fuel cells and could effectively remove the excess carbon dioxide generated.	1
	(e) (i)	Galvanic cell	1
	(ii)	Anode	1
	(iii)	$\text{CO}_{(g)} + \text{H}_2\text{O}_{(l)} \rightarrow \text{CO}_{2(g)} + 2\text{H}^+_{(aq)} + 2\text{e}^-$	2
14	(a)	An economic factor is the lower cost of lithium battery technology compared to hydrogen fuel cell vehicles (FCVs). - Lithium battery EVs have benefited from the rapid decline in battery production costs over time due to advancements in manufacturing and economies of scale. - In contrast, hydrogen FCVs involve high costs for fuel cell technology and the development of hydrogen refuelling infrastructure, making them less economically competitive.	2
	(b)	A social and cultural factor is the strong branding and public perception of lithium battery EVs. - Companies like Tesla have built a cultural association with innovation and environmental friendliness, leading to widespread acceptance and adoption of lithium EVs. - In contrast, hydrogen FCVs have struggled to achieve the same level of visibility and consumer trust, limiting their social and cultural impact.	2
	(c)	An environmental factor is the greater reliance on renewable electricity for lithium battery EVs. - Lithium battery EVs can be charged using renewable energy sources like solar and wind power, which reduces overall carbon emissions. - Hydrogen FCVs, however, rely on green hydrogen production, which is energy-intensive and not yet widespread, limiting their immediate environmental benefits.	2

Question	Part	Author's Response	Marks
15	(a)	Any two points: (must include comparison) Photovoltaic cells harness energy from the Sun. This energy is renewable. Power stations harness heat energy from the combustion of coal as a fossil fuel. Fossil fuels are non-renewable. Photovoltaic cells do not produce pollutants during operation. Burning coal in power stations releases vast quantities of carbon dioxide and oxides of nitrogen and sulfur to the atmosphere as pollutants, leading to global warming, photochemical smog, and acid rain. Photovoltaic cells do not require water for electricity generation, whereas coal-fired turbines consume large amounts of water for steam production and cooling. Photovoltaic systems can be installed close to the point of use (e.g., on rooftops), reducing transmission losses and infrastructure needs. Once installed, photovoltaic systems require little maintenance and no fuel, significantly lowering operational costs compared to coal-fired plants. Photovoltaic cells harness locally available sunlight, reducing reliance on imported coal and enhancing energy security.	4
	(b) (i)		1
	(ii)	$\text{Zn}_{(s)} \rightarrow \text{Zn}^{2+}_{(aq)} + 2e^{-}$	2
	(iii)	Zinc is deposited as a solid electrode, rather than the cell containing only ions in solution.	1
	(iv)	Any four: The flow cell can remain depleted for extended periods of time. Residents can leave it depleted while away and recharge on returning to the premises. The flow cell provides a consistent power output. The cell can be used for extended periods without a decrease in performance. Virtually unlimited capacity as electrolytes are stored externally. They can be sized to suit the household requirements. The cells are rechargeable meaning that electrolytes can be used indefinitely. They are quickly charged through the addition of electrolyte. Components of the cell can be laid out in varying configurations, which can include burying the electrolyte tanks underground. This may suit the layout of the dwelling or industry.	4
	(v)	(1) Electrical energy to chemical energy	2
		(2) $2\text{Br}^{-}_{(aq)} \rightarrow \text{Br}_2 + 2e^{-}$	2
		(3) Bromine could be released from the cell which is potentially toxic.	1

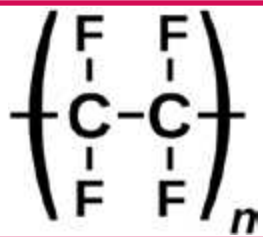
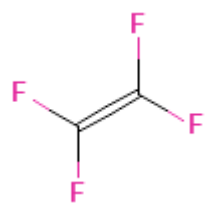
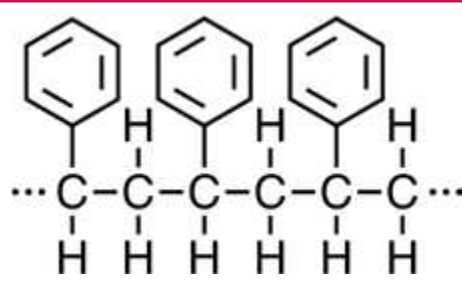
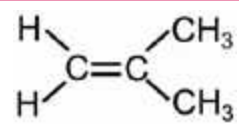
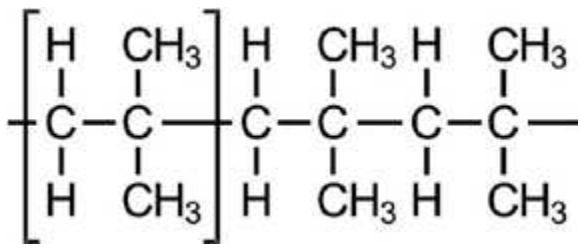
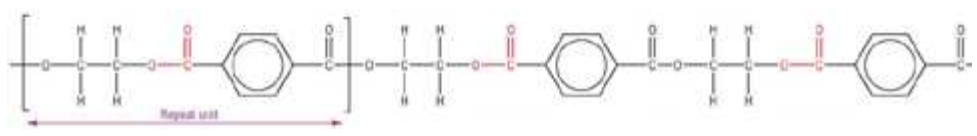
Question	Part	Author's Response	Marks
16	(a) (i)	C=C, carbon–carbon double bond.	1
	(ii)	Cationic	1
	(1)	$\text{Al}_2(\text{SO}_4)_{3(s)} \xrightarrow{\text{H}_2\text{O(l)}} 2\text{Al}^{3+}_{(aq)} + 3\text{SO}_4^{2-}_{(aq)}$	2
	(iii) (2)	Aluminium has a higher charge density (3+) compared to the surface of polyDADMAC (1+).	1
	(3)	It is a large molecule effective at physically trapping particles.	1
	(iv)	The positively charged surface of polyDADMAC effectively neutralises the negatively charged surface of clays.	1
		This destabilises the clay suspension leading to coagulation as micro-floc forms.	1
		Micro-floc aggregate, assisted by the polymer, entrapping the clay particles.	1
		The larger floc that form settle out from suspension.	
	(b) (i)	Residual magnesium concentration is at a maximum when pH is low (pH = 4.5) and high (pH = 9). Residual magnesium concentration is at a minimum at a pH of 6.	2
	(ii)	Value obtained from graph at pH 6, 0.01 mg L ⁻¹	
		= 0.01 mg in 1 L	1
		= 0.01 mg in 1000 mL	
		$= \frac{0.01}{1000} \times 300 \text{ mg in } 300 \text{ mL}$ = 3 × 10 ⁻³ mg = 3 × 10 ⁻⁶ g	2
	(iii)	1.5 mg in 1 L	
		= 3.0 mg in 2 L	
		= 3.0 mg in 60 kg	
		$= \frac{3.0}{60} \text{ mg in } 1 \text{ kg}$	
		= 0.050 ppm	3
	(c)	The seeds are easily obtained and processed. There is no requirement for expensive and specialised equipment and infrastructure.	2
		The polymers come from a natural source. The natural polymers are not toxic and are biodegradable when added to water.	2

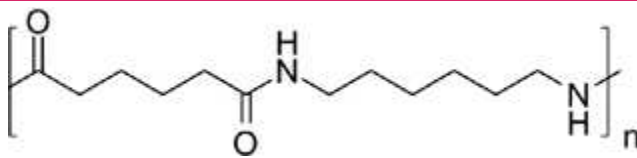
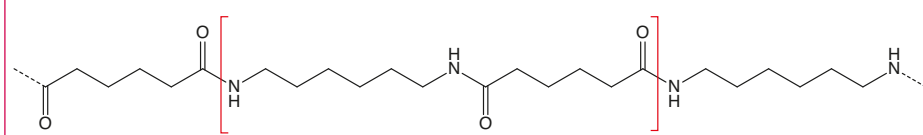
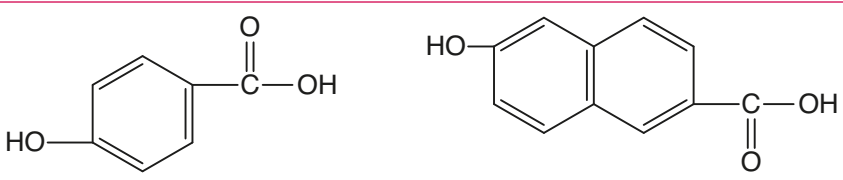
Question	Part	Author's Response	Marks
17	(a)	Hard water	1
	(b)	Pressure is applied on one side of a semipermeable membrane to overcome the osmotic pressure.	1
		Water is forced to the side of the membrane with a lower concentration of dissolved salts, leaving the ions present on the other side of the membrane.	1
	(c) (i)	The equation represents a chemical equilibrium.	1
		Removal of carbon dioxide gas as the water is heated places a stress on the system at equilibrium.	1
		The system responds to counteract the stress, according to Le Châtelier's principle, by shifting the position of equilibrium in the forward direction to replace carbon dioxide.	1
		This results in the formation of calcium carbonate.	1
	(ii)	$2\text{NH}_4\text{SO}_3(\text{aq}) + \text{CaCO}_3(\text{s}) \rightarrow \text{Ca}(\text{NH}_4\text{SO}_3)_2(\text{aq}) + \text{H}_2\text{O}(\text{l}) + \text{CO}_2(\text{g})$	2
	(d) (i)	Zeolites have negatively charged surfaces.	1
		Zeolites have exceptionally large surface area.	1
	(ii)	An increased concentration of aqueous calcium ions places a stress on the system at equilibrium.	1
		(1) The system responds to counteract the stress, according to Le Châtelier's principle, by shifting the position of equilibrium to favour the forward reaction.	1
			1
		This results in the calcium ions exchanging onto the surface of the zeolite releasing aqueous sodium ions.	1
	(2)	By increasing the aqueous concentration of sodium ions, through the addition of a concentrated sodium chloride solution to the zeolite.	1
	(e)	The colloidal particles are so fine that they pass through the filter and form a suspension.	1

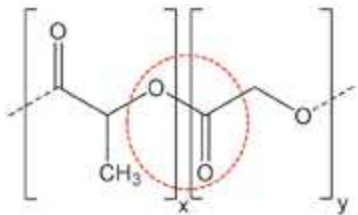
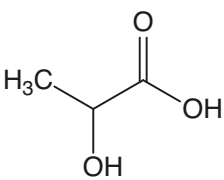
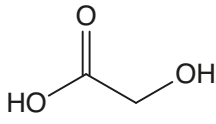
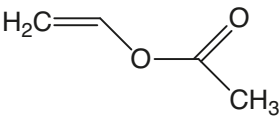
Question	Part	Author's Response	Marks
18	(a) (i)	$\text{Cl}_{2(g)} + 2\text{H}_2\text{O}_{(l)} \rightleftharpoons \text{HClO}_{(aq)} + \text{Cl}^{-}_{(aq)} + \text{H}_3\text{O}^{+}_{(aq)}$	2
	(ii)	(1) Oxidising agent (oxidant/oxidiser)	1
		(2) Low pH	1
	(iii)	Any one: (1) It is not charged, and therefore can more easily enter the cell wall. It is a stronger oxidising agent.	1
		(2) The three-dimensional protein (enzyme) structure determines the function of the protein. The three-dimensional structure of the enzyme is altered as it is degraded. The function of the protein is lost.	1
			1
			1
	(b) (i)	Endothermic	1
	(ii)	Cyanuric acid forms an equilibrium reaction with hypochlorite ions.	1
		Absorption of UV from sunlight decomposes hypochlorite ions.	1
		(1) This places a stress on the system at equilibrium.	1
		According to Le Châtelier's principle, the equilibrium system counters the change.	1
		The position of equilibrium is shifted backwards, replacing hypochlorite ions.	
		Cyanuric acid absorbs a component of UV radiation.	1
	(2)	This UV radiation is not being absorbed by hypochlorite ions, leading to their decomposition.	1
	(c) (i)	$3.0 \times 10^4 \text{ ng in 1 L}$ $= 3.0 \times 10^1 \mu\text{g in 1 L}$ $= 30 \text{ ppb}$ $\therefore$ Less than WHO limits.	1
			1
	(ii)	$\text{N} \equiv \text{C} - \text{Cl}$	2
	(iii)	(1) Trigonal pyramidal	1
		Trichloramine is a relatively small polar covalent molecule.	1
		(2) Secondary dipole-dipole forces are experienced between molecules.	1
		At room temperature, these secondary interactions can be overcome allowing the molecules to exist as a gas.	1
	(iv)	Less compounds of chlorine are available for disinfection.	1
	(d) (i)	Dissociated aluminium ions contain a positive charge (3+).	1
		The positive charge is able to neutralise the charge on the surface of colloidal particles destabilising the suspension during coagulation.	1
		Colloidal particles form micro-floc, which aggregate during flocculation. Larger floc settle out.	1
	(ii)	The water becomes clearer.	1

Question	Part	Author's Response	Marks
19	(a)	Adding HCl to the second equilibrium increases the concentration of $\text{H}^+/\text{H}_3\text{O}^+$ ions.	1
		System will adjust to counteract the change by decreasing the concentration of $\text{H}^+/\text{H}_3\text{O}^+$ ions.	1
		System moves towards LHS/reactant side.	1
		Concentration of $\text{HClO}_{(\text{aq})}$ increases.	1
	(b)	Photochemical decomposition	1
20	(a) (i)	Fixed nutrients are nutrients bound within mineral or organic compounds, which makes them less accessible to plants until they undergo chemical changes that make them soluble.	1
	(ii)	Available nutrients are nutrients in a soluble form, allowing them to be easily absorbed through the roots of plants.	1
	(b) (i)	Nitrate, NO_3^-	1
	(ii)	Dihydrogen phosphate, H_2PO_4^-	1
21	(a) (i)	$\text{H}_2\text{O} + \text{NH}_2\text{OH} \rightarrow \text{NO}_2^- + 5\text{H}^+ + 4\text{e}^-$	2
	(ii)	$\text{H}_2\text{O} + \text{NO}_2^- \rightarrow \text{NO}_3^- + 2\text{H}^+ + 2\text{e}^-$	2
	(b)	The first half-reaction is an oxidation.	1
		Electrons are shown on the right side of the equation, indicating that they are being lost. Oxidation is a loss of electrons.	1
		The second half-reaction is an oxidation.	1
		Electrons are shown on the right side of the equation, indicating that they are being lost. Oxidation is a loss of electrons.	1
		<i>Alternatively, oxidation is indicated by the fact that the oxidation number of nitrogen increases in both reactions.</i>	
	(c) (i)	-1	1
	(ii)	+3	1
	(iii)	+5	1
	(iv)	0	1
22	(a) (i)	Many answers possible, including classes of compounds (e.g., amino acids, proteins/polyamides, DNA, etc.) or specific compounds (e.g., caffeine).	1
	(ii)	Anaerobic conditions (no oxygen)	1
	(iii)	Methane (CH_4)	1
	(b)	Lightning provides the high temperatures needed to break molecular nitrogen (N_2) and oxygen (O_2) bonds in the atmosphere, which react to give nitrogen oxides (NO and NO_2).	4
		Nitrogen dioxide (NO_2) reacts with water vapor (H_2O) in the atmosphere to produce nitric acid (HNO_3) and nitrous acid (HNO_2) through chemical reactions.	
		$\text{N}_2 + \text{O}_2 \rightarrow 2\text{NO}$	
		$2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2$	
		$\text{H}_2\text{O} + 2\text{NO}_2 \rightarrow \text{HNO}_3 + \text{HNO}_2$	
	(c)	Increased algal growth blocks sunlight, reducing photosynthesis for submerged plants, which subsequently die and decompose.	1
		The decomposition process consumes oxygen in the water, leading to oxygen depletion, which suffocates aquatic animals.	1
		Under anaerobic conditions, decay produces toxic substances like hydrogen sulfide and methane, further harming aquatic life and creating "dead zones" unsuitable for most organisms.	1

Question	Part	Author's Response	Marks
23	(a) (i)	Plants absorb essential nutrients, such as nitrate, from the soil for growth.	1
		These are not naturally replenished at the same rate they are absorbed by agricultural crops.	1
	(ii)	Legume crops increase the concentration of available nitrate ions in the soil because they contain nitrogen-fixing bacteria in their root nodules.	1
		These bacteria convert atmospheric nitrogen into ammonia, which is then converted into nitrates in the soil, enriching its nitrogen content.	1
	(iii)	Tilling legume plants into the soil increases nitrate ion concentration because the decomposing plant material releases organic nitrogen compounds.	1
		Soil microbes break down these compounds, producing ammonia.	1
		The ammonia is then converted into nitrates through nitrification, enriching the soil with available nitrogen.	1
	(b) (i)	(1) NH_4NO_3	2
		(2) Nitrate and ammonium ions are soluble in soil solution.	1
	(ii)	(1) Eutrophication	1
		(2) $6\text{CO}_{2(g)} + 6\text{H}_2\text{O}_{(l)} \xrightarrow{\text{energy}} \text{C}_6\text{H}_{12}\text{O}_{6(s)} + 6\text{O}_{2(g)}$	2
24		Zr_2SiO_4	2
25		$\text{Sc}_2\text{Si}_2\text{O}_7$	2
26		2–	2
27		$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3, x = 3$	2
28		1 of 2, 50%	2
29	(a) (i)	Soil porosity decreases from 0% to 25% clay content. From 25% to 100% clay content, soil porosity increases.	2
		(ii) Layers of clay in the soil are held together with cations. Clays provide soil structure, maintaining soil aeration between soil particles.	2
	(b) (i)	$[\text{H}^+] = 10^{-\text{pH}}$	2
		$[\text{H}^+] = 10^{-5.7}$	
		$[\text{H}^+] = 2.0 \times 10^{-6} \text{ mol L}^{-1}$	
	(ii)	$2\text{H}^+_{(aq)} + \text{Ca}^{2+}_{(\text{clay})} \rightleftharpoons \text{Ca}^{2+}_{(aq)} + 2\text{H}^+_{(\text{clay})}$	1
		Increasing the concentration of aqueous hydrogen ions places a stress on the system at equilibrium.	
		According to Le Châtelier's principle, the system counteracts the stress by shifting the position of equilibrium to favour the formation of products.	
		As a result, metal cations on the surface of the clay, such as calcium, are exchanged in to the soil solution while hydrogen ions are deposited on the clay surface.	
	(iii)	Cations of magnesium (Mg^{2+}) and calcium (Ca^{2+}) maintain flocculation in clays by binding the layers of clay within the soil.	1
		Replacing these cations with hydrogen ions (H^+), through cation exchange, weakens the electrostatic attraction between layers of clay, resulting in their separation.	1
	(iv)	Aluminium ions released through cation exchange are toxic to plants and reduce growth.	1
	(v)	(1) $2\text{H}^+_{(aq)} + \text{Ca}(\text{OH})_{2(s)} \rightleftharpoons \text{Ca}^{2+}_{(aq)} + 2\text{H}_2\text{O}_{(l)}$	2
		(2) It poses a risk to line markers and athletes. It can lead to the degradation of the soil in the sporting arena.	1

Question	Part	Author's Response	Marks
29	(c)	Water molecules can hydrogen bond to the hydroxyl groups present between layers of clay, causing the clay to swell. If the turf becomes too dry through the loss of water, the layers of clay contract and hydrogen bond to one another, leading to cracking.	2
	(d) (i)	Increasing the concentration of aqueous sodium ions places a stress on the system at equilibrium.	1
		According to Le Châtelier's principle the system counteracts the stress by shifting the position of equilibrium to favour the products.	1
		As a result, metal cations on the surface of the clay, such as calcium, are exchanged into the soil solution, reducing their concentration on the surface of clays.	1
	(ii)	Replacing these cations with larger less positively charged sodium ions (Na^+), through cation exchange, weakens the electrostatic attraction between layers of clay, leading to soil dispersion. Dispersion weakens aggregates in the soil, leading to structural collapse of the soil. Soil structure is lost.	1 1
30	(a)		1
	(b)		1
31			3
32	(a)		2
	(b)		3
33			3

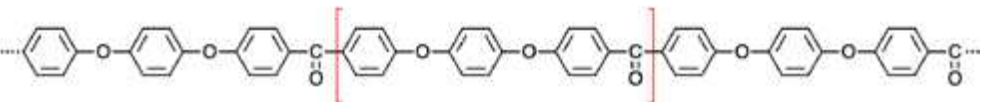
Question	Part	Author's Response	Marks
34	(a)		3
35	(a) (i)	Proteins (polypeptides/polyamides)	1
	(1)	Condensation	1
	(ii)	(2)  Other bracket positions are acceptable as long as exactly one repeating unit is included.	1
	(1)	Similar secondary interactions are present between polymer chains: hydrogen bonding in nylon, and dipole–dipole interactions in Vectran®. Neither polymer has branching that is able to generate cross-links.	2
	(iii)	(2) 	4
	(iv)	Amide groups are formed as the monomers condense.	1
		These provide multiple opportunities for hydrogen bonding between the polymer chains.	1
		Hydrogen bonding is a stronger secondary interaction; to overcome this, a large amount of energy is required. This increases the strength of the fibres.	1
	(v)	(1) Addition	1
		Thermoplastic	1
		(2) The polymer chains are formed through the addition of a monomer containing one carbon–carbon double bond and no other functional groups.	1
		This does not allow the formation of cross-linking.	1
	(3)	Weak dispersion forces are in operation between polymer chains. These can be overcome to allow the chains to move past one another.	1
	(b)	With no cross-linking present, chains are able to slide past one another, allowing the polymer to stretch until it breaks.	1
		Limited cross-linking in the polymer allows the chains to be shifted to the limits of the cross-links as forces are applied.	1
		When the forces are removed, the polymer chains return to their original positions, generating an elastic material.	1
	(c) (i)	The branches can generate cross-linking between the carbon fullerenes. Increased cross-linking results in increased rigidity in the racquet.	2
	(ii)	Stiffer, more rigid racquets flex less and transfer more energy to the ball during play.	1

Question	Part	Author's Response	Marks
36	(a) (i)		1
	(ii)	Condensation	1
	(iii)	 lactic acid  glycolic acid	2 2
	(b) (i)	Hydrogen bonding	1
	(ii)	Ester groups undergo hydrolysis.	1
		This breaks down the long polymer chains into individual units that further decompose in the body.	1
		It allows for the slow release of the pharmaceutical (drug).	1
	(c)	Rate of degradation would be reduced.	1
		Fewer ester groups are present over the length of the polymer chain.	1
		There are fewer opportunities for hydrolysis to occur throughout the chain.	1
37	(a) (i)	Addition	1
	(ii)		2
	(b) (i)	Structural isomer	1
	(ii)	ethanal	2
	(c) (i)	methyl ethanoate	2
	(ii)	As the percentage of ester groups replaced is increased, the solubility in water increases.	1
		More ester groups are replaced with hydroxyl groups.	1
		Greater opportunity exists for hydrogen bonding to occur with polymer chains.	1
	(iii)	Any two (use and reason): Polymer sachets to hold dishwasher tablets:	1
		Caustic active ingredients are safe to handle and are released when the raised temperature in the dishwasher makes the polymer soluble.	
		Dissolvable stitches: The ester groups would make the polymer degrade.	1

Question	Part	Author's Response	Marks
38	(a)	$\%Cu = \frac{M(Cu)}{M(CuFeS_2)} \times 100$ $\%Cu = \frac{63.55}{183.52} \times 100$ $\%Cu = 34.63\%$	2
	(b) (i)	Crushing and grinding exposes the mineral, increasing surface area.	1
	(ii)	Froth flotation concentrates the mineral from the ore.	1
	(iii)	(1) Gangue (waste rock) is removed, so it does not have to be transported at a cost, and can be returned to the mine site.	2
		(2) Fewer emissions of carbon dioxide and pollutants are released during the transportation of the concentrated ore which excludes the gangue.	1
	(c) (i)	$CuS_{(s)} + O_{2(g)} \rightarrow Cu_{(s)} + SO_{2(g)}$	2
	(ii)	Copper is a metal of relatively low activity.	1
		Chemical reduction with a reducing agent is sufficient to reduce copper ions to copper.	1
	(d) (i)	Refining removes impurities from the blister copper.	1
	(ii)	Impurities increase the resistance of electrical current in copper.	1
	(iii)	Negative (–)	1
	(e) (i)	$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$	2
	(ii)	Reduction of water.	1
		Reduction is occurring in an aqueous electrolytic cell.	1
		Once the copper is reduced, the water present in the cell is reduced in preference to calcium ions. Calcium is an active metal.	1
39	(f) (i)	(1) Oxidation	1
		(2) Any one: Limited yield. or Environmental issues associated with adding acid to the soil and water.	1
	(ii)	$Fe_{(s)} + Cu^{2+}_{(aq)} \rightarrow Fe^{2+}_{(aq)} + Cu_{(s)}$	1
		Iron is a more active metal than copper.	1
		Iron displaces copper ions from solution.	1
	(a) (i)	Molar mass of dolomite = Ca + Mg + 2 (C + 3 × O) = 40.08 + 24.31 + 2(12.01 + (3 × 16.00)) = 184.41 g mol ⁻¹	1
		Percentage of Mg = $\frac{\text{molar mass of dolomite} \times 100}{\text{mass of Mg}}$	1
		= $\frac{24.31 \times 100}{184.41}$	
		= 13.2%	
	(ii)	$CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2$	2
	(b)	$2MgO + 2CaO + Si \rightarrow 2Mg + Ca_2SiO_4$	2

Question	Part	Author's Response	Marks
39	(c)	Increases the rate of reaction.	1
		Increasing temperature increases the thermal energy of the system and increases the kinetic energy of the particles. Particles are more likely to collide successfully. Frequency of successful collisions increases.	1
		Additionally, at higher temperatures, more particles have energy greater than or equal to activation energy. Hence, rate of reaction increases.	1
	(d) (i)	Non-volatile impurities are left behind (Ca_2SiO_4 or other by-products)	1
		Not contaminated with other gases, so only Mg gas is condensed.	1
	(ii)	Enhances the market value and versatility of the product. Manufacturer can increase costs for this high-purity magnesium.	1
	(e)	<i>One suggestion and explanation could include:</i>	
		Could lead to increased prices of magnesium / magnesium-based products:	1
		With reduced supply and continued or growing demand for magnesium (used in aluminium alloys, automotive components, and electronics), market forces would drive prices up, increasing costs for manufacturers that rely on magnesium.	1 Or
		Could lead to supply shortages of magnesium / magnesium-based products:	1
		Industries such as automotive and aerospace, which use magnesium alloys, may face production delays, increased costs, or be forced to seek alternative materials, potentially compromising performance or efficiency.	1
	(f) (i)	$\text{MgCl}_{2(aq)} + \text{Ca(OH)}_2 \rightarrow \text{Mg(OH)}_{2(s)} + \text{CaCl}_{2(aq)}$	2
	(ii)	(1) $\overset{+2}{\text{Mg}}\overset{-2}{(\text{OH})}_2 + \overset{+1}{2}\text{H}\overset{-1}{\text{Cl}} \rightarrow \overset{+2}{\text{Mg}}\overset{-1}{\text{Cl}}_2 + \overset{+1}{2}\text{H}\overset{-2}{\text{O}}$	1
		(2) No, not redox (no change in oxidation states).	1
	(iii)	$\text{Mg}^{2+} + 2\text{e}^- \rightarrow \text{Mg}_{(s)}$	2
	(iv)	<i>Any one of:</i> Abundance of raw material (sea water). Renewable and sustainable source. Environmentally friendly, as opposed to the Pidgeon process, which uses mined dolomite and silicon, and also requires energy-intensive high temperatures.	1

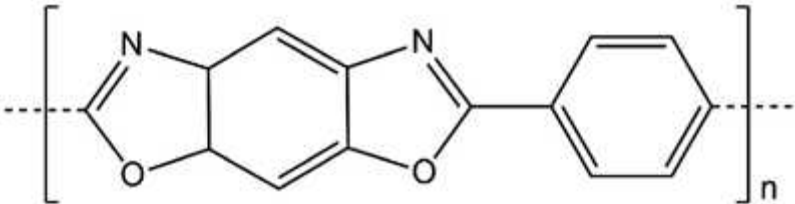
Question	Part	Author's Response	Marks
40	(a)	Geology: Geologists identified and mapped the geological formations in Western Australia where PGMs are likely to be found, particularly in layered igneous rocks.	1
		Mining and Chemical Engineering: Mining engineers provided expertise in designing and scaling up the extraction processes, ensuring that the metals can be efficiently and safely extracted.	1
		Environmental Science: Environmental scientists assessed the potential ecological impact of mining and refining activities. They developed strategies for waste reduction and minimising environmental damage during the extraction and processing stages.	1
		Material Science & Physics: Exploring new uses & innovations for PGMs in technologies like fuel cells.	
	(b)	Geologists, chemists, and environmental scientists must collaborate to locate, extract, and refine PGMs efficiently, ensuring optimal methods that are both effective and environmentally responsible.	1
		Effective coordination ensures sustainable practices and prevents costly environmental damage, optimising both the extraction process and ecological protection.	1
		Poor communication between these fields can lead to inefficient extraction methods, causing harmful environmental impacts like water contamination or ecosystem damage.	1
	(c)	Any three well-explained points: Advanced technologies improve accuracy in locating PGM deposits, reducing costs and environmental impact. Enables more efficient, environmentally friendly extraction with lower energy use and fewer emissions. Environmentally sustainable. Minimises harmful emissions, energy consumption, and environmental damage, aligning with growing sustainability demands. Improves efficiency by reducing extraction and refining costs, increasing profitability and ensuring a more reliable supply of PGMs. Improves worker safety and operational productivity. Reduces human error and enables safer, more efficient processes.	3
		Increased demand: As hydrogen fuel cells become more widely adopted for clean energy applications, the demand for PGMs, especially platinum, will rise due to their use as catalysts in fuel cells.	1
	(d)	Increased drive towards clean energy: The growth of hydrogen infrastructure and fuel cell applications across various sectors will further drive the demand for PGMs. Growth of fuel cell technology could drive innovations and greater demand in energy storage technologies; for example, advanced batteries or grid energy storage.	1

Question	Part	Author's Response	Marks
41	(a) (i)	Condensation	1
	(ii)	Amide	1
	(iii)	Hydrogen bonding is an electrostatic attraction between the δ^+ hydrogen in the N–H dipole in one polymer molecule to the δ^- oxygen in the C=O dipole in another polymer molecule.	2
	(iv)	Can be recycled.	1
		Hydrogen bonding is a secondary interaction between polymer chains that can be overcome on heating the polymer.	1
		The polymer will melt and soften and can be reshaped.	1
	(b) (i)	Contains an amide functional group that can be broken.	1
	(ii)	Fewer raw materials are required. Lowers costs, as wastes are converted to raw materials.	2
		Depolymerisation forms the original monomers.	1
		This makes the formation of new polymers simpler, as there are lower costs associated with processing of raw materials.	1
42	(a) (i)	Nylon is derived from petroleum, a non-renewable feedstock.	1
		Less energy, pollution, and environmental damage are associated with the extraction and processing petroleum by recycling the raw material.	1
	(a) (i)	Lead paste, air (oxygen)	2
		Increasing the oxygen concentration increases the frequency of collisions between reactant particles.	1
		A larger number of collisions of reactant particles reach and exceed the activation energy. More productive collisions occur per unit time, thus increasing the rate of reaction.	1
	(b) (i)	Lead is a metal of relatively low activity.	1
		Chemical reduction with a reducing agent is sufficient to reduce lead ions to lead.	1
	(ii)	Less energy intensive.	1
43	(a) (i)	Lower costs associated with obtaining the raw material.	2
		Less mining, processing and use of a finite resource.	
	(a) (i)		1
		Dipole–dipole interactions	1
	(b) (i)	By creating a composite material, the properties of the reinforcement (carbon fibre) and matrix (polymer) are enhanced.	1
		The composite offers great strength as an implant in the spine. The composite is flexible in the spine.	1
		The resulting composite improves on the strength of the carbon fibre and the flexibility of the polymer.	1
	(ii)	The polymer may be a thermoplastic polymer that, when heated, will melt, allowing it to be separated from the reinforcement.	1
	(iii)	Any one:	
		The composite may be present in the body for many years and cannot be rejected.	1
		The composite must not release toxic compounds or compounds that interfere with the body.	
		The polymer cannot break down under the conditions experienced in the human body.	

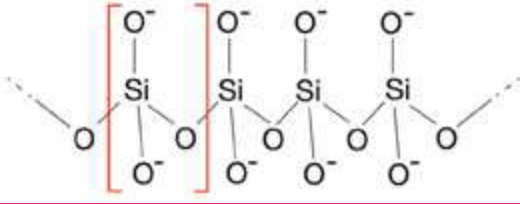
Question	Part	Author's Response	Marks
44		PLA is derived from renewable resources like corn starch, so it does not rely on fossil fuels.	1
	(a)	PLA decomposes into water and carbon dioxide under controlled conditions, which minimises long-term environmental waste.	1
	(b)	The lower melting point of PLA allows for reduced energy consumption during the manufacturing and moulding processes, making production more energy-efficient.	1
		PLA's lower melting point can limit its use for packaging applications involving high temperatures, such as hot food containers, as it may deform or lose structural integrity.	1
	(c)	PLA is prone to degradation when exposed to moisture, heat, and microbial activity, which can compromise its structural integrity over time	1
	(d)	Blending PLA with other biodegradable materials could improve its properties, such as strength, flexibility, or durability.	1
		This could expand its applications to include products requiring these enhanced properties.	1

Summary test 4 solutions: Managing resources

Question	Part	Author's response	Marks
1	(a) (i)	$\text{C}_6\text{H}_{12}\text{O}_{6(\text{aq})} \rightarrow 2\text{C}_2\text{H}_5\text{OH}_{(\text{l})} + 2\text{CO}_{2(\text{g})}$	2
	(ii)	$\text{C}_2\text{H}_5\text{OH}_{(\text{l})} + 3\text{O}_{2(\text{g})} \rightarrow 2\text{CO}_{2(\text{g})} + 3\text{H}_2\text{O}_{(\text{l})} \quad \Delta H = -1371 \text{ kJ mol}^{-1}$	4
	(iii)	$M(\text{C}_2\text{H}_5\text{OH}) = 46.068 \text{ g mol}^{-1}$ $\frac{\text{kJ}}{\text{mol}} \div M \frac{\text{kJ}}{\text{g}}$ $= \frac{1371}{46.068}$ $= 29.76 \text{ kJ g}^{-1} \text{ (4 sig. fig.)}$	2
	(iv)	Racing teams want to extract the maximum energy from every litre of fuel. Racing teams want to complete as many laps as possible from each tank of fuel, to reduce the number of fuel stops.	1
	(v)	E85 is produced from a large component of bioethanol, which can be made from biomass (unlike petrol, which is derived from crude oil, a fossil fuel).	1
		Biomass is renewable, fossil fuels are non-renewable.	1
	(b) (i)	$\Delta m = 1.8 \text{ g}$ $M(\text{CH}_3\text{OH}) = (2 \times 12.01) + (6 \times 1.008) + 16.00$ $M(\text{CH}_3\text{OH}) = 32.04 \text{ g mol}^{-1}$ $n = \frac{m}{M}$ $= \frac{1.8}{32.04} = 0.0561 \text{ mol}$ $\Delta H = \frac{m \times c \times \Delta T}{1000 \times n} \text{ (kJ mol}^{-1}\text{)}$ $\Delta H = \frac{100 \times 4.18 \times 30}{1000 \times 0.0561}$ $= -223.212 \text{ kJ mol}^{-1}$ $= -220 \text{ kJ mol}^{-1} \text{ (3 sig. fig.)}$	4
		(2) Heat is lost to the surroundings. Incomplete combustion of the methanol.	1
	(ii)	More oxygen is available for every carbon atom in methanol, as it has a shorter carbon chain compared to octane.	1
	(iii)	Decomposition of nitrous oxide provides a higher concentration of oxygen in the air-fuel mixture. A higher concentration of oxygen increases the frequency of collisions. A larger number of productive collisions occur per unit time.	3
	(iv)	(1) Condensation	1
		(2) Hydrogen bonding	1
	(c)	(1) 4–	1
		(2) Magnesium is a more active metal than titanium Therefore magnesium metal can displace titanium ions to form solid titanium.	1 1

Question	Part	Author's response	Marks
1	(ii)	(1) 	1
		(2) Increased rigidity in the composite material.	1
		(3) As a composite, the properties of the individual materials are enhanced, such as increased strength or durability.	1
		(4) Heating the composite will not melt the thermoset polymer, it will char and decompose. This makes it extremely difficult to separate the matrix from the fibres, to allow recycling.	1 1
	(d)	Any four of the following points (or alternatives). The science must be clearly identified, and explicit links made to society (people). Application and limitation The application of CFRP in materials innovation has increased due to its many advantages as a composite material. These include lower density and increased strength which allow industries to produce stronger, safer, and more efficient vehicles. The advantages of CFRP as a composite material also provide challenges for recycling, leading to issues of disposal and persistence in the environment. The nature of thermosetting polymers used for the matrix material means that they cannot be melted to separate the carbon fibre reinforcement. Extensive cross-linking hinders recycling. Existing chemical and mechanical methods applied for recycling result in potentially hazardous wastes and issues of disposal of the products formed. This may impact upon human health due to environmental exposure. The application of new methods by researchers has allowed cross links to be broken and the expensive carbon fibres separated intact while also retaining the polymer matrix for reuse. This ensures less raw materials are required for the future manufacture of CFRP and energy and resources associated with their production. This will reduce the demand on finite resources and impact less on the environment in terms energy production. This directly impacts upon human health from environmental exposure.	4
		Development As a composite material, CFRP provides challenges in recycling, leading to issues of disposal and persistence in the environment. The nature of thermosetting polymers used for the matrix material means that they cannot be melted to separate the carbon fibre reinforcement. Extensive cross-linking hinders recycling. The new method of recycling developed by researchers offers a way of recycling CFRP composites. Previous attempts using chemical or mechanical methods have been ineffective due to the formation of potentially hazardous wastes introducing issues for disposal. This may impact upon human health due to environmental exposure. The application of new methods by researchers has allowed cross-links to be broken and the expensive carbon fibres separated intact will also retaining the polymer matrix for reuse. This ensures less raw materials are required for the future production of CFRP and energy and resources associated with their production. This will reduce the demand on finite resources and impact less on the environment in terms energy production. This will reduce pollutants responsible for global warming which impact humans via climate change.	

Question	Part	Author's response	Marks
2	(a) (i)	Any two: Soot is a fine particulate that when it enters the lungs, decreases respiratory function.	1
		This can lead to acute bronchitis, aggravate asthma, and increases the risk of cardiovascular disease.	1
		Carcinogens are transported on the surface of soot particles that enter the bloodstream.	
	(ii)	Any one: Depletion of a non-renewable resource.	
		Emissions of oxides of nitrogen and sulfur may lead to the formation of acid rain or photochemical smog.	1
		Emissions of carbon dioxide contribute to global warming.	
	(b) (i)	Chlorine is formed as gas that can be toxic.	1
	(ii)	$\text{Li}^+ + \text{e}^- \rightarrow \text{Li}$	2
	(iii)	Chemical reduction is not effective, as lithium is a highly active metal.	1
		A molten electrolytic cell is required. In an aqueous cell, water would be reduced in preference to lithium ions. Hydrogen gas would be produced instead of lithium.	1
	(c) (i)	Electrolytic	1
	(ii)	Electrode 1	1
		During recharging, cell reactions are reversed. The reaction at Electrode 1 would demonstrate a loss of electrons indicating oxidation. Oxidation occurs at the anode.	1
	(iii)	(1) Renewable energy source.	1
		(2) Wind turbines only generate electricity when conditions are favourable (windy, but not higher gusts).	1
		(2) The battery can store electrical energy, for times when there is no electricity generation from the turbines.	1
	(1)	Any one: • The battery will have to be replaced at some stage and it will decrease in its capacity to store electricity. • The battery may not be able to store electricity for extended periods of time.	1
	(iv)	Any one: • Flow batteries can remain charged or uncharged for extended periods of time without loss of storage capacity. • The performance of flow batteries does not degrade with charge/recharge cycles. • Discharged electrolytes can easily be replaced with charged electrolytes.	1

Question	Part	Author's response	Marks
3	(a) (i)	$1s^2 2s^2 2p^6 3s^2 3p^6$	2
	(ii)	8–	2
	(iii)	$\text{Si}_3\text{O}_{10}^{4-}$, $x = 10$	1
	(b) (i)		1
	(ii)	Na_2SiO_3	2
	(iii)	Sodium cations (Na^+) adsorbed onto the negatively charged surface of soil silicate particles are held in an equilibrium system with hydrogen ions (H^+). When plants release H^+ ions into the soil, or the concentration of $[\text{H}^+]$ otherwise increases, they exchange with the Na^+ ions on the soil silicate, displacing the Na^+ into the soil solution. $\text{H}^+_{(\text{aq})} + \text{Na}^+_{(\text{clay})} \rightleftharpoons \text{H}^+_{(\text{clay})} + \text{Na}^+_{(\text{aq})}$ This displacement allows Na^+ ions to become available in the aqueous phase, where they can be absorbed by the plant roots.	1 1 1 1
	(iv)	Increased algal growth blocks sunlight, reducing photosynthesis for submerged plants, which subsequently die and decompose. The decomposition process consumes oxygen in the water, leading to oxygen depletion, which suffocates aquatic animals. Under anaerobic conditions, decay produces toxic substances like hydrogen sulfide and methane, further harming aquatic life and creating "dead zones" unsuitable for most organisms.	3
	(c) (i)	Any two: SRPs could improve soil fertility by replenishing nutrients. They provide essential macronutrients and micronutrients, reducing the need for synthetic fertilisers and supporting long-term soil health. SRPs could help reduce water pollution. Their ability to adsorb contaminants from water can mitigate the impact of agricultural runoff on nearby ecosystems. SRPs could contribute to climate change mitigation. They capture atmospheric CO_2 through chemical reactions, potentially lowering greenhouse gas levels. The largescale mining and transport of SRPs could have environmental downsides. These activities can lead to habitat destruction, energy consumption, and carbon emissions if not sustainably managed.	4
	(ii)	Any two: SRPs could reduce the money spent on synthetic fertilisers. By replenishing essential nutrients, they would lower dependence on other fertilisers. SRPs could increase crop yields and profitability. Enhanced soil fertility can lead to higher agricultural productivity and revenue for farmers. The initial cost of applying SRPs to soil could be high. Expenses related to mining, processing, and transportation of SRPs may pose a financial burden, especially for small-scale farmers. Use of SRPs in agriculture could create new economic opportunities elsewhere. Increased demand for SRPs may create jobs in mining, processing, and distribution sectors.	4

Question	Part	Author's response	Marks
4	(a)	As a composite, CFRP is stronger and lighter than alternative materials. It combines the strength of carbon fibre reinforcement with the low weight of the polymer matrix.	2
	(b)	CFRP's high strength-to-weight ratio reduces the overall weight of aircraft and racing cars, improving fuel efficiency and speed. Additionally, its strength enhances structural integrity and safety.	2
	(c)	CFRP is a composite material, requiring complex processes to separate the carbon fibres from the polymer matrix. In contrast, metals can be melted and reformed relatively easily without losing their properties.	1 1
5	(a)	Cross-linking in thermoset polymers creates a rigid, three-dimensional network that cannot be remelted or reshaped, making them difficult to recycle. In contrast, thermoplastics have linear or branched structures that can be melted and reformed, making them easier to recycle.	2
	(b)	Chemical recycling breaks down cross-links, allowing valuable materials such as fibres or monomers to be recovered and reused, reducing waste.	1
		The process can be energy-intensive, expensive, or require specific chemicals, limiting its scalability and environmental benefits.	1
	(c)	Cross-linking in epoxy resins creates strong chemical bonds between the molecules, forming a solid, interconnected network. This network makes the material stiff and resistant to bending or breaking.	1
6	(a)	Developing effective recycling processes for carbon fibre composites reduces the waste sent to landfills and avoids the production of new carbon fibres. This minimises resource consumption and decreases the environmental footprint associated with manufacturing.	2
	(b)	The high cost of producing carbon fibre encourages the development of recycling technologies in order to save money by reusing the material.	1
		Therefore, recycling could make carbon fibre cheaper and more accessible.	1
		This would help industries, including aviation and automotive, use lightweight materials more widely, improving fuel efficiency and performance.	1
	(c)	The advancement in composite recycling is the use of mild acids and solvents to break down the matrix while preserving the reinforcement fibres.	1
		This allows both the fibres and the matrix to be recovered and reused in new composites, reducing waste. This process conserves resources, lowers production costs, and reduces the environmental impact of composite disposal.	1 1
	(d)	Any three points plus an example: Society's focus on reducing waste and conserving natural resources has driven the development of technologies for recycling composites. Governments have implemented policies and regulations that encourage or mandate recycling of materials, spurring innovation in composite recycling processes. The economic benefits of reusing materials, such as reducing costs associated with raw materials and waste disposal, have motivated advancements in recycling technologies. Partnerships between scientists, engineers, industries, and governments have allowed the development of efficient recycling methods and new applications for recycled composites. Example: Recycled carbon-fibre composites can be used to manufacture lightweight car components, improving fuel efficiency and reducing overall emissions. Example: Recycled fibreglass composites can be repurposed for panels, flooring, or reinforcement materials in building construction. Example: Recycled composites can be used to manufacture lightweight and durable wind turbine blades, enhancing renewable energy production while reducing material waste.	4

Question	Part	Author's response	Marks
7	(a) (i)	$ \begin{array}{c} \text{H} & & \text{H} & & \text{H} \\ & \diagdown & & & \\ & \text{C} = \text{C} - & \text{C} - \text{H} \\ & & \\ & \text{H} & \text{H} \end{array} $  or	2
	(ii)	$ \begin{array}{cccc} \text{H} & \text{H} & \text{H} & \text{H} \\ & & & \\ -\text{C} & -\text{C} & -\text{C} & -\text{C}- \\ & & & \\ \text{H} & \text{CH}_3 & \text{H} & \text{CH}_3 \end{array} $	1
	(iii)	Addition	2
	(b) (i)	Polyolefins do not contain any cross-linking and are thermoplastic polymers.	1
		Thermoplastic polymers can be recycled by melting and reforming them.	1
	(c) (i)	methylpropene	2
	(ii)	$ \left[\begin{array}{cc} \text{CH}_3 & \text{H} \\ & \\ -\text{C} & -\text{C}- \\ & \\ \text{CH}_3 & \text{H} \end{array} \right]_n $	2
	(iii)	Any one: Converting plastic waste back into monomers reduces the need for fossil fuels to produce new plastics. This lowers greenhouse gas emissions and other pollution. It could also lower overall costs for manufacturers. Recycling plastics into monomers decreases the volume of plastic waste sent to landfills. This reduces waste management costs and the environmental impact of landfill.	2
	(1)	Catalysts increase the rate of a reaction... by providing an alternate reaction pathway... with lower activation energy. Catalysts also provide an environment where particles can orientate themselves correctly.	1 1 1
	(iv)	Any two of the following: Reduction in overall production costs, making processes more efficient and cost-effective. This allows industries to save money and improve profit margins. Reduction in the use of rare heavy metals, minimising the environmental impact of mining and extraction activities. This helps preserve ecosystems and reduces pollution from mining operations.	4
	(2)	Lowers energy requirements by enabling faster or lower-temperature reactions. This conserves energy resources and reduces greenhouse gas emissions. Aligns with societal demand for sustainable practices. This fosters innovation and public support for environmentally friendly solutions. Lowers cost of production supports equitable access to industrial innovations, especially for industries in developing nations. This helps bridge the gap in technological advancement between developed and developing regions.	

Question	Part	Author's response	Marks
7	(3)	Any four of the following points (or alternatives). The science must be clearly identified, and explicit links made to society (people). Application and Limitation A reduction in the amount of plastic entering landfills and oceans mitigates harm to ecosystems and biodiversity. By creating a method to efficiently recycle plastics, scientists provide a solution to reduce environmental pollution and resource depletion. By enabling plastics to be broken down into their original monomers, this approach creates a circular economy where resources are reused instead of discarded. This addresses a limitation of current recycling processes. Development The development of this method reflects the interdisciplinary nature of scientific progress, combining advances in polymer chemistry and process engineering. It shows how new technologies can reveal solutions to long-standing environmental challenges. Previous recycling methods for plastics had limits including high energy consumption or generation of secondary waste. The innovation of monomer recovery has overcome these issues, providing a pathway for plastics to be fully recycled without loss of quality. By creating a closed-loop system for polyolefin polymers, this approach reduces the demand for virgin plastic production and conserves finite resources such as fossil fuels. Over time, this development can lead to significant reductions in greenhouse gas emissions and other pollutants linked to climate change. This innovation highlights the role of collaboration between scientists, governments, and industries to promote sustainable practices. Public support for environmentally friendly solutions and economic incentives can further accelerate the adoption of such recycling technologies.	4

Appendices

Appendix 1: Molar Masses of the Elements

Name	Symbol	At. No.	At. Mass.	Name	Symbol	At. No.	At. Mass.
Actinium	Ac	89	227*	Mendelevium	Md	101	258*
Aluminum	Al	13	26.98	Mercury	Hg	80	200.6
Americium	Am	95	243*	Molybdenum	Mo	42	95.94
Antimony	Sb	51	121.8	Neodymium	Nd	60	144.2
Argon	Ar	18	39.95	Neon	Ne	10	20.18
Arsenic	As	33	74.92	Neptunium	Np	93	237.0
Astatine	At	85	210*	Nickel	Ni	28	58.71
Barium	Ba	56	137.3	Niobium	Nb	41	92.91
Berkelium	Bk	97	245*	Nitrogen	N	7	14.01
Beryllium	Be	4	9.012	Nobelium	No	102	255*
Bismuth	Bi	83	208.9	Osmium	Os	76	190.2
Bohrium**	Bh	107	272	Oxygen	O	8	16.00
Boron	B	5	10.81	Palladium	Pd	46	105.4
Bromine	Br	35	79.90	Phosphorus	P	15	30.97
Cadmium	Cd	48	112.4	Platinum	Pt	78	195.1
Calcium	Ca	20	40.08	Plutonium	Pu	94	244*
Californium	Cf	98	248*	Polonium	Po	84	209*
Carbon	C	6	12.01	Potassium	K	19	39.102
Cerium	Ce	58	140.1	Praseodymium	Pr	59	140.9
Cesium	Cs	55	132.9	Promethium	Pm	61	145*
Chlorine	Cl	17	35.45	Protactinium	Pa	91	231.0
Chromium	Cr	24	52.00	Radium	Ra	88	226.0
Cobalt	Co	27	58.93	Radon	Rn	86	222*
Copper	Cu	29	63.55	Rhenium	Re	75	186.2
Curium	Cm	96	245*	Rhodium	Rh	45	102.9
Damstadtium	Ds	110	271	Roentgenium	Rg	111	272
Dubnium	Db	105	262	Rubidium	Rb	37	85.47
Dysprosium	Dy	66	162.5	Rutherfordium	Rf	104	261
Einsteinium	Es	99	254*	Ruthenium	Ru	44	101.1
Erbium	Er	68	167.3	Samarium	Sm	62	150.4
Europium	Eu	63	152.0	Scandium	Sc	21	44.96
Fermium	Fm	100	254*	Seaborgium	Sg	106	271
Fluorine	F	9	19.0	Selenium	Se	34	78.96
Francium	Fr	87	223*	Silicon	Si	14	28.09
Gadolinium	Gd	64	157.3	Silver	Ag	47	107.9
Gallium	Ga	31	69.72	Sodium	Na	11	22.99
Germanium	Ge	32	72.59	Strontium	Sr	38	87.62
Gold	Au	79	197.0	Sulphur	S	16	32.064
Hafnium	Hf	72	178.5	Tantalum	Ta	73	180.9
Hassium	Hs	108	277	Technetium	Tc	43	99*
Helium	He	2	4.003	Tellurium	Te	52	127.6
Holmium	Ho	67	164.9	Terbium	Tb	65	158.9
Hydrogen	H	1	1.008	Thallium	Tl	81	204.4
Indium	In	49	114.8	Thorium	Th	90	232.0
Iodine	I	53	126.9	Thulium	Tm	69	168.9
Iridium	Ir	77	192.2	Tin	Sn	50	118.7
Iron	Fe	26	55.85	Titanium	Ti	22	47.90
Krypton	Kr	36	83.80	Tungsten	W	74	183.9
Lanthanum	La	57	138.9	Uranium	U	92	238.0
Lawrencium	Lw	103	260*	Vanadium	V	23	50.94
Lead	Pb	82	207.2	Xenon	Xe	54	131.3
Lithium	Li	3	6.941	Ytterbium	Yb	70	173.0
Lutetium	Lu	71	175.0	Yttrium	Y	39	88.91
Magnesium	Mg	12	24.31	Zinc	Zn	30	65.38
Manganese	Mn	25	54.94	Zirconium	Zr	40	91.22
Meitnerium	Mt	109	268				

* **Mass number of most stable isotope Source of Information:** Atomic weights of the elements 2005 (IUPAC Technical Report) (*Pure Appl. Chem.*, 2006, Vol. 78, No. 11, pp. 2051–2066)

Appendix 2: The Periodic Table of Elements

1	2																
1	2	3	4	5	6	7	8	9	10								
H hydrogen [1.007, 1.008]	He helium 4.003																
3	4																
Li lithium [6.938, 6.997]	Be beryllium 9.012																
11	12																
Na sodium 22.99	Mg magnesium [24.30, 24.31]																
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K potassium 39.10	Ca calcium 40.08	Sc scandium 44.96	Ti titanium 47.87	V vanadium 50.94	Cr chromium 52.00	Mn manganese 54.94	Fe iron 55.85	Co cobalt 58.93	Ni nickel 58.69	Cu copper 63.55	Zn zinc 65.38(2)	Ga gallium 69.72	Ge germanium 72.63	As arsenic 74.92	Se selenium 78.97	Br bromine [79.90, 79.91]	Kr krypton 83.80
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb rubidium 85.47	Sr strontium 87.62	Y yttrium 88.91	Zr zirconium 91.22	Nb niobium 92.91	Mo molybdenum 95.95	Tc technetium	Ru ruthenium 101.1	Rh rhodium 102.9	Pd palladium 106.4	Ag silver 107.9	Cd cadmium 112.4	In indium 114.8	Sn tin 118.7	Sb antimony 121.8	Te tellurium 127.6	I iodine 126.9	Xe xenon 131.3
55	56	57-71 lanthanoids	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Cs caesium 132.9	Ba barium 137.3		Hf hafnium 178.5	Ta tantalum 180.9	W tungsten 183.8	Re rhenium 186.2	Os osmium 190.2	Ir iridium 192.2	Pt platinum 195.1	Au gold 197.0	Hg mercury 200.6	Tl thallium [204.3, 204.4]	Pb lead 207.2	Bi bismuth 209.0	Po polonium	At astatine	Rn radon
87	88	89-103 actinoids	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Fr francium	Ra radium		Rf rutherfordium	Db dubnium	Sg seaborgium	Bh bohrium	Hs hassium	Mt meitnerium	Ds darmstadtium	Rg roentgenium	Cn copernicium	Nh nihonium	Fl flerovium	Mc moscovium	Lv livermorium	Ts tennessine	Og oganesson

57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.3	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.0	71 Lu lutetium 175.0
89 Ac actinium	90 Th thorium 232.0	91 Pa protactinium 231.0	92 U uranium 238.0	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium	103 Lr lawrencium

Lanthanide Series

Actinide Series

Appendix 3: SI prefixes, symbols and values

The following table, shows SI prefixes, their symbols and their values, and is useful when answering questions that involve the conversion of units:

SI Prefix	tera	giga	mega	kilo	centi	milli	micro	nano	pico
Symbol	T	G	M	k	c	m	μ	n	p
Value	10^{12}	10^9	10^6	10^3	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}