**VCE CHEMISTRY UNIT 3 & 4**
Australian Curriculum

**WORKBOOK**

# Chemistry

## TOPICS

**UNIT 3: HOW CAN DESIGN AND INNOVATION HELP TO OPTIMISE CHEMICAL PROCESSES?**

Area of Study 1: What are the current and future options for supplying energy?

Area of Study 2: How can the rate and yield of chemical reactions be optimised?

**UNIT 4: HOW ARE CARBON-BASED COMPOUNDS DESIGNED FOR PURPOSE?**

Area of Study 1: How are organic compounds categorised and synthesised?

Area of Study 2: How are organic compounds analysed and used?



SASTA South Australian Science Teachers Association
Supporting Teachers of Science
**Advancing Science Education**


**FIRST EDITION**


Rhys Lewis

# Contents

## UNIT 3: HOW CAN DESIGN AND INNOVATION HELP TO OPTIMISE CHEMICAL PROCESSES?

### Area of Study 1:
### What are the current and future options for supplying energy?



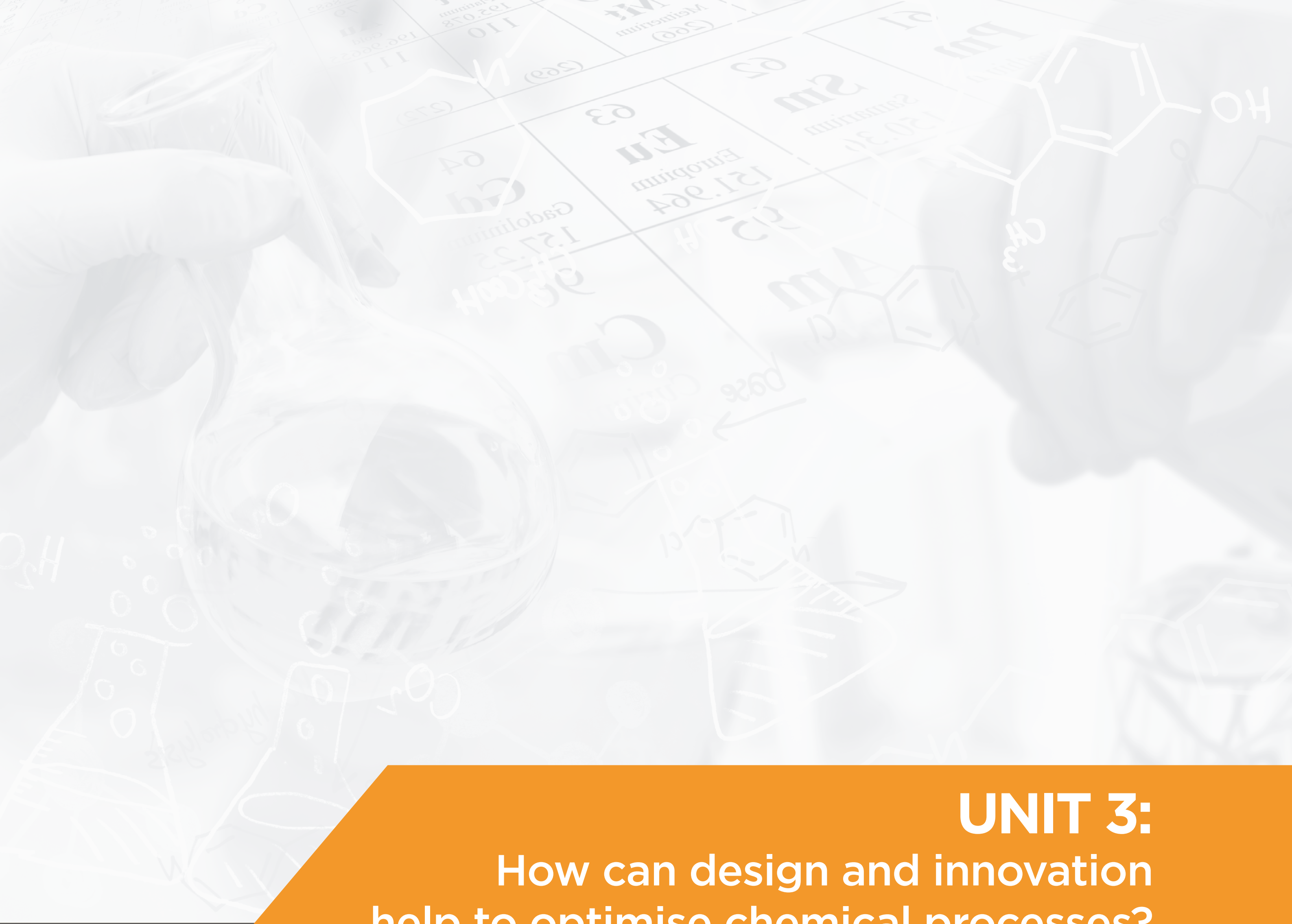
### Area of Study 2:
### How can the rate and yield of chemical reactions be optimised?

## UNIT 4: HOW ARE CARBON-BASED COMPOUNDS DESIGNED FOR PURPOSE?

### Area of Study 1:
### How are organic compounds categorised and synthesised?



### Area of Study 2:
### How are organic compounds analysed and used?



# UNIT 3:
## How can design and innovation help to optimise chemical processes?

### AREA OF STUDY 1: What are the current and future options for supplying energy?

#### 3.1 Carbon-based fuels

## 3.1 Carbon-Based Fuels

### 3.1.1 Fuels

Discuss the definition of a fuel, including the distinction between fossil fuels (coal, natural gas, petrol) and biofuels (biogas, bioethanol, biodiesel) with reference to their renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)



A **fuel** is a substance that stores energy in its molecular structure, which can be released in a controlled manner through combustion. Fuels are typically reduced substances, meaning they have a high proportion of hydrogen or carbon atoms that undergo oxidation when burned. Common examples include hydrogen ($H_2$), carbon (C), methane ($CH_4$), and octane ($C_8H_{18}$), all of which react with oxygen during combustion to release energy.

## Fossil Fuels

**Fossil fuels**, including **coal**, **petroleum**, and **natural gas**, are the primary energy sources that have powered human civilisation for centuries. These carbon-based fuels formed over millions of years through the anaerobic decomposition of dead plants, animals, and microorganisms subjected to intense heat and pressure beneath the Earth's surface (see Figure 3.01).

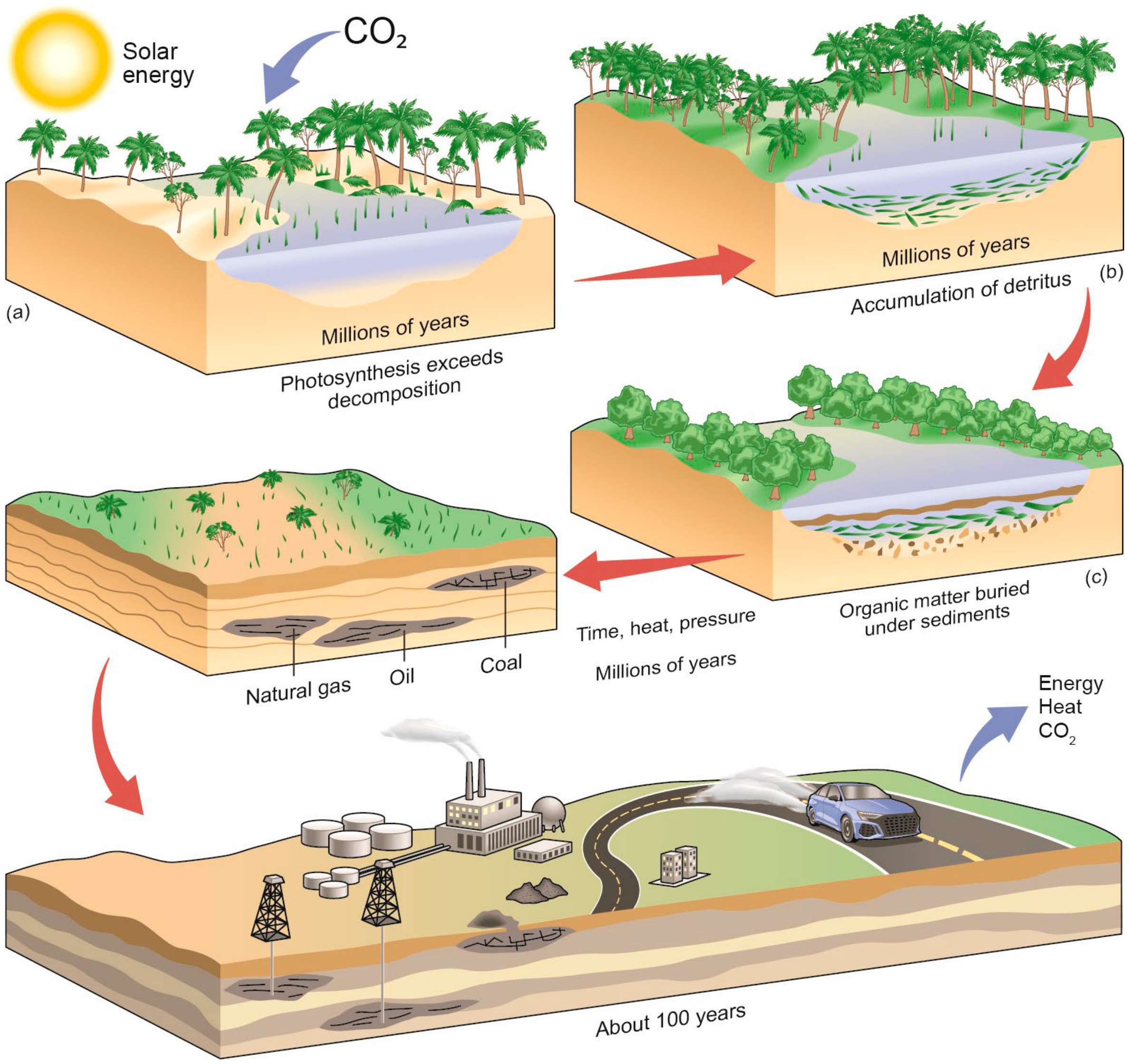



Figure 3.01: Fossil fuel formation and extraction

Fossil fuels are complex mixtures of hydrocarbons that release energy through combustion (see Figure 3.02). These fuels currently provide over 85% of the world's energy, supporting modern infrastructure, economic growth, and global development. Their high energy density and reliability make them essential for transportation, electricity generation, and industrial processes.

However, the extraction, processing, and combustion of fossil fuels produce carbon dioxide ($CO_2$), a major greenhouse gas responsible for global warming and climate change. Additionally, because fossil fuels take millions of years to form, they are **non-renewable** resources with a finite supply (see Figure 3.03). As global energy demands continue to rise, concerns about resource depletion and environmental impact have led to increased efforts in developing cleaner, more sustainable energy alternatives.

| Thermochemical Equation | |
|---|---|
| **Coal** | |
| $C_{(s)} + \frac{1}{2}O_{2(g)} \rightarrow CO_{(g)}$ | $\Delta H = -111\ kJ\ mol^{-1}$ |
| $C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$ | $\Delta H = -394\ kJ\ mol^{-1}$ |
| $CO_{(g)} + \frac{1}{2}O_{2(g)} \rightarrow CO_{2(g)}$ | $\Delta H = -283\ kJ\ mol^{-1}$ |
| $H_{2(g)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(g)}$ | $\Delta H = -286\ kJ\ mol^{-1}$ |
| **Petroleum** | |
| $C_6H_{6(l)} + \frac{15}{2}O_{2(g)} \rightarrow 3H_2O_{(l)} + 6CO_{2(g)}$ | $\Delta H = -3270\ kJ\ mol^{-1}$ |
| $C_8H_{18(l)} + \frac{25}{2}O_{2(g)} \rightarrow 9H_2O_{(l)} + 8CO_{2(g)}$ | $\Delta H = -5054\ kJ\ mol^{-1}$ |
| **Natural gas** | |
| $CH_{4(g)} + 2O_{2(g)} \rightarrow 2H_2O_{(l)} + CO_{2(g)}$ | $\Delta H = -890\ kJ\ mol^{-1}$ |
| $C_2H_{6(g)} + \frac{7}{2}O_{2(g)} \rightarrow 3H_2O_{(l)} + 2CO_{2(g)}$ | $\Delta H = -1560\ kJ\ mol^{-1}$ |

Figure 3.02: Combustion of fossil fuels

| Fossil fuel | Reserves ($\times 10^{12}$ kg) | Consumption ($\times 10^{12}$ kg/y) | Predicted lifetime (y) |
|---|---|---|---|
| **Coal** | 1033 | 7.77 | 133 |
| **Petroleum** | 224 | 4.82 | 47 |
| **Natural gas** | 163 | 3.12 | 52 |

Figure 3.03: Fossil fuel reserves

## Biofuels

**Biofuels** are renewable energy sources derived from biological materials such as plants, algae, and organic waste (Figure 3.04). Unlike fossil fuels, which take millions of years to form, biofuels can be produced continuously and naturally replenished within short time frames, making them a more sustainable alternative.

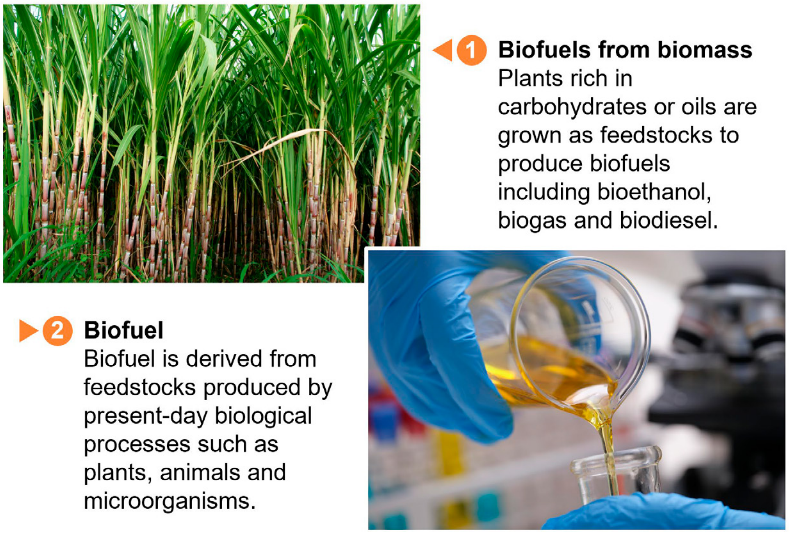



Figure 3.04: Biofuels

They are categorised into three generations based on their source and production method. **First-generation** biofuels come from food crops like corn and sugarcane, while **second-generation** biofuels are derived from non-food sources such as agricultural waste and cellulose. **Third-generation biofuels** are produced from algae and other fast-growing biomass, offering an even more efficient and scalable solution for renewable energy. Two of the most widely used biofuels are bioethanol and biodiesel, both of which may be classified as first or second-generation biofuels depending on their source.

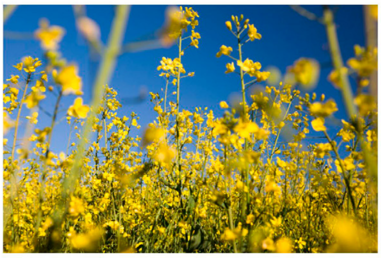
**Bioethanol** ($C_2H_5OH$) is primarily produced through anaerobic fermentation of sugar-rich and starchy crops such as corn, sugarcane, and wheat (see Chapter 3.1.5). It can also be derived from wood and agricultural waste, making it a versatile biofuel. The main application of bioethanol is as a fuel additive to reduce petrol dependency (see Figure 3.05). The biofuel is blended with petrol to create ethanol-petrol mixtures such as E10 (10% ethanol, 90% petrol) and E20 (20% ethanol, 80% petrol), which help conserve petroleum reserves. These blends offer similar cost and energy efficiency to petrol while producing lower carbon dioxide emissions, thereby reducing the environmental impact and contributing to the mitigation of global warming and climate change.


**1 Bioethanol at pumps**
Biothanol is mixed with petrol to form mixtures such as E10 (10% ethanol) that burn cleaner and reduce fossil fuel consumption.


**2 Comparable prices**
Bioethanol blends such as E10 have similar prices to traditional unleaded petrol (ULP) and similar fuel economy.

Figure 3.05: Bioethanol fuels

**Biodiesel** is produced through the transesterification of vegetable oils such as soybean, palm, and rapeseed oil (see Figure 3.06) or from waste cooking oil and animal fats, making it a sustainable alternative to petroleum diesel. In the transesterification process, organic compounds called triglycerides react with methanol or ethanol, forming methyl or ethyl esters, which make up biodiesel. The primary use of biodiesel is as a replacement for petroleum diesel, helping to reduce dependence on fossil fuels while powering vehicles and electric generators in a more environmentally friendly manner.



**1 Biodiesel sources**
Biodiesel is sourced primarily from triglycerides in plant oils including rapeseed oil, palm oil and soybean oil.


**2 Biodiesel fuel**
Biodiesel has similar fuel economy and offers cleaner combustion, and reduced emissions, making it a more environmentally friendly alternative to petroleum diesel.

Figure 3.06: Biodiesel fuels

**Biogas** is a second-generation biofuel produced from organic waste, including agricultural residues, manure, and food waste. It is generated through anaerobic digestion, a process in which microorganisms break down biodegradable materials, releasing a methane-rich gas that can be used as a renewable energy source. Unlike first-generation biofuels, biogas does not rely on food crops, making it a more sustainable and environmentally friendly alternative to fossil fuels.

As global energy demands rise and concerns over climate change and resource depletion intensify, biofuels are increasingly being used to replace fossil fuels in transportation, electricity generation, and industrial applications. The primary advantage of biofuels is their lower carbon footprint. Plants and algae absorb $CO_2$ from the atmosphere as they grow, which offsets the $CO_2$ emitted in their combustion, making them carbon-neutral or low-emission alternatives. Additionally, biofuels reduce dependence on oil imports, enhance energy security, and create economic opportunities in agriculture and biofuel production.

Despite their benefits, biofuels face challenges, including land use concerns, competition with food production, and energy-intensive processing methods. Scientists are currently investigating methods of improving the energy efficiency of biofuels, including their production methods, environmental impact, and their potential role in transitioning toward a more sustainable energy future.

## Question 1

Biofuels are emerging as sustainable alternatives to fossil fuels, contributing to renewable energy production, reduced carbon emissions, and energy security in Australia's transportation and electricity sectors.

Which one of the following is a biofuel?

- ◯ A Methane from natural gas
- ◯ B Octane from petroleum
- ◯ C Hydrogen from coal
- ◯ D Methyl palmitate from plant oils

(1 mark)

## Question 2

Methane can be sourced from various origins. It is the primary component of natural gas and exists in coal deposits as coal seam gas, which can be extracted by drilling. In addition, large reserves of methane are stored in ice as methane hydrates. More recently, methane has been generated through the microbial decomposition of organic matter from plants and animals.

Methane is considered a renewable energy source when it is derived from

- ◯ A Coal seam gas
- ◯ B Natural gas
- ◯ C Microbial decomposition
- ◯ D Methane hydrates

(1 mark)

## Question 3

A renewable energy resource

- ◯ A is naturally replenished on a short timescale through biological or geological processes.
- ◯ B provides unlimited energy and never requires replenishment.
- ◯ C produces no environmental impact when used for electricity generation.
- ◯ D can be regenerated through natural processes faster than it is consumed.

(1 mark)

## Question 4

Consider the following statements about biofuels.

I. The production of biofuels does not damage the environment.
II. The combustion of both biofuels generates greenhouse gases.
III. Biofuels are renewable as they are replaced by natural processes over short timescales.

Which of the statements above are correct?

- ◯ A I and III only
- ◯ B II and III only
- ◯ C I and II only
- ◯ D III only

(1 mark)

## Question 5

Petrol, also called gasoline, is the primary fuel used in motor vehicles.


(a) Define a fuel using the example of petrol.

(1 mark)

(b) Petrol is derived from the fossil fuel petroleum.

i. Describe the formation of fossil fuels.

(2 marks)

ii. Global petroleum reserves are predicted to be exhausted in the next 50 years.

Explain why it is not possible to produce more petroleum.

(1 mark)

(c) In many countries, ethanol is being added to petrol to produce blended fuels.

Ethanol is produced by the fermentation of carbohydrates derived from plants.

i. Explain why ethanol produced by fermentation is referred to as a biofuel.

(1 mark)

ii. State one advantage to society of blending ethanol with petrol.

(1 mark)

iii. State one advantage to the environment of blending ethanol with petrol.

(1 mark)

## Question 6

Coal and natural gas are fossil fuels used to generate electricity.

(a) Currently, most of Victoria's electricity is generated by burning coal and natural gas.

i. State one advantage of using coal and natural gas to generate electricity.

(1 mark)

ii. State one disadvantage of using coal and natural gas to generate electricity.

(1 mark)

(b) Biofuels, including bioethanol and biodiesel can be used to generate electricity.

Both bioethanol and biodiesel are derived from plants.

i. State why bioethanol and biodiesel are described as renewable energy sources.

(1 mark)

ii. Explain why generating electricity from bioethanol and biodiesel results in lower carbon dioxide emissions compared to using coal and natural gas.

(2 marks)

iii. Describe two challenges associated with replacing coal and natural gas with bioethanol and biodiesel for electricity generation.

(2 marks)

## Question 7

Methane is a fuel obtained from natural gas deposits or biomass such as decomposing plant matter.

(a) Explain which of these sources of methane would be considered more sustainable.

(2 marks)

(b) Compare the environmental impact of methane sourced from decomposing plant matter with those of methane extracted from natural gas reserves.

(2 marks)

## 3.1.2 Fuel sources for the body

Explore fuel sources for the body, including carbohydrates, proteins and lipids (fats and oils). The energy content of these fuels is measured in kilojoules per gram, kJ $g^{-1}$



The human body requires a continuous supply of energy to sustain essential functions such as movement, growth, repair, and metabolism. This energy is obtained from three primary macronutrients: **carbohydrates**, **proteins**, and **lipids** (fats and oils). Each of these biological fuel sources plays a unique role in the body, providing energy at different rates and efficiencies.

### Carbohydrates

Carbohydrates are naturally occurring organic compounds in the cells and tissues of living things. All living things use carbohydrates for **respiration**, an energy-releasing reaction, and to produce complex macromolecules that store energy. The term "carbohydrate" is used interchangeably with the terms "**saccharide**" and "**sugar**". Most carbohydrates contain carbon, hydrogen, and oxygen in a ratio of 1:2:1, with molecular formulas satisfying the expression $C_n(H_2O)_y$ or $C_xH_{2y}O_y$. Some examples of carbohydrates satisfying this definition are ribose, $C_5H_{10}O_5$, glucose, $C_6H_{12}O_6$, and sucrose, $C_{12}H_{22}O_{11}$.

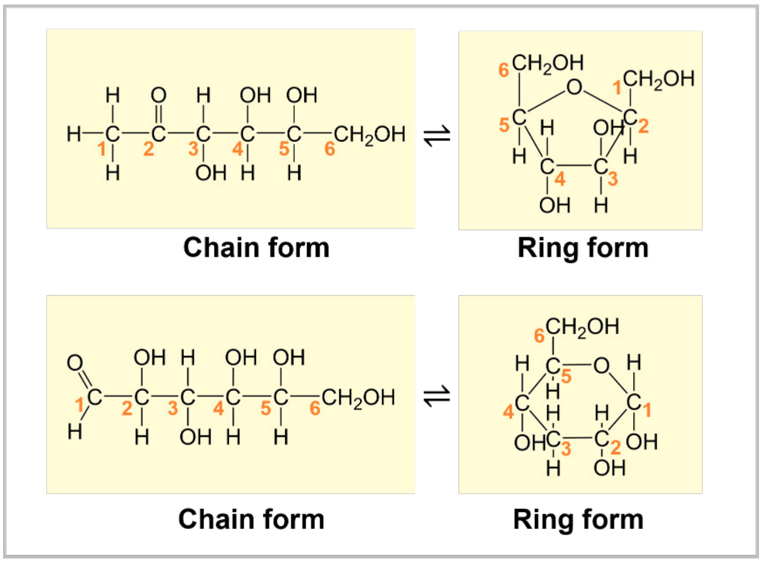



Figure 3.07: Cyclisation of carbohydrates

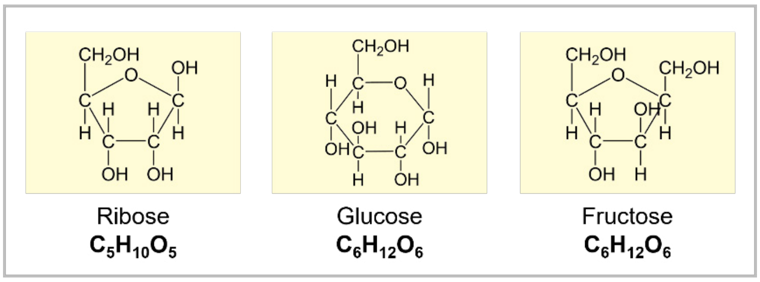



Figure 3.08: Monosaccharides

When carbohydrate molecules with five or six carbon atoms are transferred to water or an aqueous solution such as blood or body tissues, they undergo cyclisation, a type of reaction in which the linear structure changes to a cyclic (ring) structure that no longer contains a carbonyl group. For example, Figure 3.07 shows the cyclisation of fructose (top) and glucose (bottom). An equilibrium is established between the chain and ring forms of these carbohydrates in an aqueous solution. The cyclic forms of carbohydrates can connect in one of several ways to produce chains of varying lengths. These chains are still referred to as carbohydrates and are classified by the number of subunits that comprise them.

**Monosaccharides** are composed of one subunit in cyclic or ring form that cannot be broken down into simpler compounds. These sugars typically contain between three and nine carbon atoms, with the most common containing five or six. Examples of monosaccharides include ribose, glucose, and fructose (see Figure 3.08). The most important of these carbohydrates for the body is glucose. When a person consumes a carbohydrate-rich meal, the food is digested, and glucose molecules are absorbed into the blood, where they are transported to cells for respiration (see Chapter 3.1.4).

Many foodstuffs also contain **disaccharides**, carbohydrates produced by the condensation reaction of two monosaccharides. For example, maltose is a disaccharide produced in the reaction of two glucose subunits, and sucrose is a disaccharide produced in the reaction of glucose and fructose (see Figure 3.09). The condensation reaction produces a covalent chemical bond between the monosaccharides called a **glycosidic bond**. When food is consumed and digested, disaccharides are absorbed into the cells of the small intestine, where they are converted to monosaccharides by a reaction with water called **hydrolysis**.

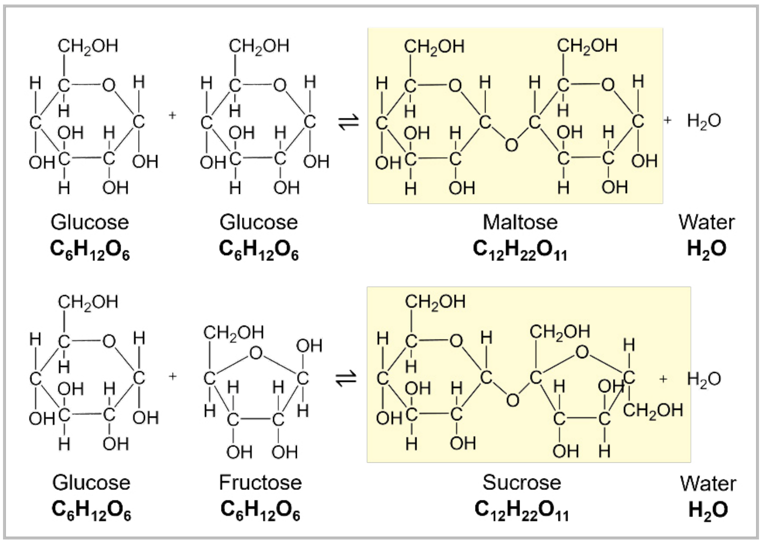



Figure 3.09: Disaccharides

**Polysaccharides** are carbohydrates composed of more than two monosaccharide subunits, with some containing as many as 10,000. Polysaccharides are produced in the condensation of many monosaccharide subunits, which occurs in living things. For example, photosynthesis produces glucose molecules that are assembled into different polysaccharides in plant cells. First, glucose monomers are assembled into **starch** $(C_6H_{10}O_5)_n$; a polysaccharide plants use to store glucose for respiration. Second, glucose monomers are arranged into **cellulose**, a polysaccharide comprising the cell walls of plant cells. Humans cannot utilise cellulose for energy as they lack the enzyme essential to its digestion. Figure 3.10 shows sections of starch and cellulose, their repeating units, and monomers. In animals, the liver and muscles assemble glucose subunits into **glycogen**, a polysaccharide that stores glucose for respiration. When animals have low blood glucose, a hormone stimulates enzymes in liver and muscle cells to catalyse the hydrolysis of glycogen, thereby releasing glucose molecules that diffuse into the blood. Enzymes facilitate the formation of polysaccharides and their hydrolysis in animals and plants.

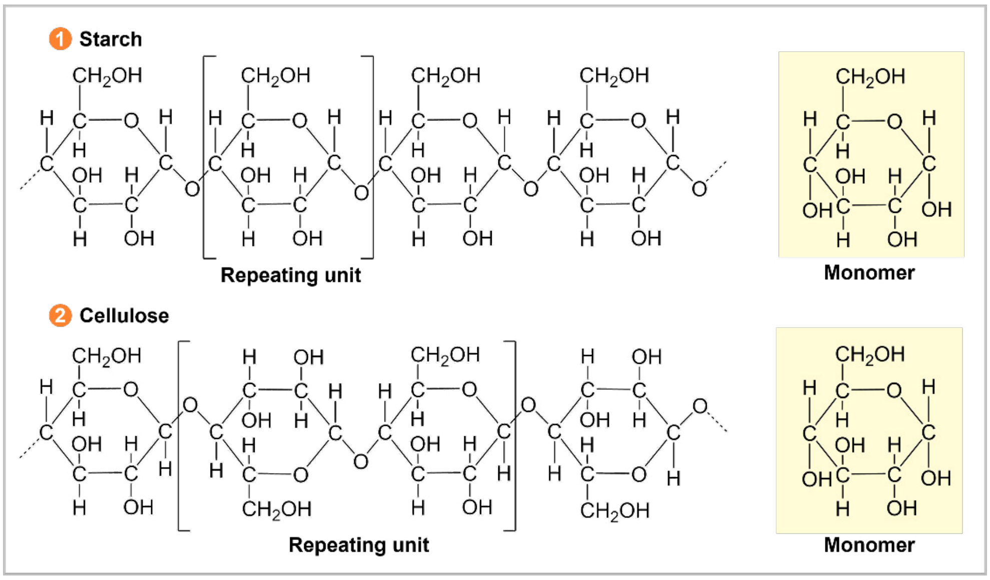



Figure 3.10: Polysaccharides

Carbohydrates are the body's preferred energy source because they can be quickly broken down into glucose, the primary fuel for cellular respiration (see Chapter 3.1.4). They are found in foods such as bread, rice, fruits, and vegetables and provide approximately 16 kJ g$^{-1}$ of energy. During digestion, carbohydrates are converted into glucose, which enters the bloodstream and is either immediately used for energy or stored as glycogen in the liver and muscles for later use. The brain and skeletal muscles are highly dependent on glucose. The brain consumes about 20-25% of total blood glucose, while skeletal muscles use 10-20% at rest and up to 80% during intense exercise.

## Lipids

Lipids, including fats and oils, are organic compounds comprised of molecules called **triglycerides** and **fatty acids** (see Figure 3.11). Both fatty acids and triglycerides are composed of molecules containing many carbon-carbon bonds. When the molecule has single carbon-carbon bonds only, the compound is **saturated,** and when one or more carbon-carbon double bonds are present, the compound is **unsaturated** (see Figure 3.12). Edible fats are comprised primarily of saturated fatty acids and triglycerides, whereas edible oils are comprised primarily of unsaturated fatty acids and triglycerides.

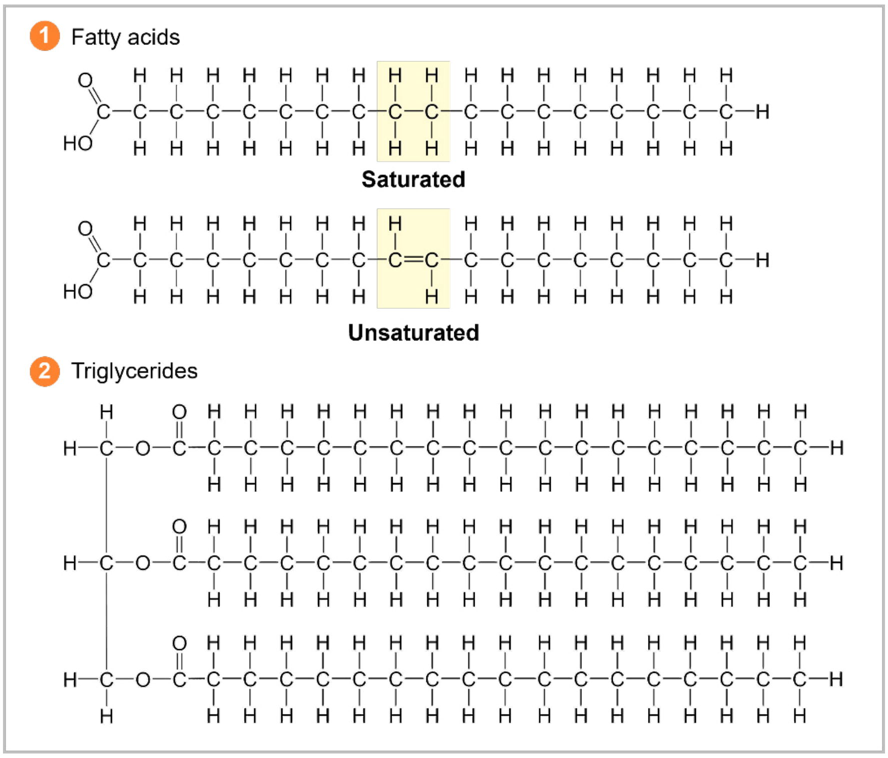



Figure 3.11: Fatty acids and triglycerides

Fats and oils are present in foods such as butter, nuts, oils, and dairy products. When consumed and digested, fats and oils are broken down slowly by **lipolysis**, a hydrolysis reaction catalysed by **lipase** enzymes in the small intestine that converts triglycerides into glycerol and fatty acids (see Figure 3.13). The fatty acids are then transported to cells, where they are broken down by oxidation, releasing energy.

| Fatty acid | Semi-structural formula |
|---|---|
| **1 Saturated fatty acids** | |
| Myristic acid | $CH_3(CH_2)_{12}COOH$ |
| Palmitic acid | $CH_3(CH_2)_{14}COOH$ |
| Stearic acid | $CH_3(CH_2)_{16}COOH$ |
| Arachidic acid | $CH_3(CH_2)_{18}COOH$ |
| **2 Unsaturated fatty acids** | |
| Palmitoleic acid | $CH_3(CH_2)_5CH=CH(CH_2)_7COOH$ |
| Oleic acid | $CH_3(CH_2)_7CH=CH(CH_2)_7COOH$ |
| Linoleic acid | $CH_3(CH_2)_4CH=CHCH_2CH=CH(CH_2)_7COOH$ |
| Linolenic acid | $CH_3CH_2CH=CHCH_2CH=CHCH_2CH=CH(CH_2)_7COOH$ |

Figure 3.12: Formulas of some fatty acids

Lipids are the most energy-dense fuel source for the body, providing around 37 kJ $g^{-1}$. They are stored in the body in adipose tissue and mobilised when needed. Unlike glycogen, fat stores are virtually unlimited and provide energy for extended periods. Lipids are used for sustained energy needs, such as during prolonged exercise, fasting, or low-carbohydrate intake.

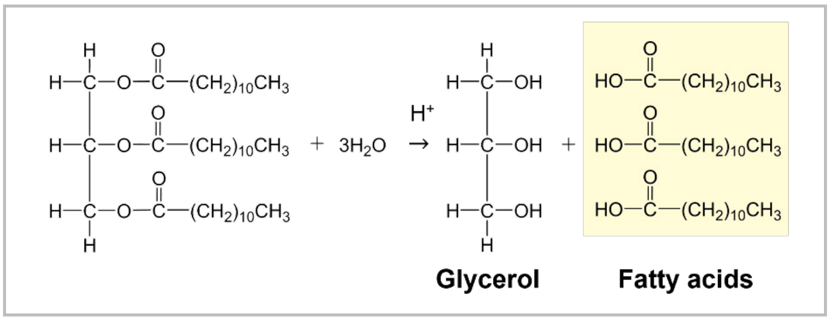



Figure 3.13: Hydrolysis of triglyceride.

## Proteins

Proteins are organic compounds composed of polymer molecules produced in the condensation reaction of monomers called **amino acids**. In the condensation reaction, the carboxyl group of one amino acid reacts with the amine group of another amino acid to produce a **peptide group** and water. Figure 3.14 shows the assembly of several amino acids into a section of a protein molecule.

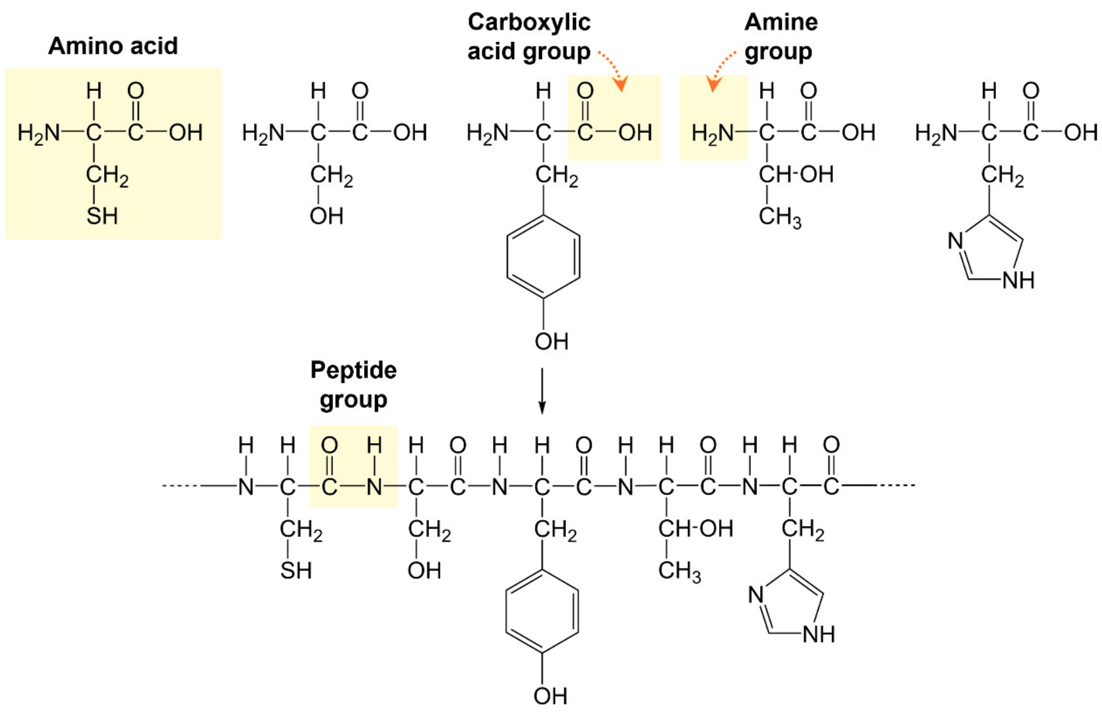



Figure 3.14: Assembly of several amino acids into a section of a protein.

Proteins primarily function in growth, repair, immunity, and enzymatic activity, but under certain conditions, they can also serve as an energy source. They are found in a variety of foods, including meat, fish, eggs, and legumes. When consumed, proteins are digested by **protease** enzymes, which break them down into amino acids (see Figure 3.15). These amino acids are then transported to the liver, where the amino groups are removed in a process called **deamination**, producing ammonia ($NH_3$) as a byproduct. The remaining carbon skeleton is converted into glucose or another energy-rich organic compound, which is then metabolised to release energy.

Proteins provide 17 kJ $g^{-1}$ of energy, a value comparable to carbohydrates, but their breakdown is less efficient. When carbohydrate and fat stores are depleted, the body utilises muscle proteins for energy, leading to significant physiological consequences. Muscle mass declines, making physical activities more challenging, while immune function weakens, increasing susceptibility to infections and slowing wound healing. Additionally, liver and kidney function can become impaired due to the high production of ammonia and urea, byproducts of excessive protein breakdown. This highlights the importance of maintaining sufficient carbohydrate and fat reserves to prevent reliance on protein as a primary energy source.

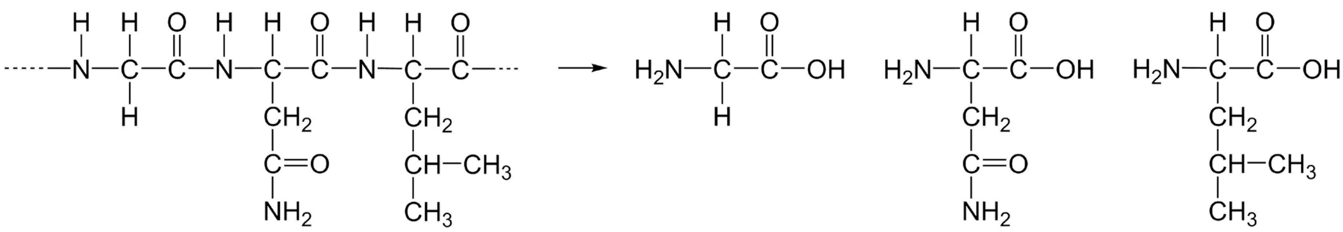


Figure 3.15: Breakdown of proteins into amino acids

## Question 8

Carbohydrates can be present in the body in many forms.

Which one of the following is a polysaccharide that stores energy in the human body?

- ◯ A Glucose
- ◯ B Cellulose
- ◯ C Starch
- ◯ D Glycogen

(1 mark)

## Question 9

Carbohydrates, fats and proteins are molecular compounds comprised of various elements.

Which one of the following elements is found in proteins but not carbohydrates or fats?

- ◯ A Carbon
- ◯ B Nitrogen
- ◯ C Oxygen
- ◯ D Hydrogen

(1 mark)

## Question 10

Fats and oils

I. are composed of molecules that may be saturated or unsaturated.
II. are only present in foods derived from animals.
III. contain more energy per gram than carbohydrates and proteins.

Which of the statements above is correct?

- ◯ A I and III only
- ◯ B II and III only
- ◯ C I and II only
- ◯ D III only

(1 mark)

## Question 11

Lactose is a disaccharide present in milk products. The digestion of lactose

- ◯ A produces a polysaccharide
- ◯ B produces glycosidic bonds
- ◯ C produces water molecules
- ◯ D produces monosaccharides

(1 mark)

## Question 12

Which one of the following statements about proteins is *incorrect*?

- ◯ A They are composed of amino acids joined by peptide bonds.
- ◯ B They can be directly used as an energy source without being digested.
- ◯ C They contain more energy per gram than carbohydrates.
- ◯ D They are composed of larger molecules than fats and oils.

(1 mark)

## 3.1.3 Photosynthesis

Describe photosynthesis as a process that converts light into chemical energy and as a source of glucose and oxygen for respiration in living things: $6CO_{2\,(g)} + 6H_2O_{(l)} \rightarrow C_6H_{12}O_{6\,(aq)} + 6O_{2\,(g)}$.



Living things require an energy source to power all activities occurring in their cells. In most living things, the primary energy source is the carbohydrate glucose ($C_6H_{12}O_6$), which is broken down in a series of chemical reactions to release the energy stored within the molecule. Scientists classify living things into one of two categories based on how they obtain glucose. One class of living things, called **autotrophs**, synthesise glucose using inorganic compounds in their environment, while a second class, called **heterotrophs**, obtain glucose by consuming and digesting other living things.

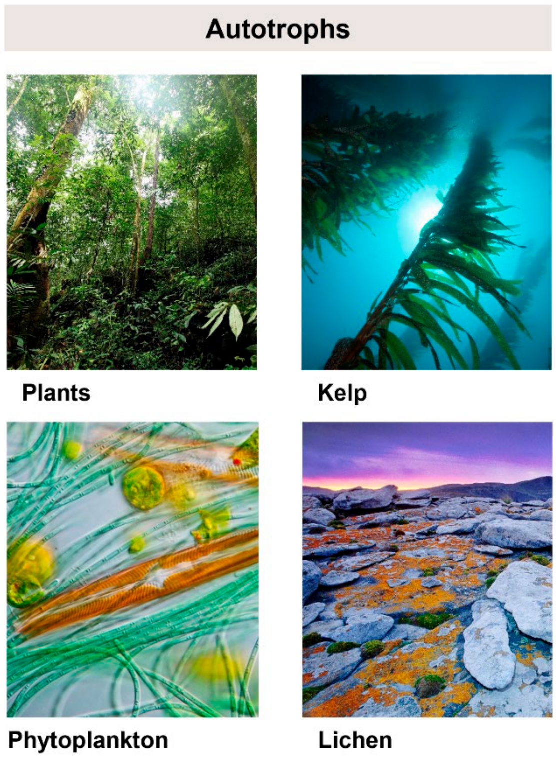



Figure 3.16: Autotrophs

**Photosynthesis** is a fundamental biological process that allows autotrophs (Figure 3.16), including plants, phytoplankton, kelp, lichen, algae, and some bacteria, to synthesise glucose ($C_6H_{12}O_6$), which serves as an energy source for themselves and other living things. Photosynthesis is a complex process involving more than twenty chemical reactions, but the overall process is summarised by the balanced equation below.

$$6CO_{2\,(g)} + 6H_2O_{(l)} \rightarrow C_6H_{12}O_{6\,(aq)} + 6O_{2\,(g)}$$

This equation illustrates that during photosynthesis, carbon dioxide ($CO_2$) and water ($H_2O$) are converted into glucose ($C_6H_{12}O_6$) and oxygen ($O_2$). Photosynthesis is an **endothermic** process, meaning it requires a net absorption of energy from the surroundings. The primary energy source is sunlight, which is captured by light-absorbing pigments. In green plants, phytoplankton, and algae, the pigment **chlorophyll** absorbs sunlight and converts it to chemical energy, enabling the synthesis of glucose and the release of oxygen.

Autotrophs, also known as **primary producers**, play a fundamental role in ecosystems by synthesising glucose, which serves as the primary energy source for all other organisms in the food chain (see Figure 3.17). The glucose produced can either be immediately used in cellular respiration to generate energy or stored as starch for future use. Additionally, the oxygen released as a byproduct of photosynthesis is essential for aerobic respiration in both plants and animals, supporting energy production at multiple levels of the ecosystem.

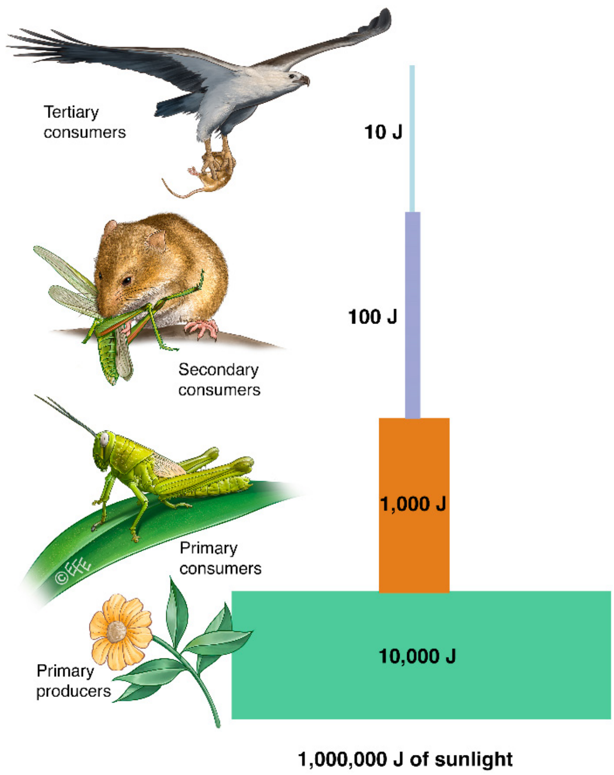



Figure 3.17: Food chain

## 3.1.4 Cellular Respiration

Describe the oxidation of glucose as the primary carbohydrate energy source, including the balanced equation for cellular respiration: $C_6H_{12}O_{6\,(aq)} + 6O_{2\,(g)} \rightarrow 6CO_{2\,(g)} + 6H_2O_{(l)}$



The previous section examined photosynthesis, the process by which autotrophs produce glucose using carbon dioxide and water from their environment. During this process, light energy absorbed by autotrophs is converted into chemical energy and stored within glucose molecules. This stored energy is later released through **cellular respiration**, providing the necessary energy for biological functions.

Cellular respiration is a fundamental biological process that allows both autotrophs and heterotrophs, including plants, animals, fungi, and many bacteria (Figure 3.18), to release the chemical energy stored in glucose to power various cellular activities necessary for growth, repair, and survival. Like photosynthesis, cellular respiration is not a single reaction, but a complex biochemical process involving more than twenty chemical reactions. The process of cellular respiration is summarised in the equation below.

$$C_6H_{12}O_{6\,(aq)} + 6O_{2\,(g)} \rightarrow 6CO_{2\,(g)} + 6H_2O_{(l)}$$

This equation illustrates that during cellular respiration, glucose ($C_6H_{12}O_6$) and oxygen ($O_2$) are converted into carbon dioxide ($CO_2$) and water ($H_2O$). Cellular respiration is an **exothermic** process, meaning it involves a net release of energy to the surroundings. The energy is released primarily as heat or chemical energy which is used to power cellular processes, including movement, transport and some chemical reactions. Cellular respiration is the complementary process to photosynthesis, as it relies on the oxygen and glucose produced by photosynthetic organisms while returning carbon dioxide and water to the environment, creating a continuous energy cycle that sustains life on Earth.

Heterotrophs, also known as **consumers**, play a crucial role in ecosystems by obtaining energy from glucose produced by autotrophs (see Figure 3.19). They rely on consuming plants, animals, or decomposing organic matter to acquire glucose, which serves as their primary energy source. The glucose obtained is either immediately used in cellular respiration or stored as glycogen or fat for future energy needs.


Figure 3.18: Heterotrophs

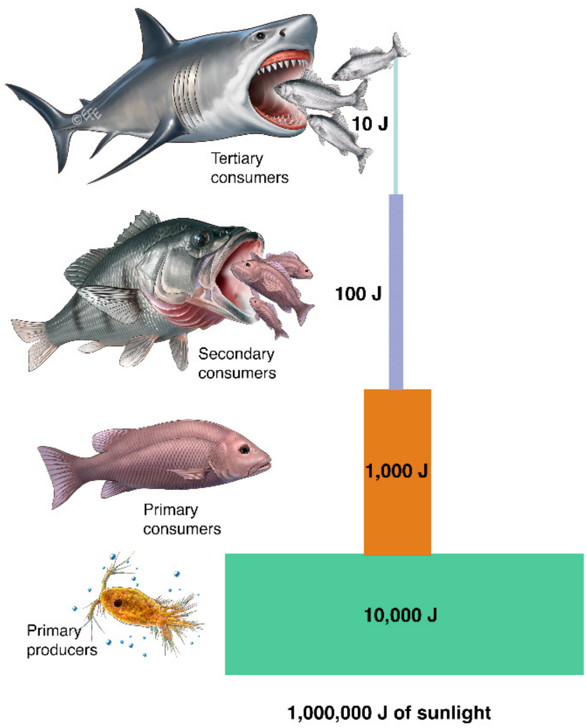



Figure 3.19: Consumers

## 3.1.5 fermentation

Describe the production of bioethanol by the fermentation of glucose and subsequent distillation to produce a more sustainable transport fuel: $C_6H_{12}O_{6\ (aq)} \rightarrow 2C_2H_5OH_{(aq)} + 2CO_{2\ (g)}$



The previous section examined cellular respiration, the process by which organisms use oxygen to extract chemical energy from glucose. However, some organisms inhabit oxygen-poor environments, while others may experience oxygen shortages that limit their ability to sustain aerobic respiration. In such cases, they rely on **fermentation**, a process that allows glucose to be broken down without oxygen to generate energy.

One of the most well-known types of fermentation is **alcohol fermentation**, in which glucose is broken down to produce ethanol ($C_2H_5OH$) and carbon dioxide. This process typically occurs in microorganisms, including yeast and certain bacteria (see Figure 3.20), enabling their survival in oxygen-poor (anaerobic) environments, such as deep soil layers and the digestive tracts of animals. In human applications, the ethanol produced is used in alcoholic beverages and as a biofuel, while the carbon dioxide is responsible for carbonation in beer and the rising of bread dough. The process of alcohol fermentation is summarised in the equation below:

$$C_6H_{12}O_{6\ (aq)} \rightarrow 2C_2H_5OH_{(aq)} + 2CO_{2\ (g)}$$

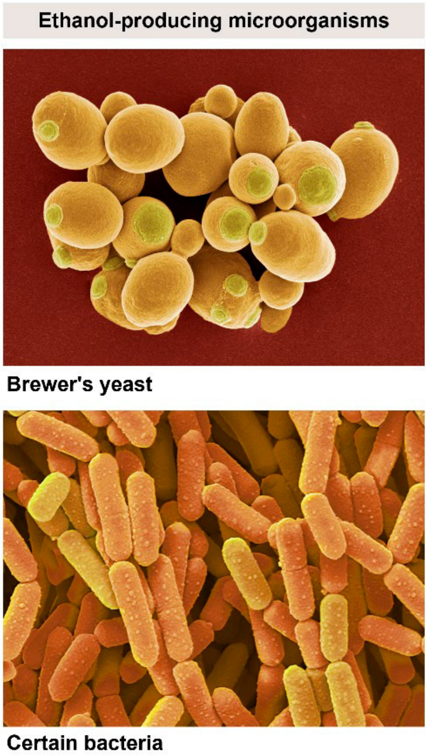



Figure 3.20: Ethanol-producing microorganisms

### Bioethanol

Bioethanol is a renewable fuel produced from plant-derived sugars through the process of fermentation, followed by distillation to increase its purity. As an alternative to fossil fuels, bioethanol reduces greenhouse gas emissions and promotes sustainable energy use, making it a key component of biofuels like E10 (10% ethanol, 90% petrol) and E85 (85% ethanol, 15% petrol) used in transportation (Figure 3.21).


Figure 3.21: Bioethanol

The production of bioethanol begins with the fermentation of glucose sourced from starch-rich crops such as corn, sugarcane, wheat, and cassava. In this process, yeast (*Saccharomyces cerevisiae*) or bacteria carry out fermentation at 30–35°C over several days, producing a mixture containing ethanol, water, and other byproducts. Since fermentation yields a dilute ethanol solution (~10-15%), distillation is required to increase the ethanol concentration. The mixture is heated in a fractional distillation column, where ethanol, with a lower boiling point (78°C), evaporates before water (100°C). The ethanol vapour is collected, condensed, and purified to around 96% ethanol.

The purified bioethanol is blended with gasoline to create biofuels, which reduces carbon emissions as plants absorb $CO_2$ during growth, offsetting emissions from combustion and enhancing fuel sustainability by using renewable crops instead of finite fossil fuels.

## Question 13

Photosynthesis, cellular respiration and fermentation are metabolic processes.

Which one of the following is a product of cellular respiration and fermentation?

- ◯ A Glucose
- ◯ B Water
- ◯ C Carbon dioxide
- ◯ D Oxygen

(1 mark)

## Question 14

Fermentation

I. occurs in the presence and absence of oxygen.
II. converts glucose to ethanol.
III. is used in the production of biofuel.

Which of the statements above is correct?

- ◯ A I and III only
- ◯ B II and III only
- ◯ C I and II only
- ◯ D III only

(1 mark)

## Question 15

Autotrophs use the products of photosynthesis in

- ◯ A combustion
- ◯ B fermentation
- ◯ C cellular respiration
- ◯ D digestion

(1 mark)

## Question 16

Giant kelp are autotrophs that synthesise glucose using carbon dioxide dissolved in seawater.

Which one of the following reactions occurs in giant kelp?

- ◯ A $C_3H_6O_3 \rightarrow C_2H_5OH + CO_2$
- ◯ B $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$
- ◯ C $C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$
- ◯ D $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

(1 mark)

## Question 17

Bioethanol

- ◯ A is produced by yeast in fermentation.
- ◯ B is produced by bacteria in cellular respiration.
- ◯ C is produced by animals in fermentation.
- ◯ D is produced by plants in photosynthesis.

(1 mark)

## Question 18

The photograph below shows a field of *Miscanthus giganteus* being grown as an energy source.

(a) *M. giganteus* produces carbohydrates in photosynthesis.

Write an equation for photosynthesis.

(1 mark)

(b) *M. giganteus* use the carbohydrate glucose as an energy source.

Write an equation for the reaction in *M. giganteus* that releases energy stored in glucose.

(1 mark)

(c) *M. giganteus* is used to produce bioethanol.

Describe, using an equation, the production of bioethanol from *M. giganteus*.

(3 marks)

(d) The concentration of carbon dioxide in the atmosphere increased by 6.25% between 2015 and 2024.

Explain the effect of this increase on the production of bioethanol from *M. giganteus*.

(2 marks)

(e) Discuss two advantages and two disadvantages of using *M. giganteus* to produce bioethanol.

(4 marks)

## 3.1.6 Energy Changes in Reactions

Compare exothermic and endothermic reactions, with reference to bond making and bond breaking, including enthalpy changes ($\Delta H$) measured in kJ, molar enthalpy changes measured in kJ $mol^{-1}$ and enthalpy changes for mixtures measured in kJ $g^{-1}$, and their representations in energy profile diagrams.



A chemical reaction results in the formation of one or more products through the rearrangement of atoms. During the reaction, existing chemical bonds in the reactants break, freeing the atoms, which then recombine to form new bonds, producing the final products. The processes of bond breaking and bond formation involve energy changes, which can be quantified and analysed. This section will examine the energy transformations that occur during chemical reactions.

### Energy Changes

A chemical reaction is a dynamic process that involves the breaking of existing bonds and the formation of new ones. Chemical bonds are electrical forces of attraction between oppositely charged particles. To break these bonds, energy must be supplied to overcome the attraction and separate the particles, weakening the bond until it eventually breaks. This bond-breaking process requires energy absorption, making it endothermic. Conversely, when oppositely charged particles move closer together to form new bonds, energy is released, making this process exothermic. Thus, a chemical reaction involves both energy absorption during bond breaking and energy release during bond formation. A reaction is classified as endothermic if the energy absorbed to break bonds is greater than the energy released when new bonds form. For example, when barium hydroxide ($Ba(OH)_2$) reacts with ammonium chloride ($NH_4Cl$), the energy required to break the ionic bonds in the reactants is greater than the energy released during the formation of new bonds in the products. This results in a net absorption of energy from the surroundings, making the reaction endothermic. When performed in a flask placed on a damp wooden block, the heat absorbed from the environment causes the water to freeze, binding the flask to the wood (see **Figure 3.22**). Conversely, a reaction is exothermic if the energy absorbed to break bonds is less than the energy released during bond formation. For example, when metallic sodium (Na) is reacted with water ($H_2O$), the energy required to break the bonds in the reactants is less than the energy released when new bonds are formed in the products. This results in a net energy release to the surroundings in the form of heat, light and sound (see **Figure 3.23**).

**Figure 3.22**: Endothermic reaction

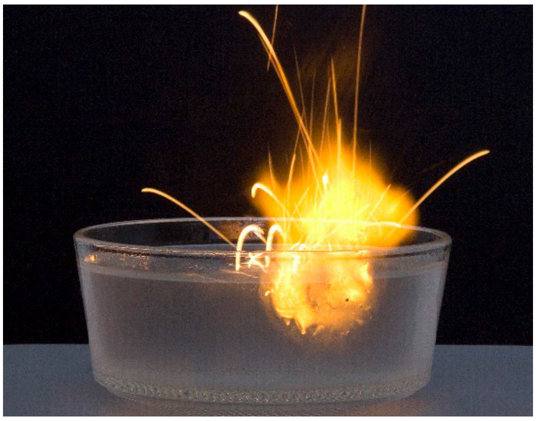


**Figure 3.23**: Exothermic reaction

The amount of energy absorbed or released during a reaction primarily depends on the strength of the bonds involved. Reactions that form stronger bonds tend to be exothermic, as they release more energy than is required to break the initial bonds. Conversely, reactions that break stronger bonds are generally endothermic, as they require greater energy input to overcome the bond strength.

## Enthalpy Changes

The energy absorbed in an endothermic reaction or released in an exothermic reaction is measured using **enthalpy change (ΔH)**, which represents the energy transferred in a chemical reaction at constant pressure. It reflects the difference in enthalpy (energy content) between reactants and products. In an endothermic reaction, energy is absorbed, resulting in products with higher energy than the reactants, making ΔH positive. Conversely, in an exothermic reaction, energy is released to the surroundings, leaving the products with lower energy than the reactants, making ΔH negative. In combustion, the enthalpy change is also called the **heat of combustion**, as it represents the quantity of heat (q) released per mole (n) of fuel reacted with oxygen.

The heat of combustion is measured using various units, depending on whether the fuel is a pure substance or a mixture. For pure substances like elements or compounds (see Figure 3.24), the enthalpy change is measured in **kilojoules per mole of fuel (kJ mol$^{-1}$)**. Alternatively, the heat of combustion of a pure substance is measured in **kilojoules per gram of fuel (kJ g$^{-1}$)** by dividing the heat of combustion in kJ mol$^{-1}$ by the molar mass (M). For example, the heat of combustion of methane ($CH_4$) in kJ g$^{-1}$ is:

$$\frac{\Delta H}{M} = \frac{890}{(12.0 + (1x4))} = 55.6 \text{ kJ g}^{-1}$$

| Fuel | Formula | Heat of combustion (kJ g$^{-1}$) | Heat of combustion (kJ mol$^{-1}$) |
|---|---|---|---|
| hydrogen | $H_2$ | 141 | 282 |
| methane | $CH_4$ | 55.6 | 890 |
| ethane | $C_2H_6$ | 51.9 | 1560 |
| propane | $C_3H_8$ | 50.5 | 2220 |
| butane | $C_4H_{10}$ | 49.7 | 2880 |
| octane | $C_8H_{18}$ | 47.9 | 5460 |
| ethyne | $C_2H_2$ | 49.9 | 1300 |
| methanol | $CH_3OH$ | 22.7 | 726 |
| ethanol | $C_2H_5OH$ | 29.6 | 1360 |

Figure 3.24: Heats of combustion of common fuels

Some fuels consist of mixtures or blends of different elements or compounds. For instance, natural gas is a mixture of methane and ethane. Because the proportions of the mixture's components can vary, calculating a single, generic molar enthalpy change is not practical. The heat of combustion values provided in Figure 3.25 represent typical values measured under standard laboratory conditions (25°C and 100 kPa), assuming complete combustion to carbon dioxide ($CO_2$) and water ($H_2O$). However, actual heat of combustion values may vary depending on the specific source and composition of the fuel.

| Fuel | State | Heat of combustion (kJ g$^{-1}$) |
|---|---|---|
| Biogas | gas | 25.0 |
| Biodiesel B20 | liquid | 42.0 |
| Bioethanol E15 | liquid | 43.0 |
| Bioethanol E10 | liquid | 44.0 |
| Diesel | liquid | 45.0 |
| Kerosene | liquid | 46.2 |
| Petrol | liquid | 47.0 |
| Natural gas | gas | 54.0 |

Figure 3.25: Heats of combustion of common blended fuels

## Energy Profile Diagrams

The enthalpy change of a chemical reaction can be illustrated using an **energy profile diagram**, which visually represents the energy changes that occur as reactants are transformed into products. The key feature of an energy profile diagram is the **reaction pathway**, a continuous curve that traces the energy changes throughout the reaction. The pathway begins at a y-coordinate, representing the enthalpy of the reactants and extends horizontally along the x-axis, which represents the reaction's progression. As the reaction proceeds, the pathway rises, indicating an increase in enthalpy as the reactants absorb the **activation energy ($E_a$)**, the minimum energy required to break chemical bonds. Once the bonds are broken, the pathway descends, reflecting the release of energy as new bonds form in the products. Finally, the reaction pathway stabilises at a new y-coordinate, representing the enthalpy of the products. The enthalpy change (ΔH) is represented on the diagram as the difference in energy between the reactants and products.

1 Exothermic reaction

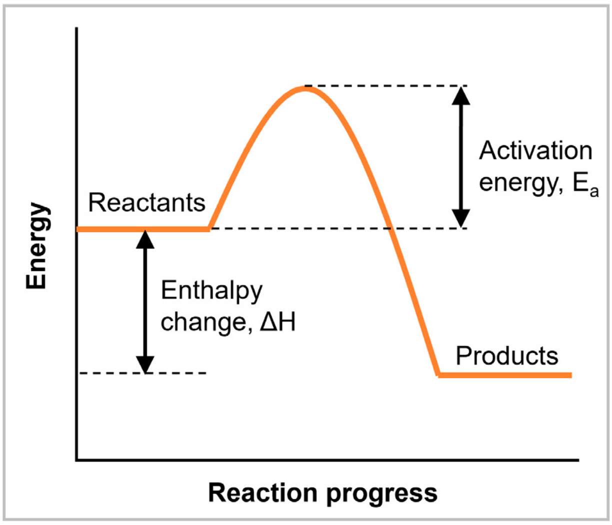



Figure 3.26: Energy profile diagram for an exothermic reaction

2 Endothermic reaction

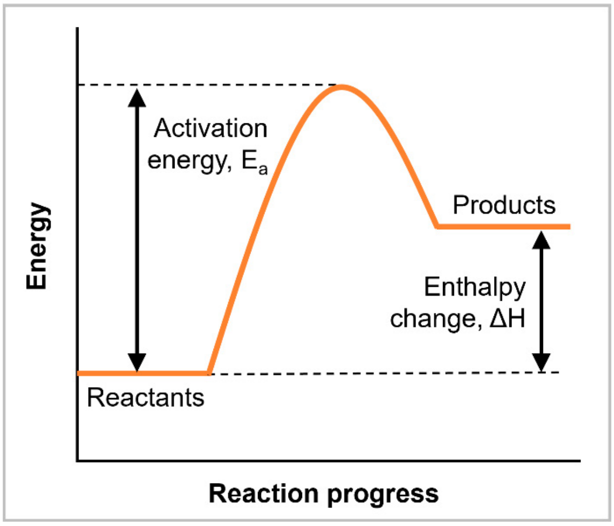



Figure 3.27: Energy profile diagram for an endothermic reaction

Despite sharing key reaction characteristics such as a reaction pathway, activation energy and enthalpy change, there are fundamental differences between the energy profile diagrams of exothermic and endothermic reactions. In an exothermic reaction, energy is released to the surroundings, making the enthalpy change (ΔH) negative (see Figure 3.26). This is visually represented by the products having a lower energy level than the reactants, indicating that energy has been released from the system to the surroundings. In contrast, an endothermic reaction absorbs energy from the surroundings, making ΔH positive (see Figure 3.27). The products are at a higher energy level than the reactants, reflecting the energy absorbed to form new bonds.

### Question 19

Calcium carbonate is decomposed according to the equation below.

$$CaCO_{3\,(s)} \rightarrow CaO_{(s)} + CO_{2\,(g)} \quad \Delta H = +178 \text{ kJ mol}^{-1}$$

Which one of the following is consistent with the information in the equation?

- ◯ A More energy is absorbed in bond-making than is released in bond-breaking.
- ◯ B More energy is released in bond-making than is absorbed in bond-breaking.
- ◯ C Less energy is absorbed in bond-making than is released in bond-breaking.
- ◯ D Less energy is released in bond-making than is absorbed in bond-breaking.

(1 mark)

## Question 20

Biogas is a fuel mixture containing methane and carbon dioxide.

Consider the following units for the heat of combustion of fuels:

I. kJ $mol^{-1}$
II. kJ $g^{-1}$
III. kJ

Which of the units is used to quantify the heat of combustion of biogas?

- A I and II only
- B II and III only
- C II only
- D III only

(1 mark)

## Question 21

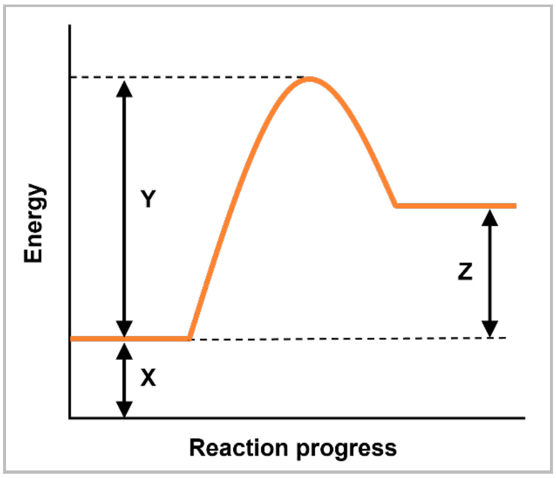
Which one of the following combinations correctly identifies a type of chemical reaction and the sign of the enthalpy change, ΔH?

| | *Type of reaction* | *Enthalpy change* |
|---|---|---|
| A | Cellular respiration | Negative |
| B | Photosynthesis | Negative |
| C | Fermentation | Positive |
| D | Combustion | Positive |

(1 mark)

## Question 22

Refer to the energy profile diagram below:




The activation energy for this reaction is equal to

- A Y – Z.
- B X + Z.
- C Y.
- D Z.

(1 mark)

## Question 23

Refer to the table below, which shows the heat of combustion of common fuels.

| Fuel | Formula | Heat of combustion ($kJ\ g^{-1}$) | Heat of combustion ($kJ\ mol^{-1}$) |
|---|---|---|---|
| hydrogen | $H_2$ | 141 | 282 |
| methane | $CH_4$ | 55.6 | 890 |
| ethane | $C_2H_6$ | 51.9 | 1560 |
| propane | $C_3H_8$ | 50.5 | 2220 |
| butane | $C_4H_{10}$ | 49.7 | 2880 |
| octane | $C_8H_{18}$ | 47.9 | 5460 |
| ethyne | $C_2H_2$ | 49.9 | 1300 |
| methanol | $CH_3OH$ | 22.7 | 726 |
| ethanol | $C_2H_5OH$ | 29.6 | 1360 |

(a) Calculate the quantity of heat released (in kJ) in the combustion of

i. 2.50 mol of methane.

(2 marks)

ii. 325 g of propane.

(2 marks)

i. 25.5 kg of ethanol.

(2 marks)

(b) Calculate the following:

i. The number of moles of ethyne combusted to release 112 kJ.

(2 marks)

ii. The mass of octane combusted to release $55.0 \times 10^3$ kJ.

(2 marks)

## 3.1.7 Limiting Reagents

Determine the limiting reactants or reagents in chemical reactions.



A chemical reaction involves the transformation of reactants into products. In most cases, the molar quantities of the reactants are unequal, meaning one reactant is present in greater excess. The reactant available in the larger quantity is referred to as the **excess reactant**, while the reactant present in the smaller quantity is known as the **limiting reactant** (or **limiting reagent**). The limiting reactant is completely consumed first, preventing any further reaction from occurring. Once it is exhausted, the reaction stops, even if other reactants remain unreacted.

Understanding limiting reagents is fundamental in stoichiometry, as it enables chemists to predict reaction yields, minimise waste, and optimise chemical efficiency. This concept is particularly crucial in industries such as pharmaceuticals, manufacturing, and environmental chemistry, where precise reagent control ensures maximum efficiency, cost-effectiveness, and sustainability.

### Limiting Reagents

A chemical reaction occurs when reactants combine in fixed mole ratios, as defined by a balanced chemical equation. To determine the limiting reagent, the available mole ratios of reactants in the reaction mixture are compared with the stoichiometric ratios required by the equation.

For example, in the reaction between hydrogen gas ($H_2$) and oxygen gas ($O_2$) to form water ($H_2O$):

$$2H_2 + O_2 \rightarrow 2H_2O$$

If five moles of hydrogen (5 mol $H_2$) and two moles of oxygen (2 mol $O_2$) are present, the limiting reagent can be determined by analysing the mole ratio. The balanced equation indicates that two moles of $H_2$ react with one mole of $O_2$ to form two moles of $H_2O$. This means that:

- Two moles of $H_2$ produce two moles of $H_2O$
- One mole of $O_2$ produces two moles of $H_2O$

Using these ratios, the available five moles of $H_2$ could theoretically produce five moles of $H_2O$, while the two moles of $O_2$ can produce only four moles of $H_2O$. Since oxygen produces the least amount of product, it is completely consumed first, making **$O_2$ the limiting reagent** in this reaction.

To determine the limiting reagent, we calculate the number of moles of each reactant present and then use the mole ratio to determine the number of moles of product produced by each reactant.

**Example 3.01**

A 40.0 g sample of calcium carbonate ($CaCO_3$) is reacted with 25.0 g of hydrochloric acid (HCl).

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$$

To determine the limiting reagent, we first calculate the number of moles of each reactant:

| | |
|---|---|
| $n(CaCO_3) = \frac{m}{M} = \frac{40.0}{100.09} = 0.400$ mol | $n(HCl) = \frac{m}{M} = \frac{25.0}{36.458} = 0.686$ mol |

Next, we determine the number of moles of one product, such as $CO_2$, each reactant can produce.

| | |
|---|---|
| $n(CO_2) = n(CaCO_3) = 0.400$ mol | $n(CO_2) = \frac{n(HCl)}{2} = \frac{0.686}{2} = 0.343$ mol |

Hence, **HCl is the limiting reagent**, as it produces the least moles of the product, $CO_2$.

Understanding limiting reagents is essential in various chemical applications. By knowing which reactant limits the reaction, chemists can accurately predict the quantities of products formed in the reaction of a specified amount of reactants.

## Question 24

Hydrazine ($N_2H_4$) is used as a fuel in spacecraft. It reacts with oxygen as follows:

$$N_2H_4 + O_2 \rightarrow N_2 + 2H_2O$$

A fuel cell contains 50.0 g of hydrazine and 64.0 g of oxygen.

Determine the limiting reagent in this reaction.

(3 marks)

## Question 25

In the thermite reaction:

$$2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$$

One thermite mixture contains 30.0 g of aluminium powder and 80.0 g of iron(III) oxide.

Determine the limiting reagent in this reaction.

(3 marks)

## Question 26

Ammonia reacts with sulfuric acid to form ammonium sulfate, a common fertiliser:

$$2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$$

A fertiliser mixture is produced by reacting 20.0 g of ammonia with 50.0 g of sulfuric acid.

Determine the limiting reagent in this reaction.

(3 marks)

## Question 27

Aspirin ($C_9H_8O_4$) is synthesised from salicylic acid ($C_7H_6O_3$) and acetic anhydride ($C_4H_6O_3$):

$$C_7H_6O_3 + C_4H_6O_3 \rightarrow C_9H_8O_4 + CH_3COOH$$

A chemist uses 10.0 g of salicylic acid and 12.0 g of acetic anhydride.

Determine the limiting reagent in this reaction.

(3 marks)

## 3.1.8 Combustion

Describe combustion (complete and incomplete) reactions of fuels as exothermic reactions, including the writing of balanced thermochemical equations, including states, for the complete and incomplete combustion of organic molecules using experimental data and data tables.



Fuels are chemical compounds that store energy, with the most common types being organic compounds, such as hydrocarbons and alcohols. Combustion is a key chemical reaction in which a fuel reacts with oxygen, releasing energy as heat and light (see Figure 3.28). As a highly exothermic process, combustion plays a crucial role in energy generation, industrial processes, and daily activities. This section examines the chemical principles of combustion, the different types of combustion reactions, and the chemical equations that describe these processes.

Figure 3.28: Combustion of methanol

### Combustion

Combustion is a redox reaction in which a fuel undergoes oxidation by reacting with oxygen ($O_2$). This process occurs at high temperatures, where the fuel and oxygen molecules absorb heat from the surroundings, causing their bonds to break. The freed atoms then recombine to form new products, releasing significant amounts of energy. When hydrocarbons or alcohols undergo combustion, the primary products are carbon dioxide ($CO_2$) and water ($H_2O$). However, the reaction products depend on the concentration of oxygen available to the reaction. When the fuel is reacted with an excess of oxygen, the only reaction products are carbon dioxide and water. Such a reaction is termed **complete combustion**, as the number of moles of oxygen present is sufficient to completely oxidise all carbon atoms in the fuel molecules, forming carbon dioxide. The complete combustion of octane ($C_8H_{18}$), a hydrocarbon present in petrol, is described in the balanced chemical equation below.

$$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$$

Figure 3.29: Incomplete combustion

However, when a fuel is reacted with a limited amount of oxygen, additional reaction products are formed, including carbon monoxide (CO) and carbon soot (C) (Figure 3.29). Such a reaction is termed **incomplete combustion**, as the number of moles of oxygen available to the reaction was insufficient, and the carbon atoms were incompletely oxidised, forming carbon monoxide and soot. The incomplete combustion of octane ($C_8H_{18}$) is described in the balanced chemical equation below.

$$C_8H_{18} + 8O_2 \rightarrow 3C + 3CO + 2CO_2 + 9H_2O$$

Incomplete combustion is more likely to occur when the fuel consists of larger molecules, as their stronger intermolecular forces limit oxygen access, preventing complete oxidation. This process is highly undesirable because it produces carbon monoxide (CO) and soot (C), both of which have harmful effects on the environment and human health.

## Thermochemical Equations

A combustion reaction is represented using a **thermochemical equation**, which is a balanced chemical equation that includes the physical states of all reactants and products under the given reaction conditions, along with the enthalpy change (ΔH).

For example, the complete combustion of methane ($CH_4$) is expressed as:

$$CH_{4\,(g)} + 2O_{2\,(g)} \rightarrow CO_{2\,(g)} + 2H_2O_{(g)} \quad \Delta H = -890 \text{ kJ mol}^{-1}$$

This equation indicates that all reactants and products are in the gaseous state, as their boiling points are lower than the temperature at which the reaction occurs. The enthalpy change signifies 890 kJ of energy is released per mole of methane combusted, making it an exothermic reaction.

Since enthalpy change is expressed per one mole of fuel combusted, the coefficient of the fuel in a thermochemical equation must always be one. As a result, oxygen ($O_2$) coefficients may sometimes appear as fractions to ensure the correct stoichiometry while maintaining one mole of fuel in the equation. For example, the complete combustion of octane ($C_8H_{18}$) is expressed as:

$$C_8H_{18\,(l)} + \frac{25}{2}O_{2\,(g)} \rightarrow 8CO_{2\,(g)} + 9H_2O_{(g)} \quad \Delta H = -5460 \text{ kJ mol}^{-1}$$

Writing an accurate thermochemical equation for incomplete combustion is not possible in the absence of experimental data, as the ratio of carbon soot, carbon monoxide and carbon dioxide is variable and unpredictable. Since incomplete combustion varies depending on oxygen availability and reaction conditions, the exact ratios of $CO_2$, CO, and C are case-dependent, requiring experimental measurements or empirical data to determine the precise stoichiometry and enthalpy change. However, if experimental data provides approximate product ratios, we can substitute those values into the equation to balance it more specifically.

For example, if $CH_4$ combustion in a low-oxygen environment produces CO only, and the molar enthalpy of combustion is 253 kJ mol$^{-1}$, we can write the thermochemical equation as follows:

$$CH_{4\,(g)} + \frac{3}{2}O_{2\,(g)} \rightarrow CO_{(g)} + 2H_2O_{(g)} \quad \Delta H = -253 \text{ kJ mol}^{-1}$$

Comparing the thermochemical equations for the complete and incomplete combustion of methane reveals that significantly less energy is released per mole of fuel during incomplete combustion. This difference arises from the fewer covalent bonds formed in the products. In complete combustion, carbon dioxide ($CO_2$) is produced, which contains two strong carbon-oxygen double bonds. In contrast, incomplete combustion produces carbon monoxide (CO), which has only one carbon-oxygen double bond. Since bond formation releases energy, the presence of fewer covalent bonds in the products leads to a lower energy release. This reduced efficiency is one of the many disadvantages of incomplete combustion, making it an undesirable process in energy production.

The inefficiency of incomplete combustion is particularly noticeable in motor vehicles. Since the combustion process relies on air as the oxygen source, which contains only 21% $O_2$ by volume, there is often insufficient oxygen to oxidise the fuel fully. As a result, carbon soot and carbon monoxide (CO) are emitted as byproducts (see **Figure 3.30**) rather than exclusively producing carbon dioxide and water. This incomplete oxidation means that less energy is extracted from the petrol combusted, reducing the overall efficiency of the engine and contributing to both pollution and wasted fuel energy.

**Figure 3.30**: Incomplete combustion in vehicles

## Question 28

The table shows the heat of combustion of some common fuels.

| Fuel | Formula | State | Heat of combustion ($kJ\ mol^{-1}$) |
|---|---|---|---|
| hydrogen | $H_2$ | gas | 282 |
| methane | $CH_4$ | gas | 890 |
| ethane | $C_2H_6$ | gas | 1560 |
| propane | $C_3H_8$ | gas | 2220 |
| butane | $C_4H_{10}$ | gas | 2880 |
| octane | $C_8H_{18}$ | liquid | 5460 |
| ethyne | $C_2H_2$ | gas | 1300 |
| methanol | $CH_3OH$ | liquid | 726 |
| ethanol | $C_2H_5OH$ | liquid | 1360 |

Write thermochemical equations for the complete combustion of:

(a) methane

(2 marks)

(b) ethane

(2 marks)

(c) propane

(2 marks)

(d) butane

(2 marks)

(e) octane

(2 marks)

(f) ethyne

(2 marks)

(g) methanol

(2 marks)

(h) ethanol

(2 marks)

## Question 29

The incomplete combustion of hydrocarbons produces soot (C) and carbon monoxide (CO).

(a) State the primary cause of incomplete combustion.

(1 mark)

(b) State and explain whether $CH_4$ or $C_8H_{18}$ is more likely to undergo incomplete combustion.

(3 marks)

(c) State three undesirable consequences of incomplete combustion.

(3 marks)

(d) Write balanced chemical equations for the following:

i. The incomplete combustion of $C_2H_6$ to produce carbon monoxide.

(1 mark)

ii. The incomplete combustion of $C_4H_8$ to produce soot.

(1 mark)

iii. The incomplete combustion of $C_8H_{18}$ to produce carbon monoxide.

(1 mark)

iv. The incomplete combustion of $C_2H_2$ to produce soot.

(1 mark)

v. The incomplete combustion of $CH_3OH$ to produce carbon monoxide.

(1 mark)

vi. The incomplete combustion of $C_2H_5OH$ to produce soot.

(1 mark)

## Review Test 1

### Questions 1 to 10

Questions 1 to 10 are **multiple-choice questions.** For each multiple-choice question, indicate the best answer to the question by clicking the bubble [O] beside it.

1. Propane, $C_3H_8$, is a primary component of LPG used in household heating systems, stoves, ovens, and water heaters. The heat of combustion of propane is 2220 kJ $mol^{-1}$.

The numerical value of the heat of combustion of propane in kJ $g^{-1}$ is

◯ **A** 44.1
◯ **B** 97.9
◯ **C** 50.3
◯ **D** 0.0199

(1 mark)

2. Which one of the following is a biofuel?

◯ **A** Glucose produced by ethanol
◯ **B** Methane produced by natural gas
◯ **C** Electricity produced by wind turbines
◯ **D** Methyl esters produced by plant oils

(1 mark)

3. Photosynthesis is a metabolic process described by the thermochemical equation below.

$$6CO_{2\,(g)} + 6H_2O_{(l)} \rightarrow C_6H_{12}O_{6\,(aq)} + 6O_{2\,(g)} \quad \Delta H = +2805 \text{ kJ mol}^{-1}$$

Which one of the following statements about photosynthesis is correct?

◯ **A** A greater quantity of energy is released than is absorbed in the reaction.
◯ **B** Producing one mole of glucose, $C_6H_{12}O_6$ releases 2805 kJ of energy.
◯ **C** More energy is used in bond breaking than is released in bond making in the reaction.
◯ **D** The reaction is exothermic because oxygen gas is a product rather than a reactant.

(1 mark)

4. The incomplete combustion of hexane ($C_6H_{14}$)

◯ **A** releases less energy than the complete combustion of hexane.
◯ **B** occurs when hexane is reacted with an excess of oxygen.
◯ **C** always produces an equal number of C, CO and $CO_2$ as products.
◯ **D** occurs when hexane is a limiting reagent in the reaction.

(1 mark)

5. 1-butanol ($C_4H_9OH$) is a fuel that undergoes complete combustion according to the equation:

$$C_4H_9OH_{(l)} + 6O_{2\,(g)} \rightarrow 4CO_{2\,(g)} + 5H_2O_{(g)}$$

When 29.6 g of 1-butanol reacts with 64.0 g of oxygen

◯ **A** $C_4H_9OH$ is the limiting reagent as a smaller mass is present.
◯ **B** $O_2$ is in excess as a greater mass is present.
◯ **C** $C_4H_9OH$ is in excess as there are more moles present when compared with $O_2$.
◯ **D** $O_2$ is the limiting reagent as it produces the least number of moles of $CO_2$.

(1 mark)

## Question 11

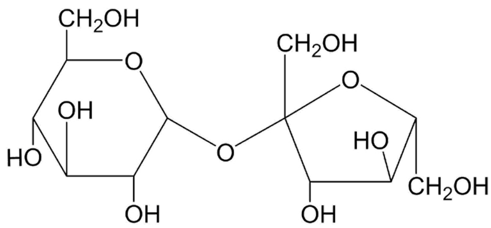
The human body requires approximately 8,400 kJ of energy per day.

This energy is supplied by cellular respiration of glucose, $C_6H_{12}O_6$.

(a) Write a balanced equation for cellular respiration of glucose.

(1 mark)

(b) Much of the body's glucose is supplied by the digestion of carbohydrates, including the disaccharide sucrose. The structural formula of sucrose is shown below:



i. Name the bond connecting the two monosaccharides in sucrose.

(1 mark)

ii. Sucrose is obtained from fruits and vegetables.

Fruits and vegetables are composed primarily of the polysaccharide cellulose.

State why cellulose cannot be used as an energy source in the human body.

(1 mark)

(c) The energy released in the cellular respiration of glucose is stored in molecules of adenosine triphosphate, $ATP^{3-}$, which have a molar mass of 507.18 g mol$^{-1}$.

The stored energy is released in the hydrolysis of ATP, which is described in the thermochemical equation below.

$$ATP^{3-}{}_{(aq)} + H_2O_{(l)} \rightarrow ADP^{2-}{}_{(aq)} + PO_4{}^{3-}{}_{(aq)} + 2H^+{}_{(aq)} \quad \Delta H = -30.5 \text{ kJ mol}^{-1}$$

Calculate the mass, in kg, of ATP broken down each day to meet the body's energy needs.

(3 marks)

(d) When adults consume more food than their energy requirements, the body stores extra energy.

State two ways in which the excess energy is stored in the human body.

(2 marks)

## Question 12

Natural gas is a fossil fuel produced from the decomposition of organic matter under high pressure and temperature over millions of years, deep within the Earth's crust.

(a) State why natural gas is non-renewable.

(1 mark)

(b) The primary components of natural gas are methane, $CH_4$ and ethane, $C_2H_6$.

The heat of combustion of ethane is –1560 kJ mol$^{-1}$.

i. Write a thermochemical equation for the complete combustion of ethane.

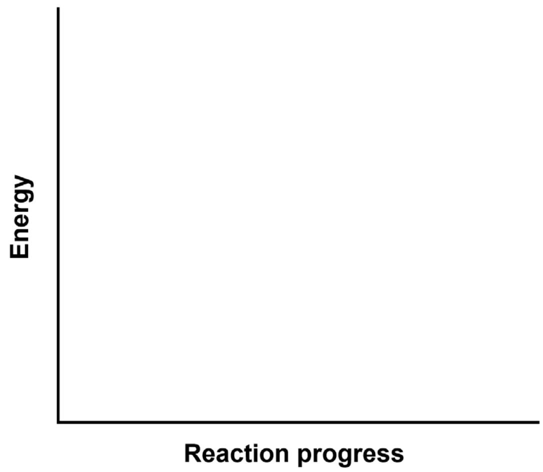
(2 marks)

ii. Describe the energy changes occurring when ethane undergoes complete combustion.

(2 marks)

iii. Draw an energy profile diagram for the complete combustion of ethane.

Ensure you label the enthalpy change, ΔH.




(2 marks)

(c) Natural gas is combusted in air to release energy for electrical power generation.

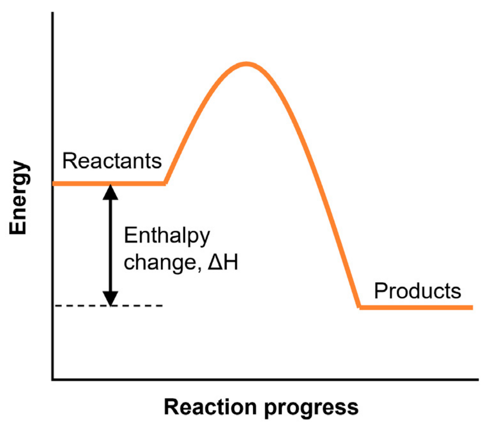
In power stations, the methane in natural gas undergoes incomplete combustion.

i. State why natural gas undergoes incomplete combustion in air.

(1 mark)

ii. Write an equation for the incomplete combustion of $CH_4$ to produce carbon monoxide.

(1 mark)

| Question | Part | | Author's response | Marks |
|---|---|---|---|---|
| 1 | | | C | 1 |
| 2 | | | D | 1 |
| 3 | | | C | 1 |
| 4 | | | A | 1 |
| 5 | | | D | 1 |
| 6 | | | B | 1 |
| 7 | | | B | 1 |
| 8 | | | C | 1 |
| 9 | | | A | 1 |
| 10 | | | D | 1 |
| 11 | (a) | | $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ | 1 |
| | (b) | i. | Glycosidic | 1 |
| | | ii. | Humans lack the enzymes needed to hydrolyse cellulose. | 1 |
| | (c) | | $n = \frac{q}{\Delta H} = \frac{8400}{30.5} = 275$ mol | 1 |
| | | | $m = nM = 275 \times 507.18 = 1.40 \times 10^5$ g | 1 |
| | | | $m = \frac{1.40 \times 10^5}{1000} = 140$ kg | 1 |
| | (d) | | As glycogen, a polysaccharide | 1 |
| | | | As fat | 1 |
| 12 | (a) | | As it's a resource that natural processes cannot replace in a relatively short period. | 1 |
| | (b) | i. | $C_2H_{6\,(g)} + \frac{7}{2}O_{2\,(g)} \rightarrow 2CO_{2\,(g)} + 3H_2O_{(g)}$ $\Delta H = -1560$ kJ mol$^{-1}$ | |
| | | | Balanced with correct states and ΔH included. | 1+1 |
| | | ii. | Energy is absorbed from the surroundings to break bonds in the ethane and oxygen molecules. | 1 |
| | | | Energy is released to the surroundings when new bonds are formed in the carbon dioxide and water molecules. | 1 |
| | | iii. |  | 2 |
| | (c) | i. | As air contains insufficient oxygen to completely oxidise the carbon atom in methane. | 1 |
| | | ii. | $2CH_4 + 3O_2 \rightarrow 2CO + 4H_2O$ | 1 |