

Molecules (Interaction and interdependence) revision notes

How molecules interact to drive life. Enzymes catalyse and control the network of metabolism, cell respiration transfers energy from carbon compounds to ATP, and photosynthesis transforms light energy into chemical energy in carbon compounds.

For IB Diploma Biology SL undefined. **HL only** is additional higher level content, for HL students only.

1 Enzymes and metabolism Spec C1.1

Enzymes as catalysts and their role in metabolism Spec C1.1.1, C1.1.2, C1.1.3

An **enzyme** is a protein that acts as a **biological catalyst**: it increases the rate of a chemical reaction and is not changed or used up by the reaction, so one enzyme molecule can be used again and again.

Without enzymes, most reactions in cells would happen far too slowly at body temperature to keep the organism alive. Raising the temperature enough to speed them up would damage cell structures.

Enzymes give fast rates at the moderate temperatures found in cells, and the cell can switch reactions on or off by making, activating or inhibiting particular enzymes.

Metabolism

Metabolism is the complex network of interdependent and interacting chemical reactions occurring in living organisms. The product of one reaction is often the substrate of the next, so reactions are linked into pathways, and pathways share molecules with each other.

Enzymes are **specific**: each one catalyses one reaction or one type of reaction. Living organisms therefore need many different enzymes, often thousands. Because every step depends on its own enzyme, control over metabolism can be exerted through these enzymes, for example by changing how much of an enzyme is made or how active it is.

Anabolic and catabolic reactions

The two types of metabolic reaction		
	Anabolism	Catabolism
What happens	Larger molecules built from smaller ones	Larger molecules broken down into smaller ones
Typical reaction	Condensation: monomers joined, water released	Hydrolysis (water used to split bonds) or oxidation
Energy	Needs an energy input (usually from ATP)	Often releases energy
Examples	Protein synthesis (amino acids joined by peptide bonds); glycogen formation from glucose; photosynthesis (carbon compounds made from CO ₂)	Hydrolysis of macromolecules into monomers in digestion; oxidation of substrates such as glucose in respiration

Anabolism	Reactions that build macromolecules from monomers, for example by condensation.
Catabolism	Reactions that break down macromolecules into monomers, for example by hydrolysis, or oxidise substrates as in respiration.

Common mistake: Photosynthesis is anabolic and respiration is catabolic. Do not describe digestion as anabolic just because it happens before new molecules are built.

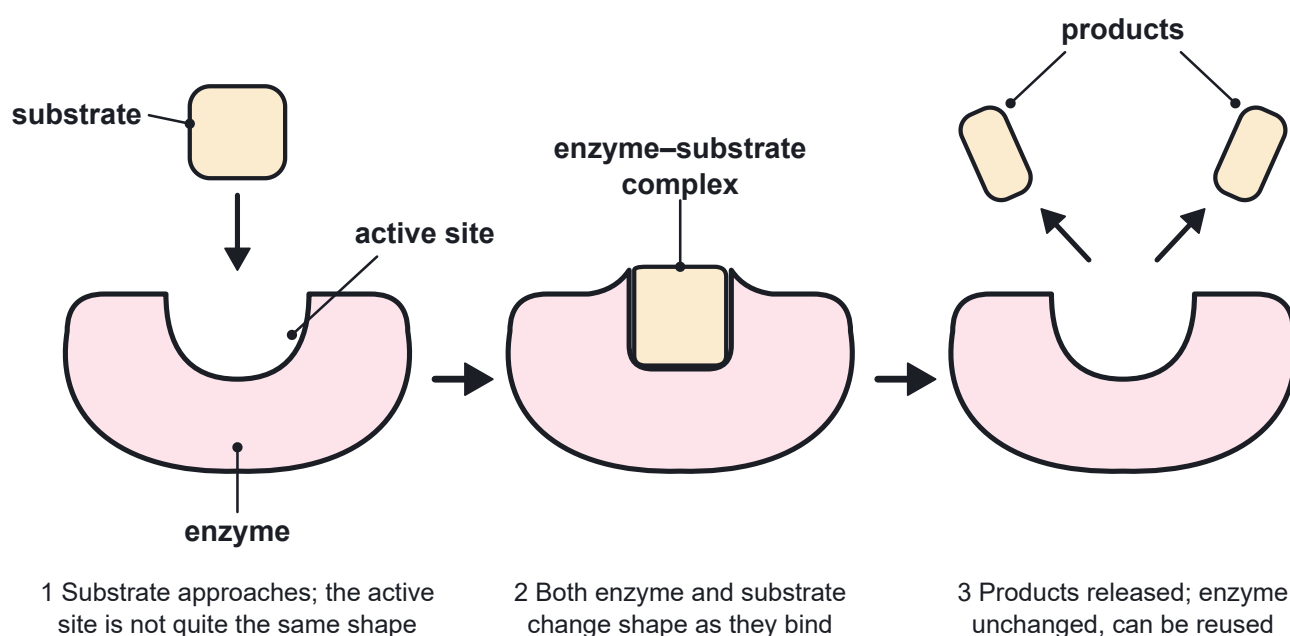
Active sites, induced fit, collisions and denaturation Spec C1.1.4, C1.1.5, C1.1.6, C1.1.7

Enzymes are **globular proteins**. The polypeptide is folded into a compact, roughly spherical shape that is usually soluble in water. Part of the surface forms the **active site**, the region where the substrate binds and the reaction is catalysed.

The active site is made of only a **few amino acids**. Their R groups give it a particular shape and chemical properties (charge, polarity, hydrophobic areas). But these few amino acids are held in exactly the right positions by interactions between amino acids throughout the rest of the protein (hydrogen bonds, ionic bonds, disulfide bonds and hydrophobic interactions). The whole three-dimensional structure is needed for the active site to work.

Induced-fit binding

The substrate binds to the active site by chemical attraction between them. In the **induced-fit** model, both the substrate and the enzyme change shape when binding occurs. The active site moulds more tightly around the substrate, which stresses bonds in the substrate and makes them easier to break or form. The products are then released and the active site returns to its original shape.



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Induced fit: **both the enzyme and the substrate change shape** as the substrate binds to the active site.

Molecular motion and collisions

For a reaction to be catalysed, a substrate molecule and an active site must **collide**, in a suitable orientation. Enzymes and substrates dissolved in water move randomly, and these collisions happen by chance. Sometimes only one of them moves: large substrate molecules (such as starch in a starch grain

or cellulose in a cell wall) may be immobilised while enzymes move to them, and some enzymes are immobilised by being embedded in membranes while their substrates move to them.

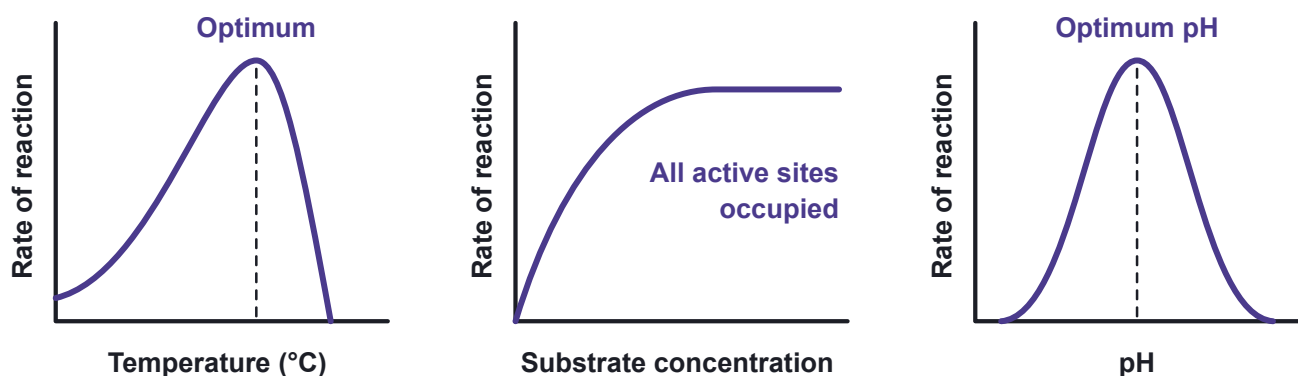
Specificity and denaturation

Enzyme-substrate **specificity** exists because only a substrate with a shape and chemical properties that match the active site can bind to it. Change the structure of the active site and binding fails.

Denaturation is a change to the three-dimensional structure of the protein, caused by high temperature or extreme pH. Bonds holding the tertiary structure break, so the active site changes shape and its chemical properties change. The substrate can no longer bind, so the enzyme cannot catalyse the reaction. Denaturation is usually permanent.

Exam tip: When explaining denaturation, link the chain: bonds in the tertiary structure break, the active site changes shape, the substrate no longer fits or binds, so no enzyme-substrate complexes form.

Effects of temperature, pH and substrate concentration Spec C1.1.8, C1.1.9



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Generalised sketch graphs for the effects of temperature, substrate concentration and pH on the rate of an enzyme-catalysed reaction.

Temperature

As temperature rises, enzyme and substrate molecules have more kinetic energy and move faster. Collisions between substrate and active site become more frequent and more of them have enough energy to react, so the rate increases. Above the **optimum temperature**, the extra vibration breaks bonds holding the enzyme's structure; more and more enzyme molecules denature, so the rate falls steeply. The curve is not symmetrical: the fall is much steeper than the rise.

pH

Each enzyme has an **optimum pH**. A change in pH alters the concentration of hydrogen ions, which changes the charges on R groups in the active site and elsewhere. Ionic and hydrogen bonds are disrupted, so the substrate binds less well and the rate falls on either side of the optimum. Far from the optimum the enzyme is denatured. For example, pepsin in the stomach works best in acid conditions, while many enzymes in the small intestine work best near neutral pH.

Substrate concentration

At low substrate concentrations, raising the concentration increases the frequency of substrate-active site collisions, so the rate rises steeply. As the concentration increases further, more active sites are occupied at any moment, so the rise slows. Eventually **all active sites are occupied** nearly all the time and the rate levels off at a maximum. Enzyme concentration is then the limiting factor.

Exam tip: Sketch graphs like these are models. They can be evaluated by comparing them with real results from enzyme experiments. When describing a graph, give the trend, the optimum or the plateau, and quote values with units.

Measurements in enzyme-catalysed reactions

The rate of an enzyme-catalysed reaction is measured as the amount of **product formed** or **substrate used** per unit time. Common methods include measuring the volume of oxygen released when catalase breaks down hydrogen peroxide (gas syringe or displacement of water), and timing how long starch takes to disappear when amylase acts on it (samples tested with iodine). Rates can also be found from secondary data.

- Mean rate = change in amount $\div$ time taken.
- Initial rate: draw a tangent to the curve at time zero and find its gradient. This is the fairest comparison because the substrate concentration has not yet fallen.
- If only a time is measured (for example, time for starch to disappear), rate can be expressed as $1 \div$ time.

Calculating rates from enzyme data

Catalase was added to hydrogen peroxide. 18 cm³ of oxygen was collected in the first 30 s and 30 cm³ by 90 s. Calculate the mean rate over the first 30 s and over the whole 90 s.

1. First 30 s: rate = $18 \text{ cm}^3 \div 30 \text{ s} = 0.60 \text{ cm}^3 \text{ s}^{-1}$.
2. Whole 90 s: rate = $30 \text{ cm}^3 \div 90 \text{ s} = 0.33 \text{ cm}^3 \text{ s}^{-1}$.
3. The rate falls over time because substrate is used up, so there are fewer collisions with active sites.

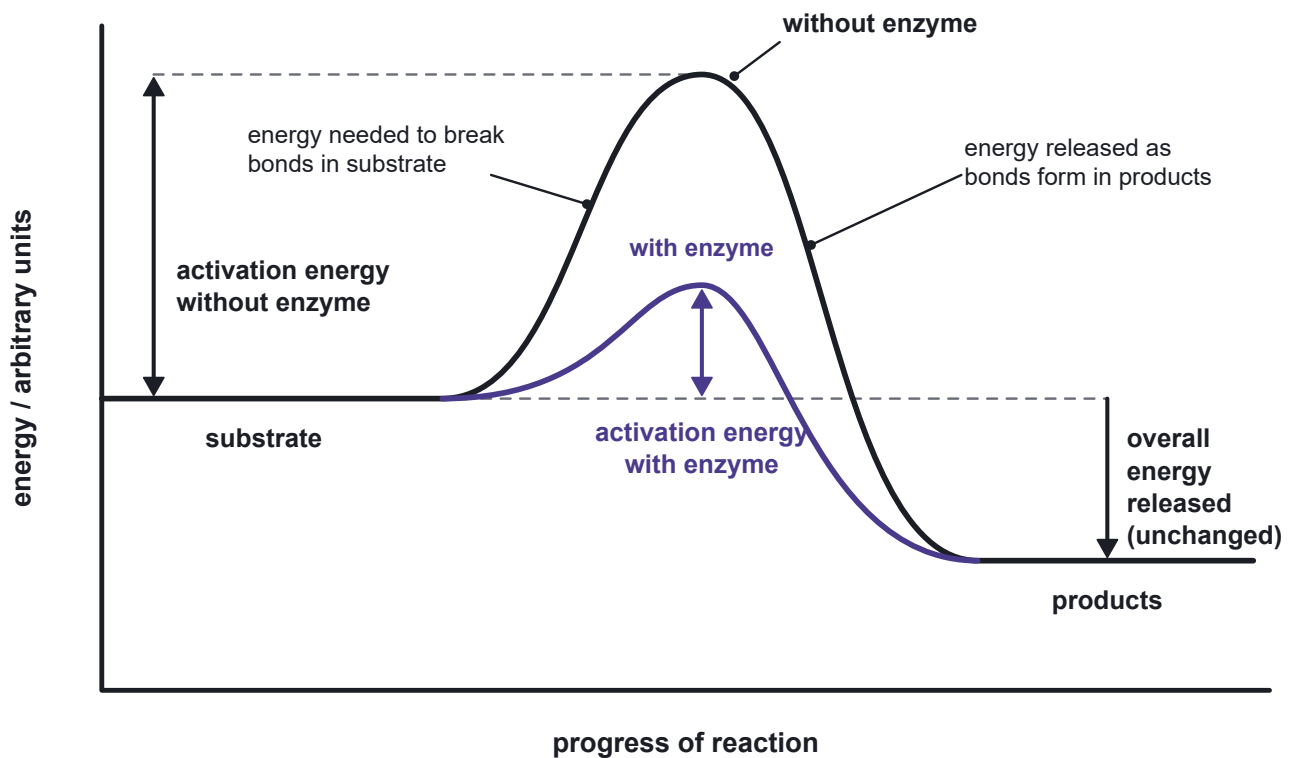
Answer: 0.60 cm³ s⁻¹ over the first 30 s; 0.33 cm³ s⁻¹ over 90 s.

Practical skill: Control temperature with a thermostatically controlled water bath, pH with buffer solutions, and keep enzyme concentration and volumes constant. Repeat each condition at least three times and calculate a mean.

Effect of enzymes on activation energy Spec C1.1.10

Before a reaction can happen, bonds within the substrate must be broken or weakened. This needs an input of energy called the **activation energy**. When new bonds form to make the products, energy is released (the energy yield). In many metabolic reactions the products have less energy than the substrates, so there is an overall release of energy.

Enzymes **lower the activation energy**. Binding to the active site stresses and weakens bonds in the substrate, so less energy is needed to reach the transition state. A larger proportion of substrate molecules then have enough energy to react, and the reaction is faster at the same temperature. The enzyme does **not** change the energy of the substrates or the products, so the overall energy change is unchanged.



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Enzymes **lower the activation energy**, measured from the substrate level to the peak; the overall energy change is unchanged.

Exam tip: On an energy graph, the activation energy is measured from the substrate level to the peak, not from the products or from zero.

Exam tip: Linking question: enzymes are a clear structure–function relationship in a macromolecule. The folded polypeptide creates an active site that lowers activation energy for one specific reaction.

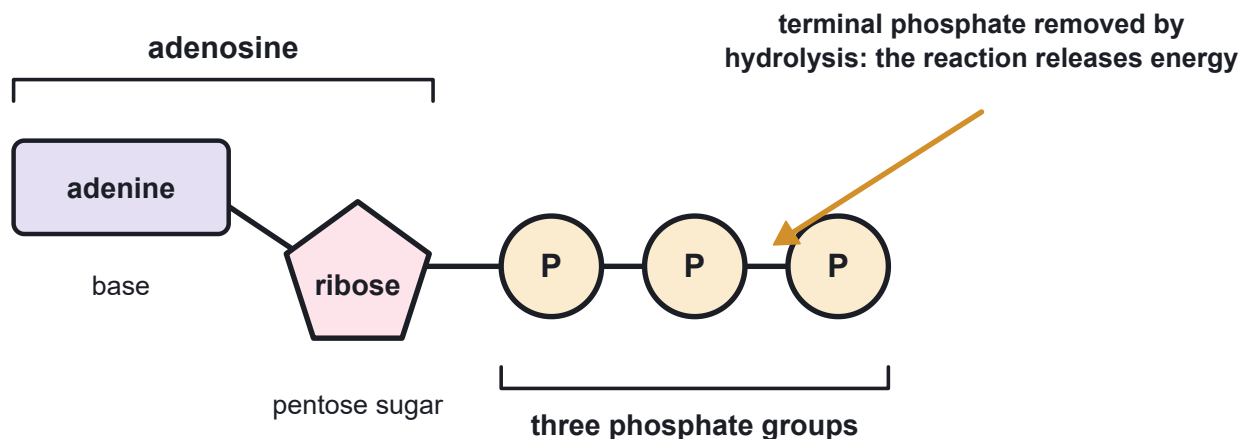
Quick check

1. What is metabolism?
2. Give one example of an anabolic and one of a catabolic reaction.
3. In the induced-fit model, what changes shape when the substrate binds?
4. What happens to the activation energy and the overall energy change when an enzyme catalyses a reaction?

2 Cell respiration Spec C1.2

ATP: the molecule that distributes energy Spec C1.2.1, C1.2.2, C1.2.3

ATP (adenosine triphosphate) is the molecule that distributes energy within cells. It is a **nucleotide**, made of the base adenine, the pentose sugar ribose and a chain of three phosphate groups.



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ATP is a nucleotide: adenine, ribose and three phosphates. Hydrolysis of the **terminal phosphate** releases energy.

Why ATP suits its role as energy currency

- It is **soluble** in water, so it moves easily to wherever energy is needed in the cell.
- It is **stable** at the pH of a cell and does not break down unless an enzyme catalyses it, so energy is not wasted.
- It **cannot pass freely through membranes**, so it stays inside the cell where it was made.
- Hydrolysis of one phosphate group releases an amount of energy that is **sufficient for many tasks** in the cell, without releasing so much that most is wasted as heat.
- It is **rapidly regenerated** from ADP and phosphate, so a small pool of ATP can be recycled many times.

Life processes that ATP supplies with energy

- **Active transport** across membranes, for example pumping ions against their concentration gradient.
- **Synthesis of macromolecules** (anabolism), such as proteins, DNA and glycogen.
- **Movement**: of the whole cell (for example muscle contraction, cilia and flagella) or of cell components such as chromosomes during cell division.

Interconversion of ATP and ADP



Energy is released by **hydrolysis of ATP** to ADP (adenosine diphosphate) and phosphate. Energy is **required to synthesise ATP** from ADP and phosphate. In cells this energy comes from cell respiration (and in photosynthetic cells also from light). Often the phosphate removed from ATP is transferred to another molecule, making it more reactive.

Common mistake: ATP does not store large amounts of energy long term; it distributes energy. Fats and carbohydrates are the energy stores.

Cell respiration: aerobic and anaerobic Spec C1.2.4, C1.2.5

Cell respiration is a system for producing ATP within the cell using energy released from carbon compounds. Glucose and fatty acids are the principal substrates, but a wide range of carbon (organic) compounds can be used, including amino acids.

Do not confuse it with **gas exchange**. Gas exchange is the diffusion of oxygen and carbon dioxide between an organism and its environment, for example across the alveoli. Cell respiration is a set of enzyme-catalysed reactions inside every living cell. Gas exchange supplies the oxygen that aerobic respiration uses and removes the carbon dioxide it produces.

Word equations (glucose as substrate)

Aerobic: glucose + oxygen → carbon dioxide + water

Anaerobic (humans): glucose → lactate

Differences between anaerobic and aerobic cell respiration in humans

	Aerobic	Anaerobic
Respiratory substrates	Carbohydrates, lipids (fatty acids) and amino acids	Glucose (carbohydrate) only
Oxygen required	Yes	No
Relative ATP yield per glucose	Large (about 30 ATP; older textbooks give 36–38)	Small (2 ATP)
Waste products	Carbon dioxide and water	Lactate
Where in the cell	Starts in the cytoplasm, mostly in mitochondria	Cytoplasm only
Mitochondria needed	Yes	No

Humans use anaerobic respiration when oxygen cannot be supplied fast enough, for example in muscles during very intense exercise. It gives ATP quickly but in small amounts, and the lactate must be removed later.

Exam tip: In 'compare' questions, write paired statements: 'aerobic respiration needs oxygen whereas anaerobic does not'. Lactate is the IB term; do not write lactic acid unless the question does.

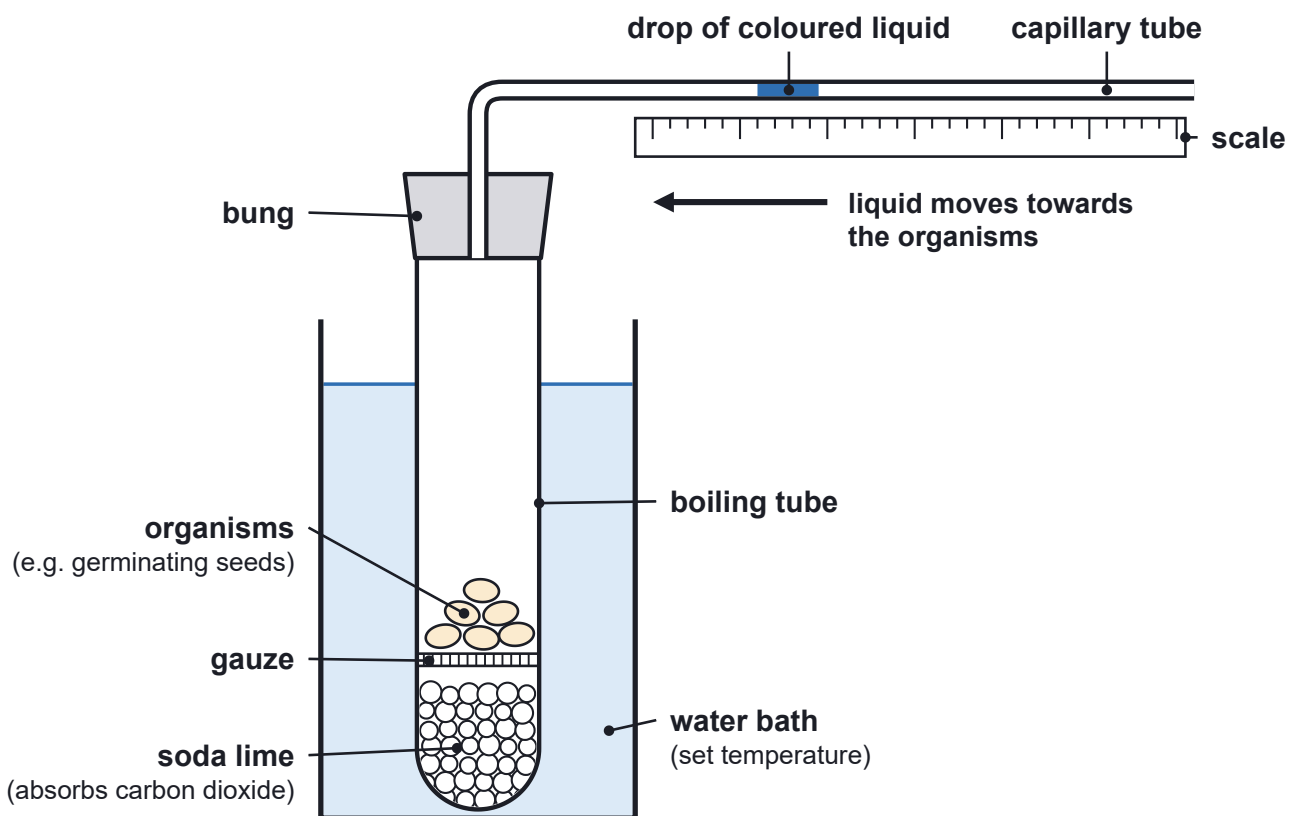
Variables affecting the rate of cell respiration Spec C1.2.6

The rate of cell respiration is the amount of oxygen used, carbon dioxide produced or substrate used **per unit time**. To compare organisms of different sizes, divide by mass, for example mm³ of oxygen per gram per minute.

Variables that affect the rate

- **Temperature:** respiration is enzyme-catalysed, so rate rises to an optimum, then falls as enzymes denature.
- **Oxygen concentration:** low oxygen limits aerobic respiration.
- **Substrate availability:** for example glucose concentration for yeast, or stored food in germinating seeds.

- Others: type and activity of the organism, pH, and stage of development (germinating seeds respire faster than dry seeds).



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A simple respirometer. Soda lime absorbs carbon dioxide, so the drop moves towards the organisms as they use oxygen.

Measuring the rate

1. Place a known mass of organisms (for example germinating seeds or invertebrates) in a sealed tube with an alkali such as soda lime to absorb carbon dioxide.
2. Keep the tube in a water bath at a set temperature and let it equilibrate.
3. Record the distance the liquid drop moves in a fixed time.
4. Set up a control tube with glass beads of the same volume instead of organisms, to correct for temperature and pressure changes.
5. Repeat at different values of the independent variable (for example temperature) and calculate rates.

Rates can also be measured with oxygen or carbon dioxide sensors and a data logger, or for yeast by measuring the volume of carbon dioxide released.

Rate of respiration from a respirometer

2.5 g of germinating seeds were placed in a respirometer. The drop in the capillary tube (radius 0.50 mm) moved 30 mm in 10 minutes. Calculate the rate of oxygen uptake per gram.

1. Volume of oxygen = $\pi r^2 h = 3.14 \times 0.50^2 \times 30 = 23.6 \text{ mm}^3$.
2. Rate = $23.6 \text{ mm}^3 \div 10 \text{ min} = 2.36 \text{ mm}^3 \text{ min}^{-1}$.
3. Per gram: $2.36 \div 2.5 = 0.94 \text{ mm}^3 \text{ g}^{-1} \text{ min}^{-1}$.

Answer: $0.94 \text{ mm}^3 \text{ g}^{-1} \text{ min}^{-1}$ (to 2 significant figures).

Maths skill: Rate = amount ÷ time. Always state units, and divide by mass when organisms or samples differ in size.

Practical skill: Use living organisms ethically: handle invertebrates gently, use gauze to keep them away from the corrosive soda lime, and return them to their habitat afterwards.

Quick check

- 1 . What is the full name of ATP and what type of molecule is it?
- 2 . Write the word equation for anaerobic respiration in humans.
- 3 . Why is soda lime used in a respirometer?

3 Photosynthesis Spec C1.3

Photosynthesis: energy, carbon dioxide, water and oxygen Spec C1.3.1, C1.3.2, C1.3.3

Photosynthesis involves the **transformation of light energy to chemical energy**. Light energy absorbed by pigments is used to make carbon compounds, and the energy is then held in the chemical bonds of those compounds. This energy transformation supplies most of the chemical energy needed for life processes in ecosystems: producers use it directly, and consumers and decomposers obtain it by feeding.

Carbon dioxide, water and glucose

Carbon dioxide is converted to glucose using **hydrogen obtained by splitting water**. Carbon dioxide provides the carbon and oxygen atoms of glucose, but glucose also contains hydrogen, which must come from somewhere: it comes from water molecules, split using energy from light.



Oxygen as a by-product

When water is split, the hydrogen is used and the oxygen is released as a **by-product**. So **the oxygen produced by photosynthesis comes from the splitting of water**, not from carbon dioxide. Oxygen-producing photosynthesis happens in **plants, algae** and **cyanobacteria**.

Common mistake: Do not write that the oxygen released comes from carbon dioxide. It comes from water; the oxygen atoms of CO₂ end up in glucose and water.

Exam tip: Linking question: the consequences of photosynthesis for ecosystems include supplying chemical energy to food chains and removing carbon dioxide from the atmosphere.

Separating photosynthetic pigments by chromatography Spec C1.3.4

Leaves contain several photosynthetic pigments. They can be separated by **chromatography**, using **paper** or a **thin-layer chromatography (TLC)** plate. Each pigment travels a different distance because it differs in how soluble it is in the solvent and how strongly it is attracted to the stationary phase.

1. Grind leaf tissue with a little sand and propanone (or another suitable solvent) to extract the pigments.
2. Draw a pencil origin line about 1 cm from the bottom of the paper or plate.
3. Apply a small, concentrated spot of extract to the origin, letting it dry between applications.
4. Stand the paper or plate in a small depth of running solvent, below the origin, in a covered container.
5. Remove it when the solvent is near the top and immediately mark the solvent front with pencil.
6. Mark the centre of each pigment spot, measure distances from the origin and calculate R_f values.

$$R_f = \text{distance moved by pigment} \div \text{distance moved by solvent front}$$

R_f values are always between 0 and 1 and have no units. Pigments are identified by their **colour** and by comparing their **R_f values** with reference values for the same solvent and stationary phase.

Common photosynthetic pigments and their colours

Pigment	Colour on the chromatogram
Carotene	Orange-yellow (usually travels furthest)
Xanthophylls	Yellow
Chlorophyll a	Blue-green
Chlorophyll b	Yellow-green

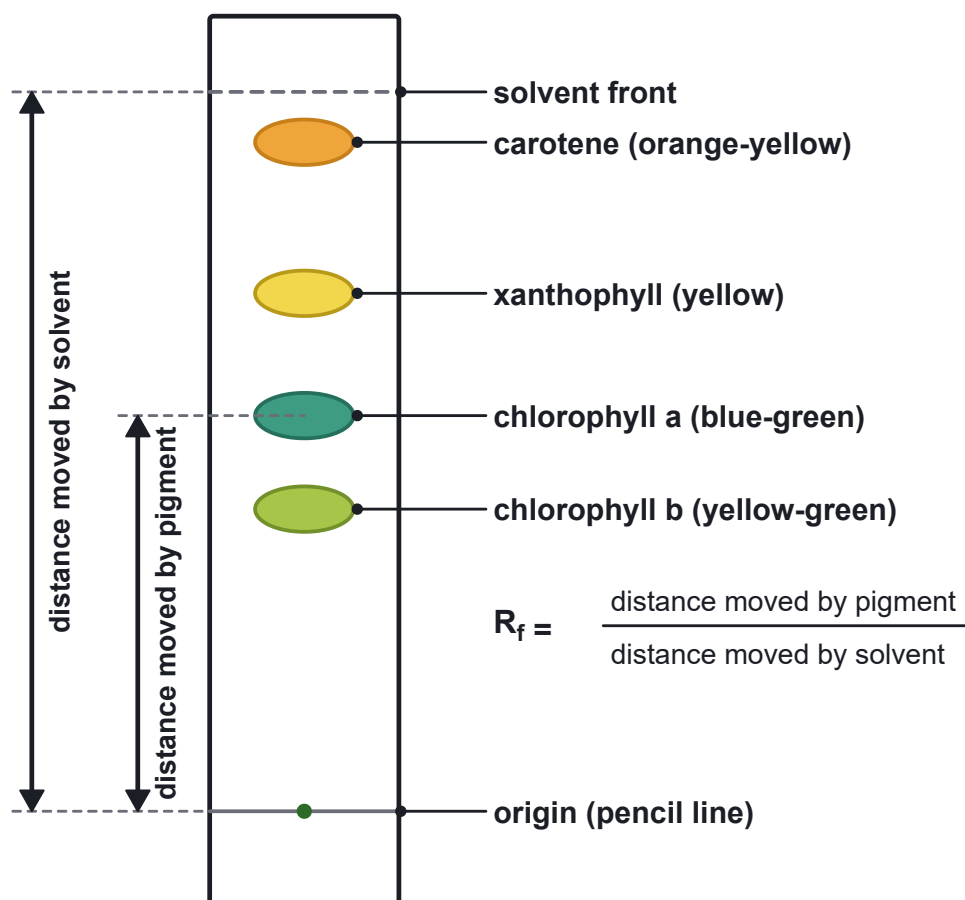
Calculating an R_f value

On a chromatogram the solvent front moved 8.0 cm from the origin. A blue-green spot moved 4.4 cm. Calculate its R_f value.

1. $R_f = \text{distance moved by pigment} \div \text{distance moved by solvent front}$.
2. $R_f = 4.4 \div 8.0 = 0.55$.

Answer: $R_f = 0.55$ (no units). With its blue-green colour this is likely chlorophyll a; confirm with reference values for the same method.

Practical skill: Use a pencil for the origin (ink would separate too), keep the origin above the solvent, and measure to the centre of each spot. R_f values depend on the solvent and medium, so only compare with references from the same method.



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A typical chromatogram of leaf pigments (illustrative positions; order and R_f values depend on the solvent and medium). $R_f = \text{pigment distance} \div \text{solvent distance}$.

Absorption of light, absorption spectra and action spectra Spec C1.3.5, C1.3.6

Absorption of specific wavelengths

When a pigment molecule absorbs light, the energy **excites an electron** within the molecule, raising it to a higher energy level. This is the first step in transforming light energy to chemical energy, because the excited electron can be passed on to other molecules.

Only some wavelengths are absorbed. Electrons in a pigment can only occupy certain energy levels, so only photons whose energy matches the gap between levels can be absorbed. Other wavelengths are reflected or transmitted. **Chlorophyll** absorbs red and blue light most strongly and reflects green light, which is why leaves look green. Accessory pigments such as carotenoids absorb other wavelengths, mainly in the blue-green region.

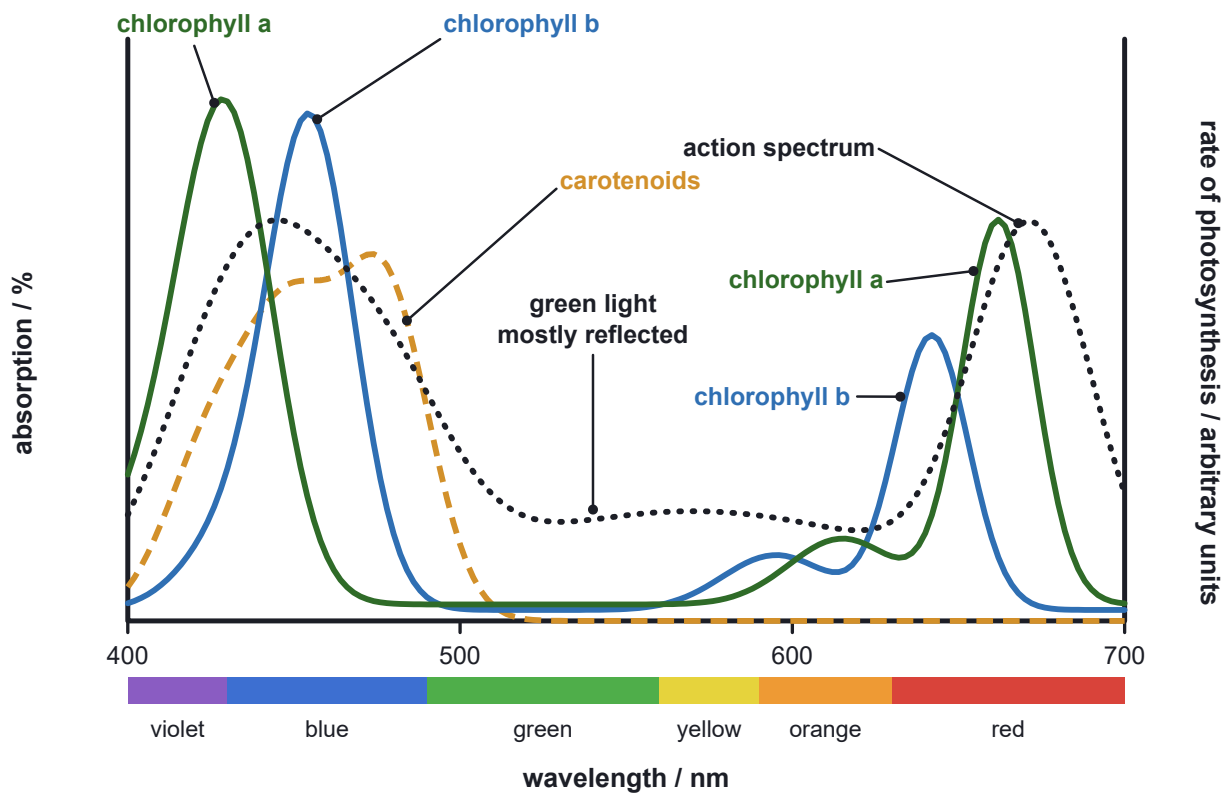
Absorption spectra and action spectra

Absorption spectrum	A graph showing the percentage of light absorbed by a pigment (or pigments) at each wavelength.
Action spectrum	A graph showing the rate of photosynthesis at each wavelength of light.

Both graphs have **wavelength** (in nm, from about 400 to 700 nm) on the horizontal axis, which should also show the **colours** of light: violet and blue at the short-wavelength end, then green, yellow, orange and red.

Similarities and differences of absorption and action spectra		
	Absorption spectrum	Action spectrum
Vertical axis	% of light absorbed	Rate of photosynthesis
Peaks	Blue and red for chlorophyll	Also blue and red
Green region	Low absorption by chlorophyll	Rate low but not zero, because accessory pigments absorb some light and some green light is absorbed as it passes through the leaf
How obtained	Shine each wavelength through a pigment extract and measure absorbance	Measure rate of oxygen production or carbon dioxide consumption under each wavelength

The **similar shape** of the two graphs is evidence that the light absorbed by these pigments is the light used in photosynthesis.



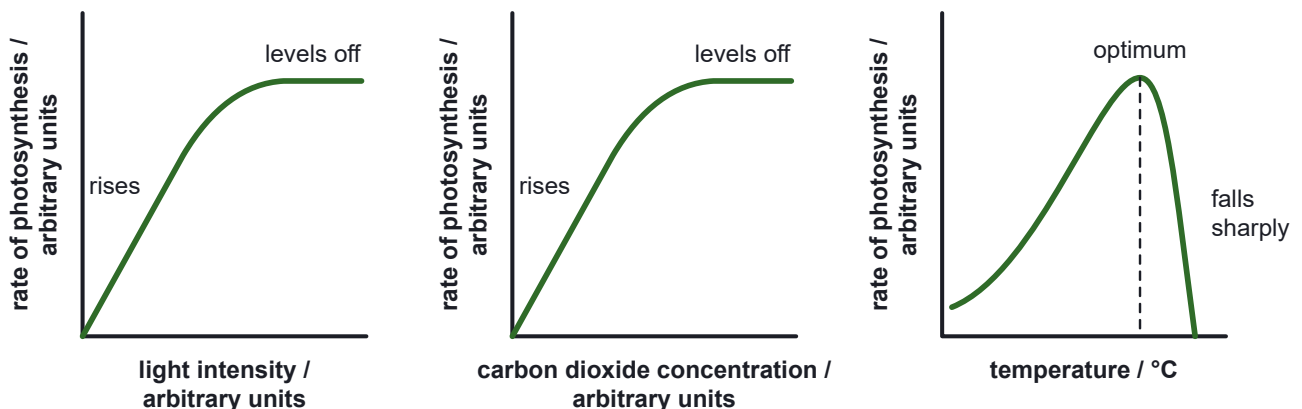
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Illustrative curves: the action spectrum **matches the absorption spectra**, with peaks in blue and red light; green light is mostly reflected.

Maths skill: To make an action spectrum, calculate the rate at each wavelength (for example volume of oxygen $\div$ time, or CO_2 uptake $\div$ time), then plot rate against wavelength with points joined by a smooth curve or straight lines.

Investigating limiting factors on photosynthesis Spec C1.3.7

The rate of photosynthesis depends on several factors. At any moment, the **limiting factor** is the one that is furthest from its optimum: increasing it raises the rate, while increasing the others does not.



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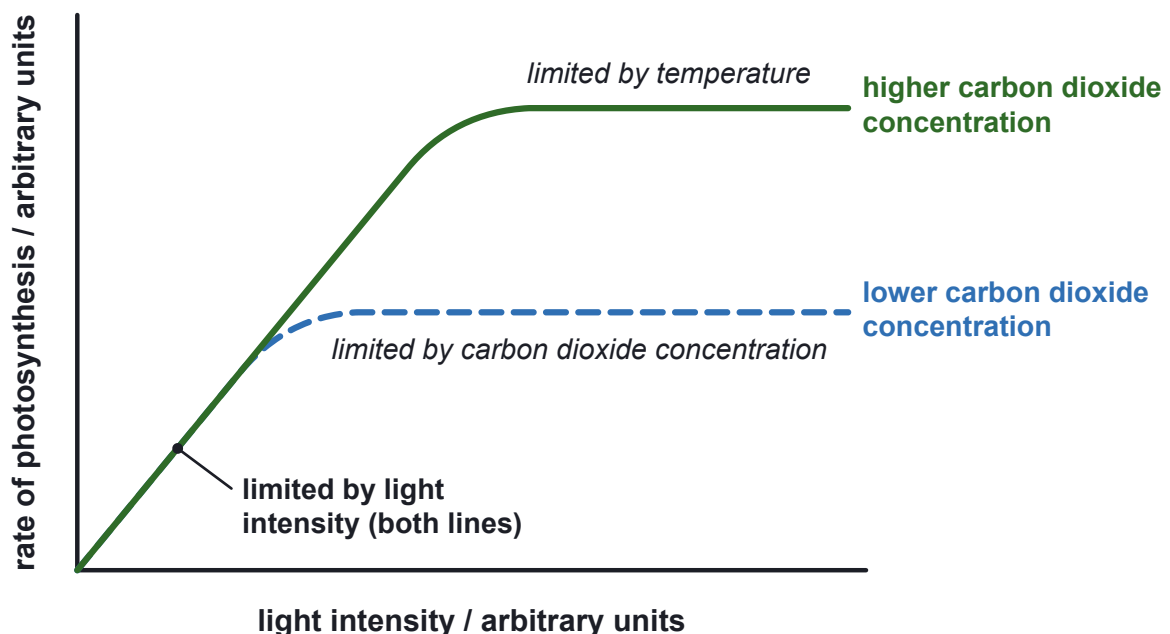
Light intensity and carbon dioxide concentration: the rate **rises, then levels off** when another factor limits. Temperature: the rate rises to an optimum, then falls as enzymes denature.

Techniques for varying each factor

How to vary each limiting factor		
Independent variable	How to vary it	Notes
Light intensity	Change the distance of a lamp from the plant, or use filters or a dimmable LED	Light intensity falls with distance (roughly proportional to $1 \div \text{distance}^2$); use an LED or a heat shield so temperature does not change
Carbon dioxide concentration	Use different concentrations of sodium hydrogencarbonate solution around aquatic plants or leaf discs	Hydrogencarbonate releases CO_2 in water
Temperature	Place the plant in water baths at different temperatures	Allow time to equilibrate; check with a thermometer

Measuring the rate

- Count bubbles or collect the volume of oxygen released by an aquatic plant such as *Elodea* or *Cabomba* per minute.
- Time how long leaf discs (with air removed so they sink) take to float as oxygen builds up.
- Measure carbon dioxide uptake with a sensor and data logger, or by the colour change of a hydrogencarbonate indicator.



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Where each line levels off, light is no longer limiting: the **factor in shortest supply** sets the plateau.

Practical skill: Identify the independent variable (the factor you change) and the dependent variable (the rate, for example oxygen per minute). Keep the other two factors constant and repeat each condition.

Exam tip: A hypothesis is a provisional explanation that needs repeated testing. You can suggest one from theory before the experiment (for example, 'rate rises with light intensity because more light energy is absorbed by chlorophyll') or from results after it.

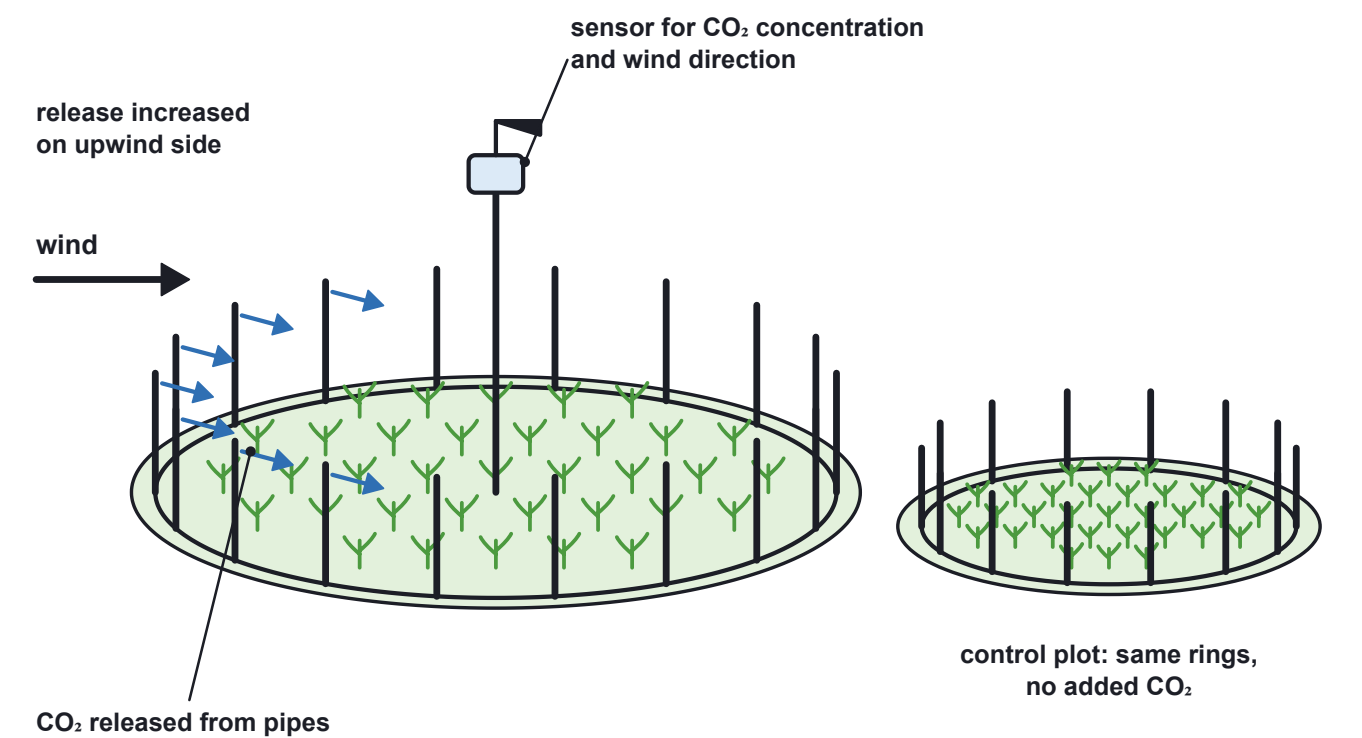
Carbon dioxide enrichment experiments Spec C1.3.8

Atmospheric carbon dioxide concentration is rising. Carbon dioxide enrichment experiments grow plants at concentrations predicted for the future to find out how rates of photosynthesis and plant growth may change.

Two types of CO ₂ enrichment experiment		
	Enclosed greenhouse experiments	Free-air CO ₂ enrichment (FACE)
Set-up	Plants grown in closed glasshouses or chambers with CO ₂ added to the air	Rings of pipes release CO ₂ around plots in a field or natural ecosystem; sensors adjust the release to hold a target concentration
Control of variables	Easier: temperature, light, water and minerals can be controlled	Harder: weather, soil and pests vary, but affect treated and control plots similarly
How realistic	Less natural: enclosure changes temperature, humidity and wind	More realistic: plants grow in field conditions with other species
Control	Identical greenhouse at current CO ₂	Plots with the same ring structure but no added CO ₂

Higher carbon dioxide generally increases the rate of photosynthesis and growth, at least for a time. However, several FACE studies of crops found smaller increases in growth and yield than enclosed experiments had predicted (the size of the gap is still debated). In the field, other factors such as water, temperature or soil nitrogen can become limiting, and the effect of extra CO₂ can shrink over the years.

Practical skill: Be able to identify a controlled variable, such as plant species, light intensity in a greenhouse, or plot size in a FACE experiment. Field experiments are less controlled than laboratory ones, but some questions can only be answered in natural ecosystems.



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A FACE experiment: pipes release CO₂ around a field plot to hold a target concentration; control plots have the same rings but no added CO₂.

Quick check

- 1 . Write the word equation for photosynthesis.
- 2 . Where does the oxygen released by photosynthesis come from?
- 3 . How is an Rf value calculated?
- 4 . What is the difference between an absorption spectrum and an action spectrum?

Quick check answers

Enzymes and metabolism

1. The complex network of interdependent and interacting chemical reactions occurring in living organisms.
2. Anabolic: protein synthesis, glycogen formation or photosynthesis. Catabolic: hydrolysis in digestion or oxidation of glucose in respiration.
3. Both the substrate and the enzyme's active site.
4. The activation energy is lowered; the overall energy change is unchanged.

Cell respiration

1. Adenosine triphosphate; a nucleotide.
2. glucose $\rightarrow$ lactate
3. It absorbs carbon dioxide, so the movement of the drop measures oxygen uptake.

Photosynthesis

1. carbon dioxide + water $\rightarrow$ glucose + oxygen
2. The splitting of water.
3. Distance moved by the pigment $\div$ distance moved by the solvent front.
4. An absorption spectrum shows light absorbed by a pigment at each wavelength; an action spectrum shows the rate of photosynthesis at each wavelength.