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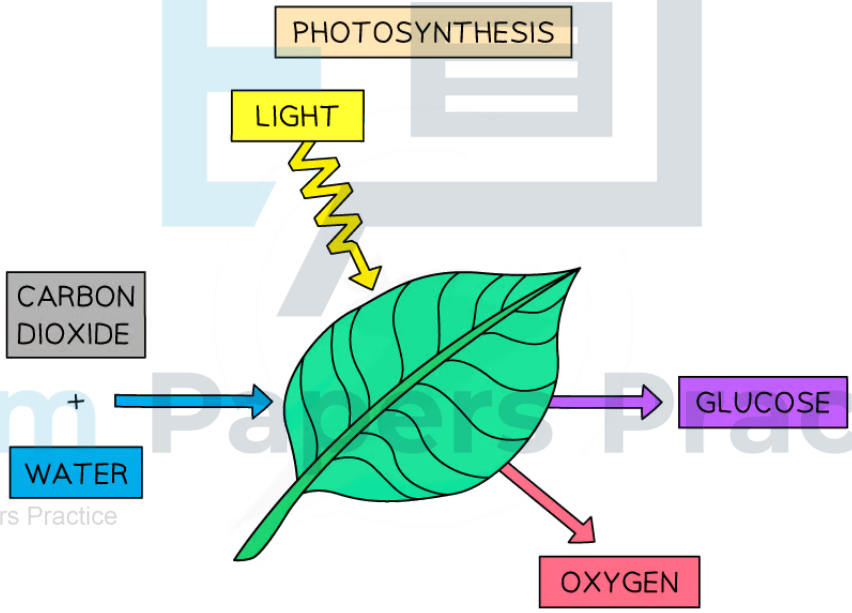
2.8 Photosynthesis

IB Biology - Revision Notes

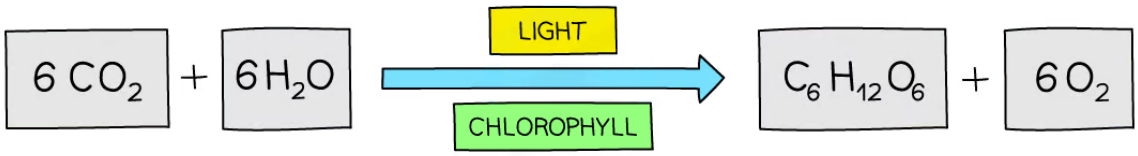
2.8.1 Photosynthesis

Photosynthesis Defined

- **Simple, inorganic compounds** are converted into complex organic ones by photosynthesis
  - The energy required is provided by **light**
- Photosynthesis occurs in autotrophic organisms such as **plants**, **algae** and **cyanobacteria**
  - H_2O and CO_2 are the **raw materials**
- Photosynthesis is a form of **energy conversion**, from **light energy** to **chemical energy**, stored in biomass
- **Energy is stored** within the bonds of these organic compounds
- Photosynthesis can be thought of as the **exact reverse of respiration**
  - Respiration is the process by which **energy is *released*** from organic molecules in living cells
- The overall **chemical equation** for photosynthesis is as follows:



The basic equation of photosynthesis as it takes place in a leaf



The chemical equation for photosynthesis

Exam Tip

Remember, energy is never created or destroyed; it is only ever converted from one form to another!

Visible Light Wavelengths

- Chloroplasts contain **pigments** in order to **absorb light**
- Pigments are **coloured**, which means they absorb **some wavelengths** (or colours) of the white light that the Sun radiates
  - The remaining light is **reflected**, giving the pigment its colour
- Chloroplasts contain several different **photosynthetic pigments**, so that they can **absorb multiple different wavelengths of light**
  - The main photosynthetic pigment is **chlorophyll**
- **Violet light** has the shortest wavelength of light in the visible spectrum (around 400nm)
- **Red light** has the longest wavelength of light in the visible spectrum (around 700nm)
- **Green light** has a wavelength in the middle of this range (around 550nm)
- The **absorption of light varies with wavelength**, as does the **rate of photosynthesis** that a plant can carry out
- When plants are exposed to light of a specific wavelength, the **rate of photosynthesis** can be measured as well as the **absorbance** (the % of the light that is absorbed by the plants)
- There are peaks in both plots at the **blue** and **red** ends of the spectrum, where photosynthesis can occur
- There are troughs in both plots for **green** light, which is **not absorbed** and so **cannot provide energy for photosynthesis**

Chlorophyll

- Plant cells contain **chloroplasts** which are the site of photosynthesis
- The main photosynthetic pigment is **chlorophyll**
- Chlorophyll absorbs red and blue light most effectively and reflects green light more than other colours
  - Chlorophyll appears green because it **absorbs red and blue light**
  - The **green light is reflected away** and so leaves appear green to the eye
  - This explains **why the majority of plants are green** (with variations in the shades of green that we can see)
- Red and blue light provides the energy needed for photosynthesis
- Chlorophyll exists in **two main forms**, ***a*** and ***b***
- There are **two groups** of pigments: primary pigments known as **chlorophylls** and accessory pigments known as **carotenoids**
- **Chlorophylls** absorb wavelengths in the **blue-violet and red regions** of the light spectrum
- **Carotenoids** absorb wavelengths of light mainly in the **blue-violet region** of the spectrum
- The combination of pigments **maximises the amount of white light energy** that can be captured

Exam Tip

Remember – chlorophyll is not the only photosynthetic pigment, others exist to maximise light energy absorption.

Photolysis of Water

- Oxygen is produced in photosynthesis from the photolysis of water
  - **Photo** - means 'with light'
  - **Lysis** - means 'breaking apart'
- Water is **broken apart using light** energy; this is called **photolysis**
- This releases **electrons** (e^-), **protons** (H^+) and the waste product, **oxygen gas**

$$2H_2O \rightarrow 4e^- + 4H^+ + O_2$$

- Whilst oxygen is a waste product, the **electrons and protons** play a crucial role in the **further reactions** of photosynthesis
  - Though oxygen is a waste product, in practice, a plant will use some of the oxygen it produces in photosynthesis for its own respiration (during the day)

2.8.2 Photosynthesis Continued

Effects of Photosynthesis

- Changes to the Earth's atmosphere, oceans and rock deposition occur due to photosynthesis
- The **first life forms** emerged around 4 billion years ago
  - At the time, there was **no oxygen in the atmosphere**
- About 3.5 billion years ago photosynthetic prokaryotes became the first organisms to carry out photosynthesis
  - **This began the release of oxygen** into the atmosphere
- Millions of years later algae and plants evolved and also carried out photosynthesis
- Around 2.2 billion years ago, the oxygen concentration in the atmosphere reached 2%
  - This is known as the Great Oxidation Event
- Other changes to the Earth occurred due to photosynthesis
  - **Minerals** in the oceans were **oxidised**
    - Photosynthetic bacteria released oxygen into the ocean
    - When dissolved iron was oxidised it formed iron oxide which is a red precipitate that lies on the sea bed
    - Over time a distinctive rock formation was produced - the banded iron formation. Layers of red iron oxide alternate with other mineral oxides
    - Banded iron formations are the most important source of iron **ores** (and consequently our supply of steel)
  - Methane and CO_2 levels in the air fell, which resulted in an **Ice Age**
    - Because methane and CO_2 are important **greenhouse gases**
- By 600 million years ago, life had evolved into **large multicellular organisms**, many of which were photosynthetic (plants)
- This pushed the oxygen concentration of the air up to 20%, **peaking at 35%** 300 million years ago
  - This contributed to the **large size of the animals** that roamed the Earth at that time
- The current atmospheric oxygen level is around 21%, due to **increased human activity** eg. burning of fossil fuels, deforestation which remove oxygen from the atmosphere

Energy Requirements

- Chemical reactions can be **exothermic** or **endothermic**
- Photosynthesis is an example of an endothermic reaction and an anabolic reaction, where the required energy input is in the form of light energy
- Energy is needed to produce carbohydrates and other carbon compounds from carbon dioxide
- The energy is not lost - it is **stored in chemical form** in the carbohydrates that are produced

Limiting Factors

Temperature, light intensity and carbon dioxide concentration are possible limiting factors on the rate of photosynthesis

- Each of these factors can **limit the rate of photosynthesis** when they are below the optimal level
  - Temperature
  - Light intensity
  - Carbon dioxide concentration
- These are known as the **limiting factors** of photosynthesis
  - A limiting factor is a variable that holds back the rate of a chemical reaction
  - If that variable is increased, the reaction rate also increases
- Under any set of conditions, only one of these factors will be limiting the rate of photosynthesis
  - At night, **light intensity** will be very low, so that is the limiting factor
  - On a cold, sunny day, **temperature** will be the limiting factor
    - An increase in the light intensity will not increase the rate of photosynthesis because the temperature is, at that point, the limiting factor

Analogy - Limiting Factors

Imagine you're on a group hike and you have to stick together with your two teammates. You are not allowed to finish the hike separately. If your legs are feeling weak, you will be walking slowly. The other two hikers will have to slow down to walk at your speed; the team progresses at the speed of the slowest member. However, after lunch, you may be feeling strengthened by the food and your legs feel good; this time, it's your teammate who is the slowest, so has taken over from you as the limiting factor. Your team only finishes when all three of you finish, and that determines your overall rate of progress.

Exam Tip

When writing about limiting factors, it's important to mention '**light intensity**', not just 'light'. Other aspects of light such as wavelength can play a role so it's important to specific about intensity.

2.8.3 Skills: Photosynthesis

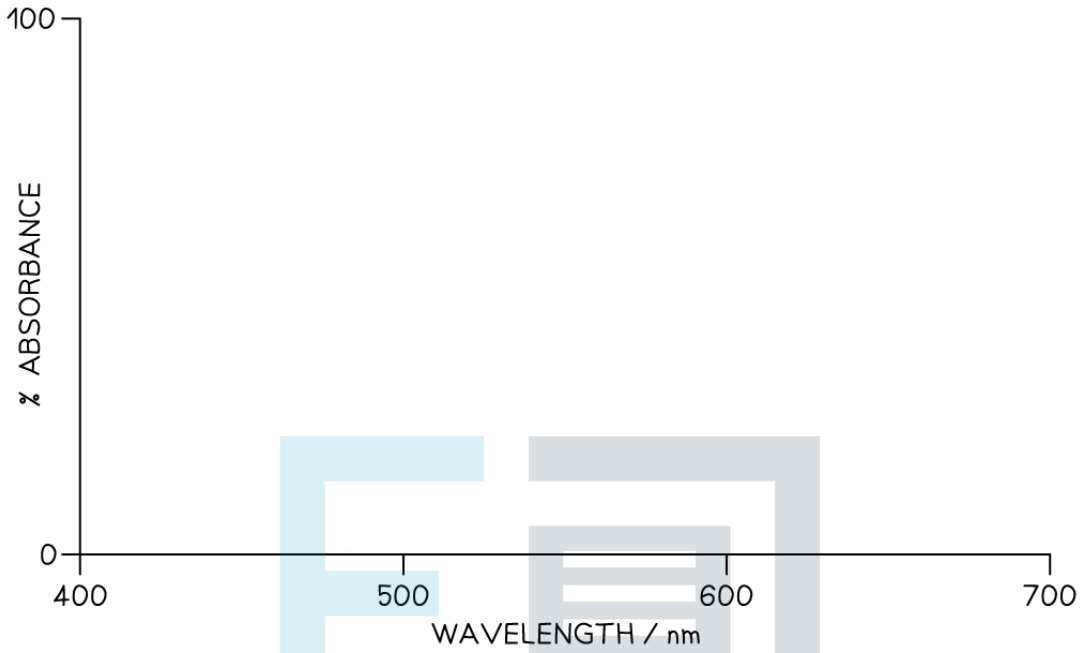
Absorption & Action Spectrums

- An **absorption spectrum** (for a particular pigment) shows how much light of different wavelengths is absorbed by the pigment
- An **action spectrum** shows how each wavelength of light affects the rate of photosynthesis that it can power
- These are two graphs that use the wavelength of light on the x-axis
  - **Violet** light is the **lowest wavelength** of the visible spectrum, at 400 nanometres (nm)
  - **Red** light is the **highest wavelength** of the visible spectrum, at 700 nanometres (nm)

Drawing an absorption spectrum for chlorophyll

Step 1: Draw and label the axes

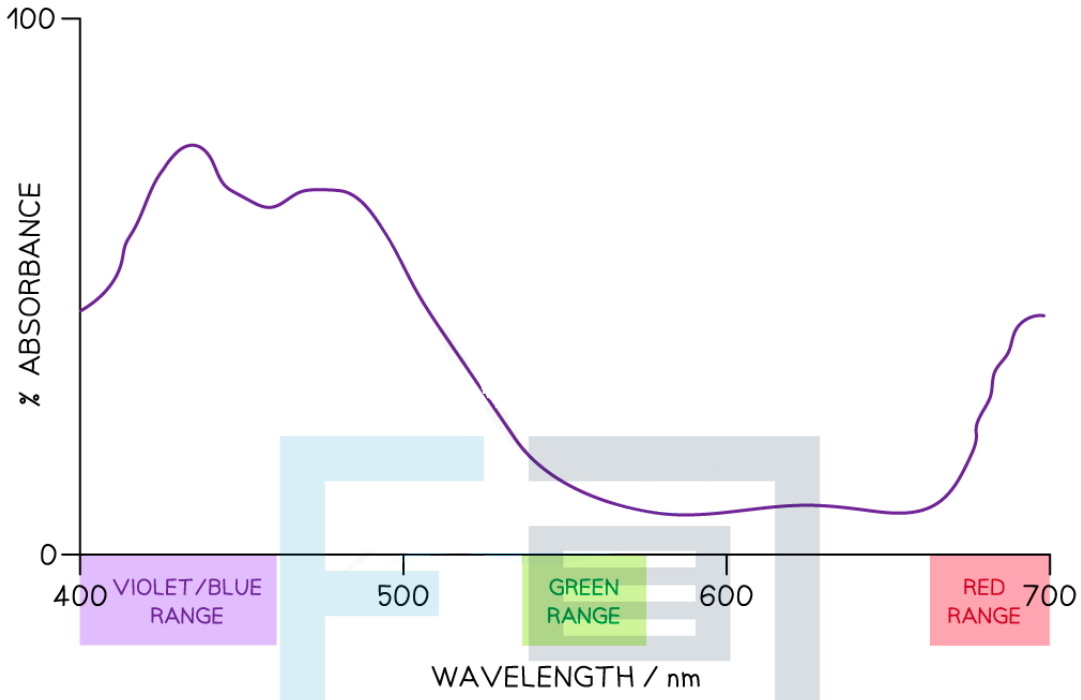
- Draw an x-axis
- Label the axis **wavelength**
- Add the units / **nm**
- Make 400 the smallest value and 700 the largest value
  - Label 500 and 600 nm on the x-axis
- Draw a y-axis
- Label it **% absorption**
- Make 0 the lowest value and 100 the highest value
  - No units are required because the y-axis is showing a percentage scale



Step 1 : Draw and label the axes

Step 2: Draw the Plot

- There should be **two absorbance peaks**
  - One peak at either end, in the blue and red areas of the spectrum
  - And a **trough** in the middle, which represents green light
  - As below, with a smooth curve



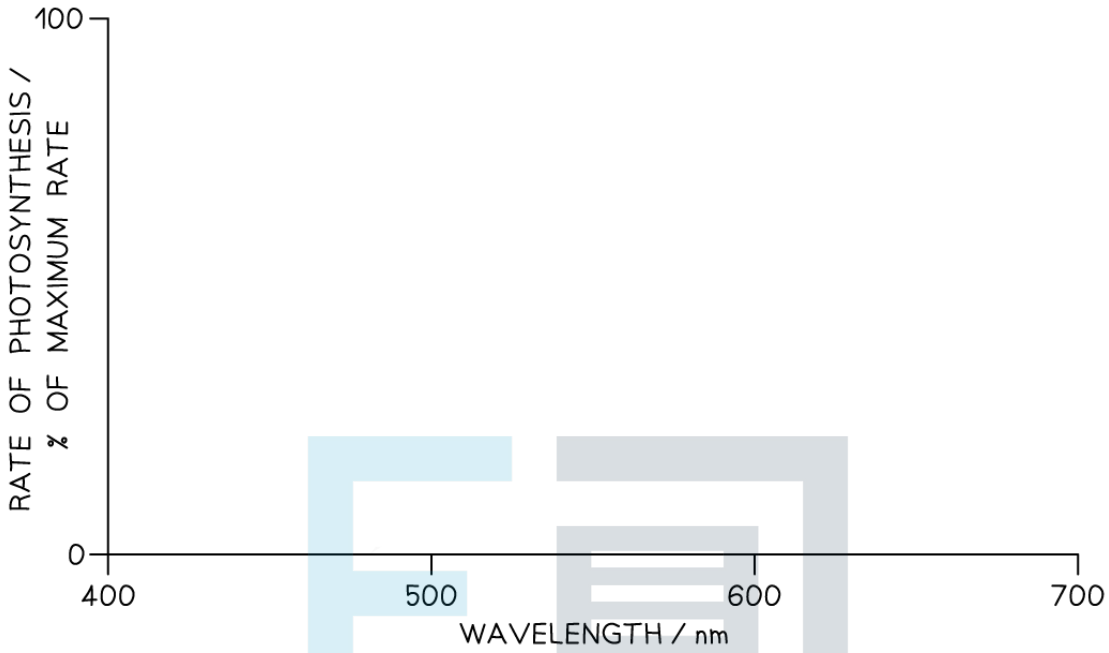
Step 2: Sketch the Curve

An absorbance spectrum for photosynthesis (colour range labels are not required)

Drawing an action spectrum for photosynthesis

Step 1: Draw and label the axes

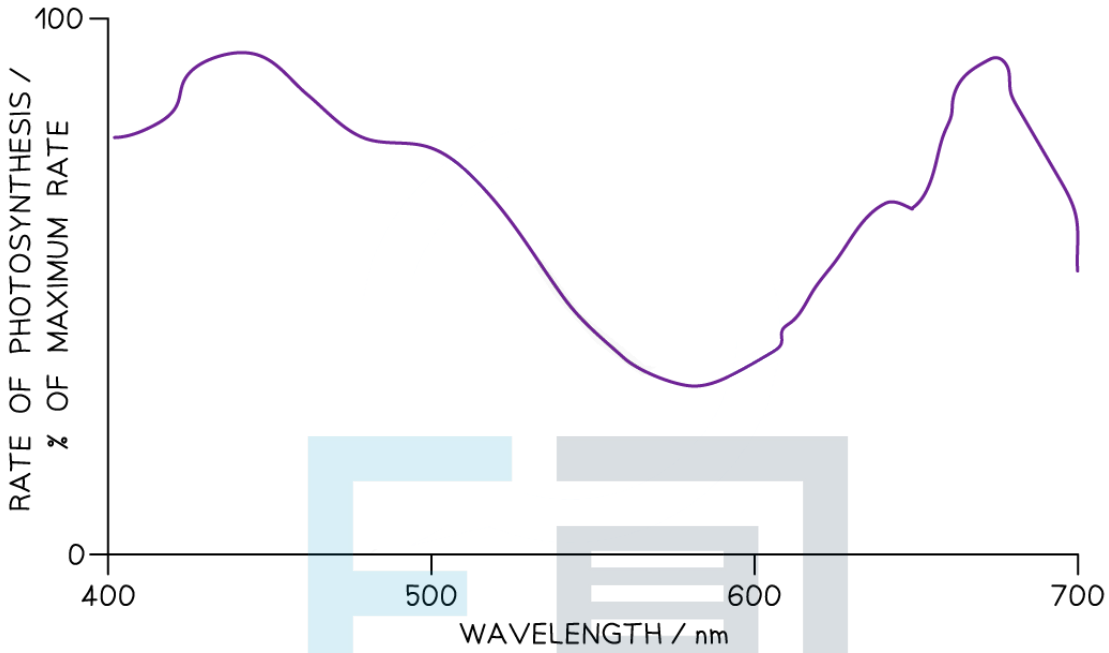
- Draw an x-axis
- Label the axis **wavelength**
- Add the units / **nm**
- Make 400 the smallest value and 700 the largest value
  - Label 500 and 600 nm on the x-axis
- Draw a y-axis
- Label it **Rate of photosynthesis / % of maximum rate**
- Make 0 the lowest value and 100 the highest value
  - No units are required because the y-axis is showing a percentage scale



Step 1 : Draw and label the axes

Step 2: Draw the plot

- There should be **two peaks of rate of photosynthesis**
  - One peak at either end, in the blue and red areas of the spectrum
  - And a **trough** in the middle, which represents green light
  - As below, with a smooth curve



Step 2: Sketch the Curve. An absorbance spectrum for photosynthesis (colour range labels are not required)

Exam Tip

Remember – the pigments themselves have a distinctive colour. This is different from the colours of light that they *absorb*. Key points to remember:

1. Label 400 - 700nm on the x-axis, in 100nm increments
2. Use a % scale on the y-axis
3. Smooth curve
4. Peaks at either end
5. Trough in the middle for green light

Investigating Photosynthesis

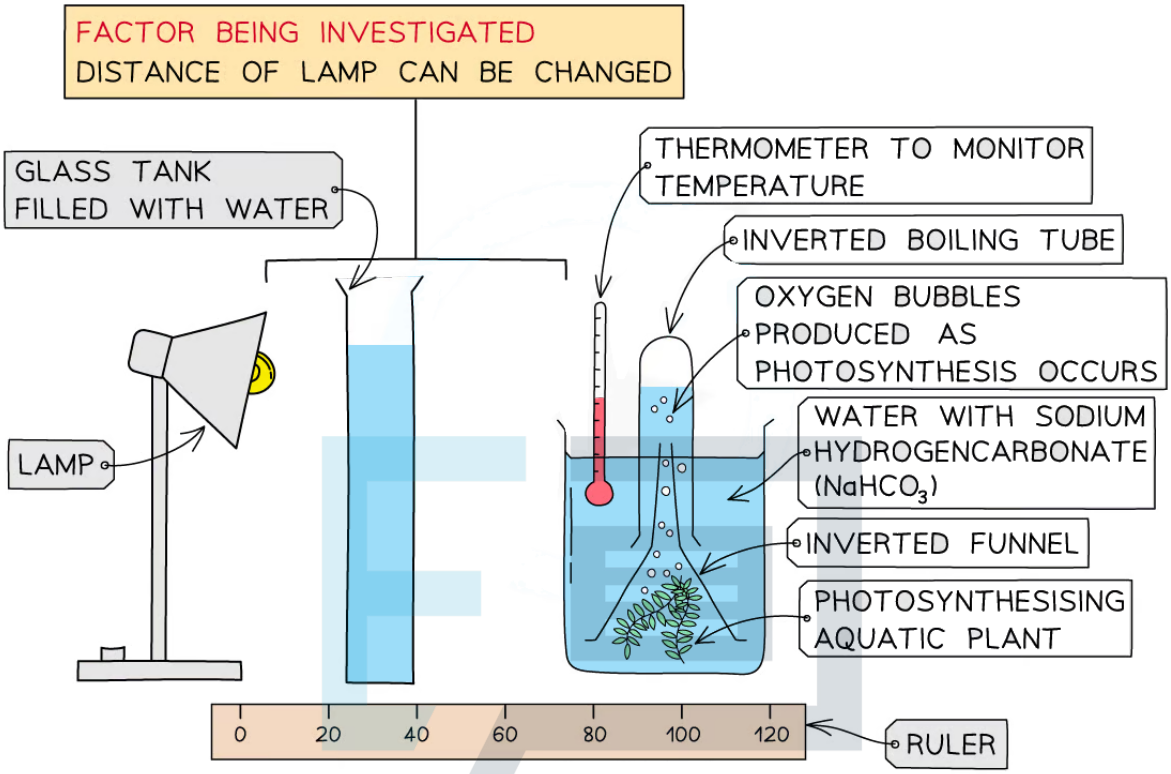
- An **aquatic plant** such as *Elodea* or *Camboba* is a good choice for investigating photosynthesis in plants, because the rate of photosynthesis can be measured by **counting oxygen bubbles** that come off a cutting of this plant
  - Oxygen output from terrestrial plants (that grow on land) would not be observable

NOS: Experimental design – controlling relevant variables in photosynthesis experiments is essential

- When designing an experiment it is crucial that all variables (apart from the independent and dependent variables being investigated) are controlled
  - The independent variable is the factor that is **deliberately manipulated** between a specific range throughout the experiment
  - The dependent variable is the factor that is **measured** during the experiment (to see if it is affected by the changes to the independent variable)
- Other variables must be controlled so that it can be said the independent variable is the only factor affecting the dependent variable during the experiment
- **Changes** in **light intensity**, **carbon dioxide concentration** and **temperature** are all limiting factors that affect the rate of photosynthesis and **can be altered experimentally** to measure the effect on the rate of photosynthesis

Effect of light intensity – experimental design

- Basic Experimental Setup
  - Aquatic plant cutting in water
  - Powdered sodium hydrogencarbonate ($NaHCO_3$)
  - Glass funnel
  - Boiling tube
  - Lamp for illumination
  - Glass tank filled with water



Measuring the Effect of Light Intensity on the Rate of Photosynthesis in Pondweed

Research Question

Does the rate of photosynthesis (number of bubbles released per min) of *Elodea* increase as the light intensity increases?

Method

- Place a piece of aquatic plant (*Elodea* or *Cabomba* are often used), into a beaker of water
- Use a light a set distance from the plant
- Record the number of bubbles observed in three minutes
- Repeat steps for different distances

Improvements

- Use a **gas syringe** to collect and measure the volume of gas produced
- For **reliability** of data, **repeat** the experiment at least twice for each distance and calculate the mean number of bubbles
- Use of a **data logger** to measure results continuously

Variables to Be Controlled

- **Temperature**
  - The glass tank filled with water absorbs any heat that is emitted from the lamp
  - Modern LED bulbs can be used as they give off less heat than filament bulbs
- **CO_2 concentration**
  - The water used around the plant is first **boiled and re-cooled** to remove any dissolved carbon dioxide
  - A **set mass of sodium hydrogencarbonate** is added to the water that surrounds the plant
  - To make the concentration approx. 0.1 mol dm^{-3}, which is not a limiting concentration

Results

- A graph of the **number of bubbles produced per minute** against the **distance between the lamp and the plant** used can be drawn to see the pattern or trend
  - Distance between the lamp and the plant is linked to the light intensity

Carbon dioxide concentration

- The **same basic experimental setup** can be used, but with varying use of the following variables
- Start with boiled and re-cooled water as before
- Add **successive masses of sodium hydrogencarbonate** to increase the concentration in increments of 0.01 mol dm^{-3}, and record the rate of photosynthesis in bubbles $minute^{-1}$
- **Keep the temperature constant** at 25°C using a water bath, monitoring with a thermometer in the water surrounding the aquatic plant
- **Keep the light intensity constant** by keeping the lamp a fixed distance from the plant

Temperature

- The **same basic experimental setup** can be used, but with varying use of the following variables
- Start with boiled and re-cooled water as before, with **sodium hydrogencarbonate at a fixed concentration** of 0.1 mol dm^{-3}, and record the rate of photosynthesis in bubbles $minute^{-1}$
- **Vary the temperature from** 5°C to 50°C using water baths, monitoring with a thermometer in the water surrounding the plant
- **Keep the light intensity constant** by keeping the lamp a fixed distance from the plant
- The rate will tail off after around 40°C due to the denaturation of important proteins involved in photosynthesis

Exam Tip

The key to this part of the spec is to appreciate how an experimental investigation can be controlled so that any effects we observe **are directly due to the one variable** that we are deliberately changing.

2.8.4 Skills: Separating Photosynthetic Pigments

Practical 4: Separation of Photosynthetic Pigments

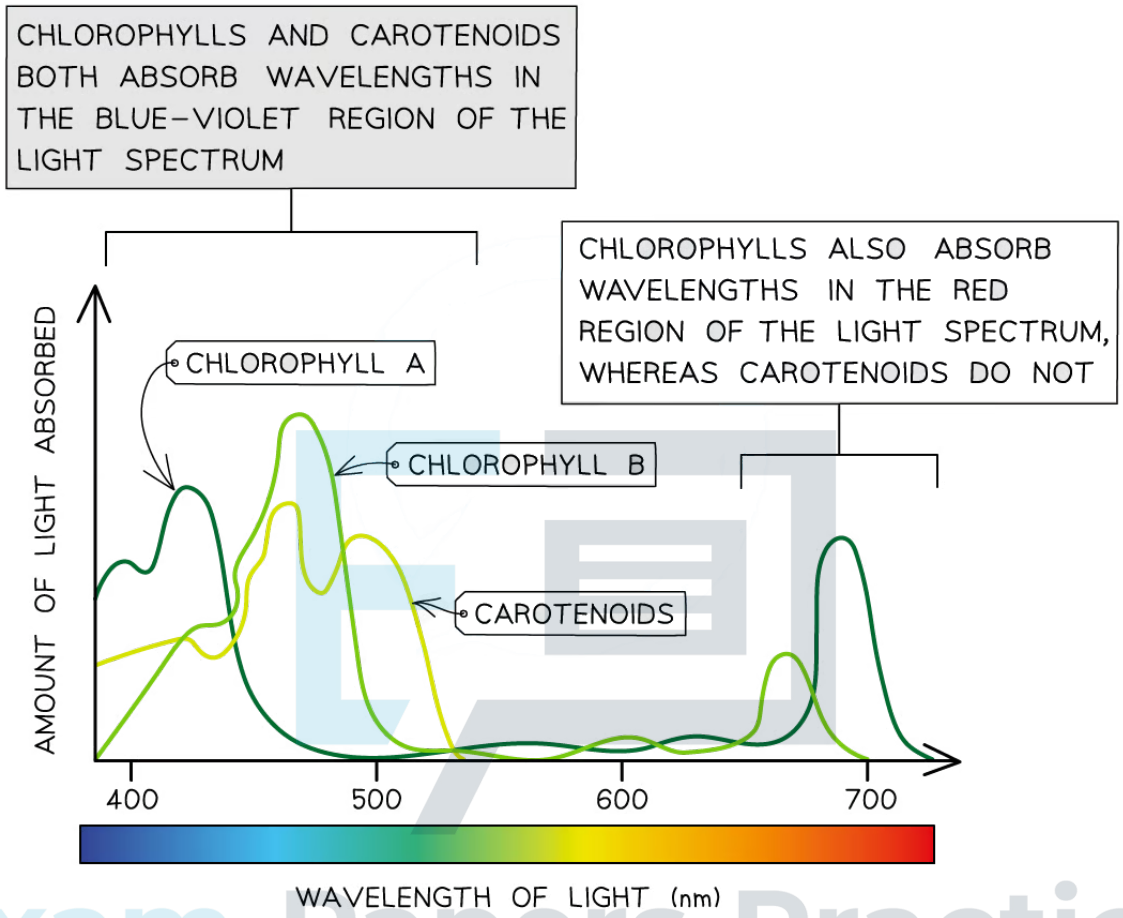
Separation of photosynthetic pigments by chromatography

- Plants contain several different **photosynthetic pigments**, which **absorb different wavelengths of light**
- There are **two groups** of pigments: **chlorophylls** and **carotenoids**
- Carotenoids surround the chlorophyll and absorb both similar and different wavelengths of light to chlorophyll
  - This **expands the range of wavelengths** that can be absorbed from light for use in photosynthesis

Chloroplast Pigments Table

Pigment group	Name of pigment	Colour of pigment
Chlorophylls	Chlorophyll a Chlorophyll b	Yellow–green Blue–green
Carotenoids	β carotene Xanthophyll	Orange Yellow

- **Chlorophylls** absorb wavelengths in the **blue-violet and red regions** of the light spectrum
  - They reflect green light, causing plants to appear green
- **Carotenoids** absorb wavelengths of light mainly in the **blue-violet region** of the spectrum



Chlorophyll and carotenoids absorb light across the visible light spectrum to use in the light-dependent reaction of photosynthesis

Chromatography

- **Chromatography** is an experimental technique that is used to **separate mixtures**
  - **Different components** within the mixture travel through the material at **different speeds**
  - This causes the different components to **separate**
  - A retardation factor (**R_f value**) can be calculated for each component of the mixture

- Two of the most common techniques for separating these photosynthetic pigments are:
  - **Paper chromatography** – the mixture of pigments is passed through paper (cellulose)
  - **Thin-layer chromatography (TLC)**– the mixture of pigments is passed through a thin layer of adsorbent (eg. silica gel), through which the mixture travels faster and separates more distinctly

- Paper chromatography can be used to separate photosynthetic pigments although **TLC gives better results**

Apparatus

- Leaf sample
- Distilled water
- Pestle and mortar
- Filter paper
- Capillary tube
- Chromatography solvent
- Propanone
- Pencil
- Ruler

Method

- Draw a straight line in pencil approximately 1cm above the bottom of the filter paper being used
  - **Do not use a pen** as the ink will separate into pigments within the experiment and obscure the results
- Cut a section of leaf and place it in a mortar
  - It is important to **choose a healthy leaf** that has been in direct sunlight so you can be sure it contains many active photosynthetic cells
- Add 20 drops of propanone and use the pestle to grind up the leaf sample and release the pigments
  - Propanone is an organic solvent and therefore fats, such as the lipid membrane, dissolve in it
  - The combination of propanone and mechanical pressure breaks down the cell and chloroplasts to **release the pigments**
- Extract some of the pigment using a capillary tube and spot it onto the centre of the pencil line you have drawn
- Suspend the paper in the chromatography solvent so that **the level of the solvent is below the pencil line** and leave the paper until the solvent has reached the top of the paper
  - The mixture is **dissolved** in the **solvent** (called the mobile phase) and the dissolved mixture then passes through a static material (called the stationary phase)
- Remove the paper from the solvent and draw a pencil line marking where the solvent moved up to
  - The pigment should have separated out and there should be different spots on the paper at different heights above the pencil line, these are the separate pigments
- Calculate the Rf value for each spot

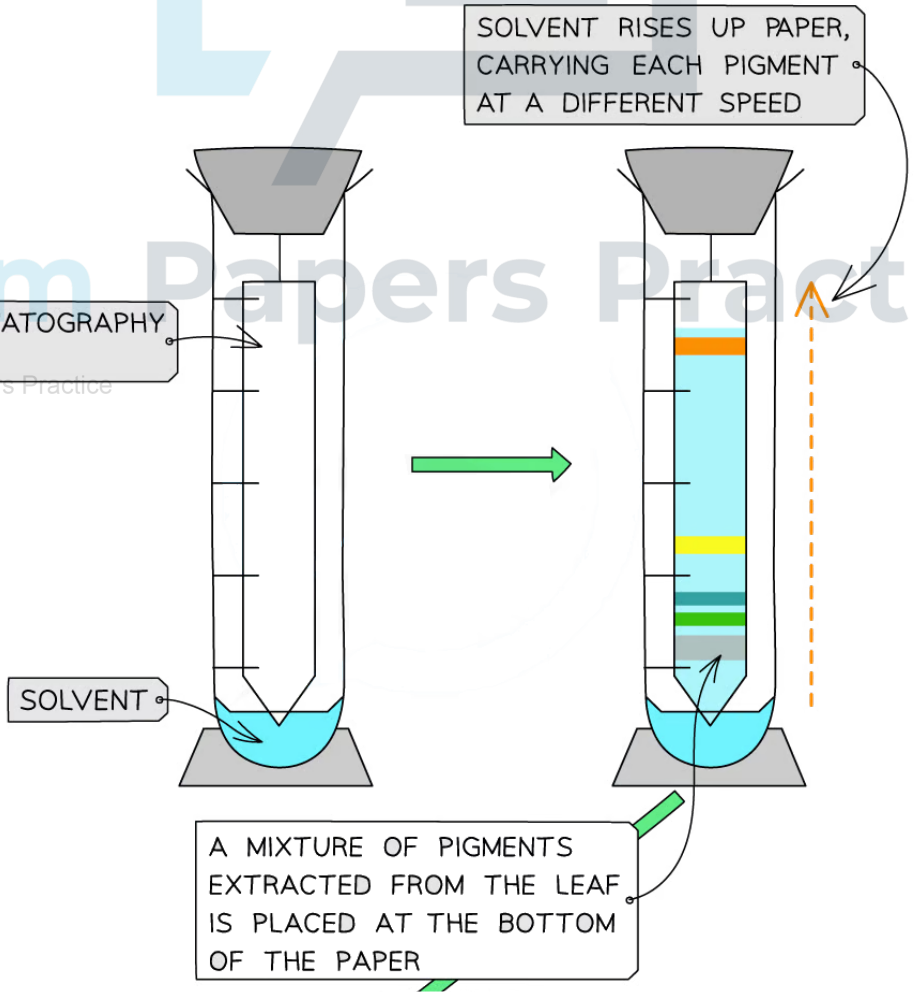
$$R_f \text{ value} = \frac{\text{distance travelled by component (pigment)}}{\text{distance travelled by the solvent}}$$

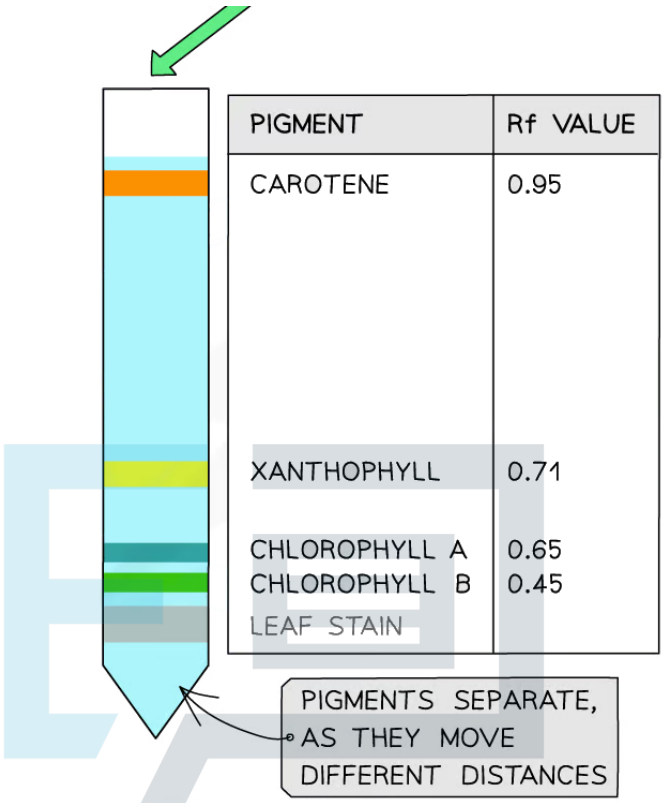
- Always measure to the centre of each spot

Results

- Chromatography can be used to **separate and identify chloroplast pigments** that have been extracted from a leaf as each pigment will have a unique R_f value
- The R_f value demonstrates how far a dissolved pigment travels through the stationary phase
  - Molecules with a higher affinity to the stationary phase, such as large molecules, will travel slower and therefore have a **smaller R_f value**
  - Molecules that are more soluble in the mobile phase will travel faster and therefore have a **larger R_f value**

- Although specific R_f values depend on the solvent that is being used, in general:
  - **Carotenoids** have the **highest R_f values** (usually close to 1)
  - **Chlorophyll *b*** has a **much lower R_f value**
  - **Chlorophyll *a*** has an R_f value somewhere **between** those of carotenoids and chlorophyll *b*
  - **Small R_f values** indicate the pigment is **less soluble** and/or **larger** in size





Paper chromatography is used to separate photosynthetic pigments. These pigments can be identified by their R_f values. In this example, a line of the mixture (rather than a spot) is added to the paper.

Limitations

- Paper chromatography is not as specific as other chromatography techniques
  - It is sufficient to separate and distinguish different pigments and to calculate their R_f value
- Chromatography does not give data on the amount of each pigment present or the wavelengths that they absorb
  - Colorimetry can be used to calculate these values

Exam Tip

Remember – the pigments themselves have colour (as described in the table). This is different from the colours of light that they *absorb*. You don't have to remember specific R_f values, just know that they differ between each type of pigment.