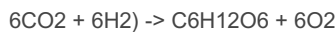


Key Terms

Photophosphorylation	Synthesis of ATP from ADP and Pi (inorganic phosphate) using light energy .
Transducers	Change energy from one form into another
Absorption Spectrum	A graph that shows how much light energy is absorbed at different wavelengths .
Action Spectrum	A graph that shows the rate of photosynthesis at different wavelength .
Antenna Complex	An array of protein and pigment molecules in the thylakoid membranes with chlorophyll a at the reaction centre. It transfers energy from light of a range of wavelengths to chlorophyll a .
Limiting Factor	A factor that limits the rate of a physical process by being in short supply .

Overview of Photosynthesis

The overall equation for photosynthesis is:



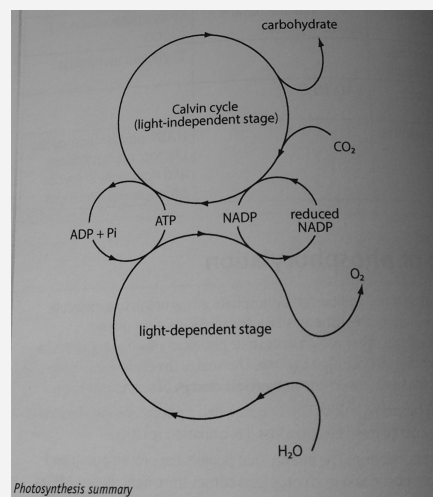
Photosynthesis involves two stages:

1. **Light-dependent stage** where **light energy** is **converted** into **chemical energy** as the **photolysis** of water **releases protons** and **electrons** which **produce ATP** via **photophosphorylation** and **reduce** the **co-enzyme NADP**.

Overview of Photosynthesis (cont)

2. **Light-independent stage** or **Calvin cycle** where **ATP** and **NADPH** from the **light-dependent reaction** **reduce carbon dioxide** to **produce glucose**.

Photosynthesis Summary



Structure of the leaf

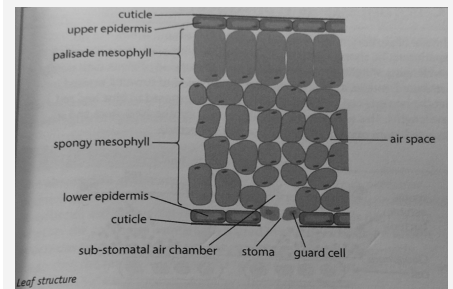
The leaf is **adapted** for **gas exchange** and **photosynthesis** by having a **large surface area** allowing the leaf to **capture light**, and having **pores** called **stomata** through which **gases diffuse**.

Air spaces between cells allow for **carbon dioxide** to diffuse to the **photosynthesising cells**.

The **highest concentration** of **chloroplasts** is found in the **palisade mesophyll** on the leaf's **upper surface**.

The **palisade cells** are **arranged vertically**, which allows **more light** to be absorbed by **chloroplasts** than if they were stacked **horizontally**, as **light** only has to pass through the **cuticle**, **epidermal cells** and one **palisade cell wall**.

Leaf structure



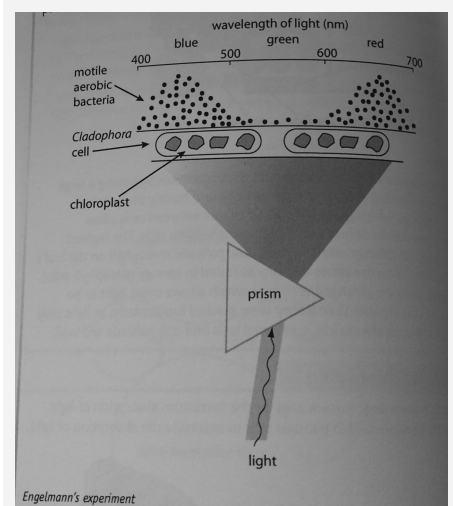
Chloroplasts as transducers

The site of **photosynthesis** was detected by **Engelmann** in 1887. In his experiment, he **shone a light** through a **prism** to separate the different **wavelengths of light**, and exposed **this** to a suspension of **algae** with evenly distributed, **motile**, aerobic bacteria. **

After a period of time, he noticed that the **bacteria congregated** around the **algae** exposed to **blue and red wavelengths**.

This was because this **algae photosynthesised more** and so **produced more oxygen**, attracting the **motile bacteria**.

Transducers



Photosynthetic pigments

In flowering plants there are 2 main types of pigments:

1. **Chlorophylls** which absorb red and blue-violet regions of the spectrum, e.g. **chlorophyll a** and **chlorophyll b**.
2. **Carotenoids** which absorb light energy from the blue-violet region of the spectrum, e.g. **B-carotene** and **xanthophylls**, and act as **accessory pigments**.

The presence of **several pigments** allows the plant to **absorb a wider range of wavelengths** of light than a **single pigment**.

Absorption and action spectra

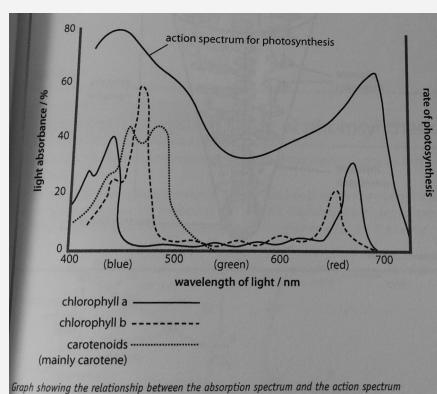
The **absorption spectrum** shows how much light energy a particular **pigment** absorbs at **different wavelengths**, for example **chlorophyll a** which absorbs red and blue-violet regions of the spectrum.

It **does not** indicate whether the **particular wavelength** is used in **photosynthesis**.

An **action spectrum** shows the **rate of photosynthesis** at **different wavelengths**, by measuring the mass of **carbohydrate** synthesised by plants.

There is a **close correlation** between the 2.

Absorption and action spectra



Light Harvesting

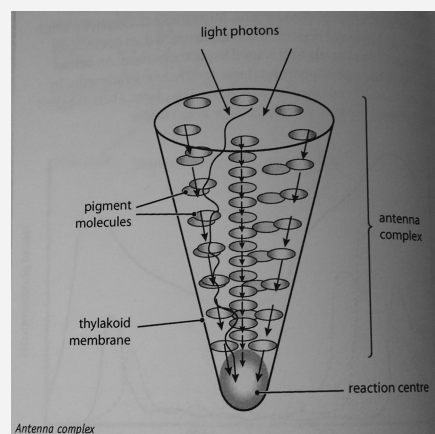
The **chlorophylls** and **accessory pigments** are found lying in the **thylakoid membranes**, grouped into **structures** called **antenna complexes**.

With the aid of **special proteins** associated with these **pigments**, **light energy** (photons) is funnelled towards the **reaction centre** at the base, containing **chlorophyll a**.

There are 2 types of reaction centre:

1. **Photosystem 1 (PS1)** chlorophyll a, with an **absorption peak** of **700nm**, also called **P700**.
2. **Photosystem 11 (PS11)** chlorophyll a, with an **absorption peak** of **680nm** also called **P680**.

Antenna Complex

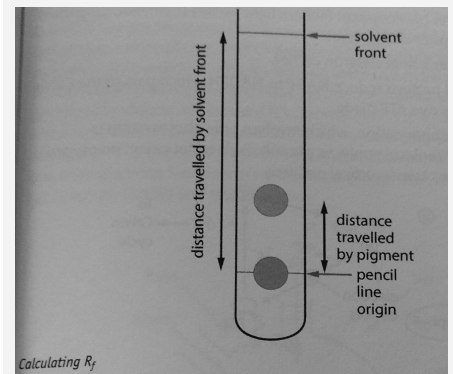


Identifying different photo pigments from chloro

Pigments can be extracted by grinding plant material in a suitable **solvent**, e.g. propanone, and separated by **paper chromatography**.

By **dividing the distance travelled** by the pigment by the **distance travelled** by the **solvent front**, the **Rf value** can be **calculated**.

Calculating the Rf value



The light-dependent stage of photosynthesis

Occurs on the **thylakoid membranes**.

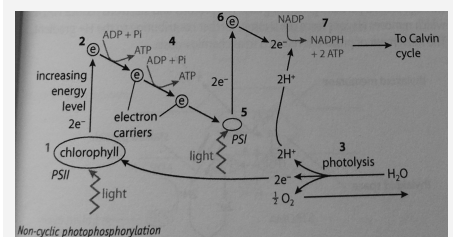
Photophosphorylation occurs via 2 **pathways**:

1. **Non-cyclic** photophosphorylation, which involves **both** photosystems 1 and 11, generating **2 ATP molecules** and **reduced NADP**.

Photolysis generates **oxygen**.

The **electrons** take a **linear pathway** which is referred to as the '**Z scheme**'.

Non-cyclic photophosphorylation



Non-cyclic photophosphorylation

1. **Light energy** (photons) strikes **chlorophyll (PS11)** exciting its **electrons**, boosting them to a **higher energy level**.
2. **Electrons** are **accepted** by an **electron carrier** in the **thylakoid membrane**.

Not published yet.

Last updated 14th November, 2024.

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Non-cyclic photophosphorylation (cont)

3. The **oxidised chlorophyll** removes **electrons** from water, producing **protons** and **oxygen** (photolysis). This occurs in the **thylakoid space**.

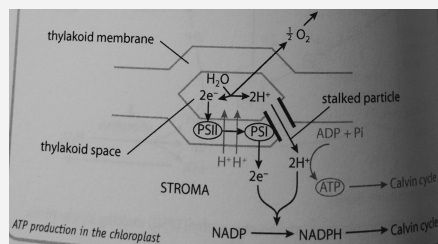
4. As **electrons** pass from **carrier to carrier**, electron **energy is lost**, which pumps **protons** from the **stroma** into the **thylakoid space**. As protons flow back through the **stalked particle**, **ADP** is **phosphorylated**; **2 ATP** are made in total.

5. Electrons enter **photosystem 1** where **light excites them**, boosting them to an even **higher energy level**.

6. **Electrons** enter a **final electron carrier**.

7. **Electrons** and **protons** **reduce NADP** to **reduced NADP** which pass to the **Calvin Cycle** with the **2 ATP** made.

ATP production in the chloroplast



Cyclic Phosphorylation

Involves only **photosystem 1**, producing **1 ATP** molecule only.

As **photolysis** does not occur, **no oxygen** is released.

Electrons take a **cyclical pathway**.

If there is **no NADP** available, then **electrons** fall back into the **electron transport chain** (at an intermediate energy level) and **generate 1 ATP**.

This **cycle continues** until **NADP** is available.

Cyclic Phosphorylation (cont)

The **ATP produced** can be used in the **Calvin Cycle**, in the **stomatal opening mechanism**, or for **other cellular processes**.

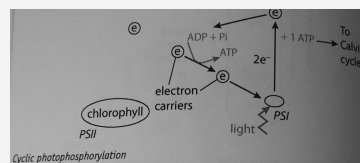
ATP is produced in the **chloroplast** when **protons** are **pumped** across the **thylakoid membrane** using **energy** from the **electrons** and **accumulate** with **protons** generated from **photolysis of water** in the **thylakoid space** generating an **electrochemical (proton) gradient**.

The **H⁺ ions** diffuse back into the **stroma** through **stalked particles** generating **ATP**.

The **protons** and **electrons** **reduce NADP**, which **removes H⁺ ions** from the **stroma**, further contributing to the **H⁺ gradient**.

The **movement of protons** is referred to as **chemiosmosis**.

Cyclic Phosphorylation



Calvin Cycle - light indep stage of photosynthesis

This stage occurs in the **stroma**.

ATP and **reduced NADP** from the **light-dependent reaction** are used to **fix carbon** from carbon dioxide with the help of the enzyme **RuBisCO**.

The sequence was first worked out by **Calvin** and his team using a **radioactive isotope of carbon (14C)** present in **hydrogen carbonate**.

At **regular intervals**, Calvin **removed samples** into **hot methanol** to **kill the chlorella algae** used and to **stop all enzyme reactions**.

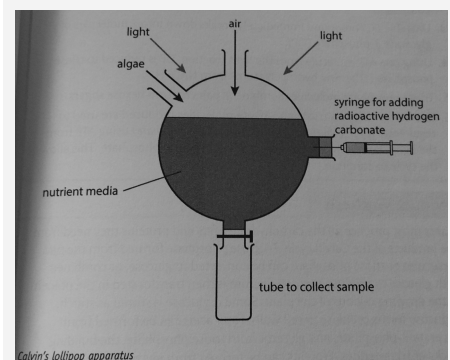
Calvin Cycle - light indep stage of photosynthesis (cont)

He then performed **chromatography** to **identify the products**.

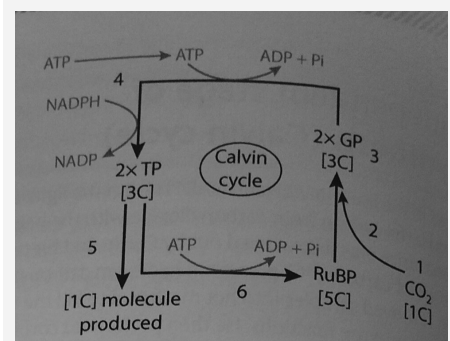
He exposed his **chromatogram** to piece of **x-ray film** which would **detect radiation** emitted from **14C** used.

This **identified** products containing **14C** in the **order** they were **produced**: first was **hydrogen carbonate** ions, then **glycerate 3-phosphate (GP)**, **triose phosphate (TP)**, **ribulose biphosphate (RuBP)** and finally **glucose**.

Calvin's lollipop apparatus



Calvin Cycle



Stages in the Calvin Cycle

1. CO₂ diffuses into leaf via **stomata**, dissolving in the **water** surrounding **palisade mesophyll** cells before **diffusing** into the **cells**.
2. CO₂ combines with the **5 carbon** compound **ribulose biphosphate** (RuBP) using the enzyme **RuBisCO** to form an **unstable 6C** compound.
3. **Unstable 6C** compound immediately **breaks down** into **2 molecules** of **glycerate 3-phosphate** (GP).
4. Using **one ATP** molecule from the **light reaction**, GP is **reduced** to **triose phosphate** (TP) using **hydrogen atoms** from **reduced HADP**.
5. **Triose phosphate** molecules **combine** in **pairs** to form **hexose sugars**.
6. **5 out of every 6 triose phosphate** molecules **produced** are used to **regenerate RuBP** (via the intermediate ribulose phosphate) using **ATP** from the **light-dependent reaction** to supply **energy and phosphate**. This allows the **cycle** to **continue**.

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Stages in the Calvin Cycle (cont)

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Product Synthesis

Plants must **produce** all the **carbohydrates, fats and proteins** they need from the **products** of the **Calvin Cycle**.

Fructose phosphate formed from the **2 molecules** of **triose phosphate** can be converted to **glucose**, or **combined** with **glucose** to produce **sucrose**.

Sucrose is then **translocated** in the **phloem** to the **growing regions** of the plant.

Some a **glucose** is **stored** as **starch**, **B glucose** forms **cellulose** in **cell walls**.

Fatty acids can be **formed** from **glycerate 3-phosphate**, and **glycerol** from **triose phosphate**, the building blocks of **triglycerides**.

Proteins can be **formed** from **glycerate 3-phosphate**, but the **amino group** requires **nitrogen** from **nitrate ions**.

Other compounds, e.g. **chlorophyll**, require additional ions e.g. **Mg²⁺**, and the middle **lamella** of **cell walls** needs **Ca²⁺**.

A **lack of nitrogen** results in **stunted growth** in plants, as plants **cannot synthesise proteins** due to **lack of nitrogen**, whereas a **lack of magnesium** causes **chlorosis**, the **yellowing** of the leaves, as **chlorophyll** cannot be **synthesised**.

This can be shown **experimentally** by placing **plants in soils** with **different nutrient** contents and **observing growth**.

Limiting factors in photosynthesis

The **rate of photosynthesis** is **controlled** by a **number of factors** including the **concentration of CO₂**, **light intensity**, and **temperature**.

The **limiting factor** is the one which is in **shortest supply** which **controls** the **rate-limiting step**, and therefore an **increase** in it **increases** the **rate of photosynthesis**.

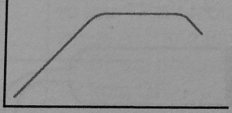
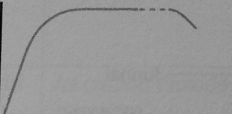
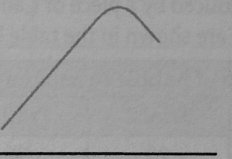
Limiting Factors Table

Factor	Explanation
Carbon Dioxide	At low concentrations , CO ₂ concentration is limiting, but above 0.5% , the rate plateaus , showing that something else must be limiting. Above 1% the stomata close , preventing the uptake of carbon dioxide .
Light intensity	As light intensity increases the rate of photosynthesis increases up to about 10,000 lux (SI unit if illuminance) when some other factor becomes limiting. At very high light intensities the rate decreases as chloroplast pigments become bleached . Different plants have evolved to be most efficient at light intensities found in their environment , e.g. sun and shade plants .

Limiting Factors Table (cont)

Temperature **Temperature increases** the **kinetic energy** of the **reactants** and **enzymes** involved in **photosynthesis**. Unlike other factors, a **plateau** is not reached as enzymes, e.g. **RuBisCO**, begin to **denature** so the **rate of photosynthesis decreases** above the **optimum temperature**. This will be **higher** in species **adapted to hot, dry environments**.

Limiting Factor Graphs

Factor	Graph
Carbon dioxide	
Light intensity	
Temperature	

Measuring the rate of photosynthesis

Aquatic plants are a good subject to use when **investigating** how **different** factors affect **photosynthesis**.

Temperature and **CO2** concentration are **more easily** controlled than with **terrestrial plants**, by using a **water bath** and **controlling hydrogen carbonate** concentration.

It is also **easy to collect** and **accurately measure** the **oxygen** produced in a **capillary tube**.

The **volume** of the **bubble** collected is **calculated** by the formula:

$$\text{Volume} = \pi r^2 \times \text{length of bubble}$$

Where $\pi = 3.14$ and $r = \text{radius or diameter}/2$