Key Terms

Photophosphorylation	**Synthesis** of **ATP** from **ADP** and 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:

6CO2 + 6H2) -> C6H12O6 + 6O2

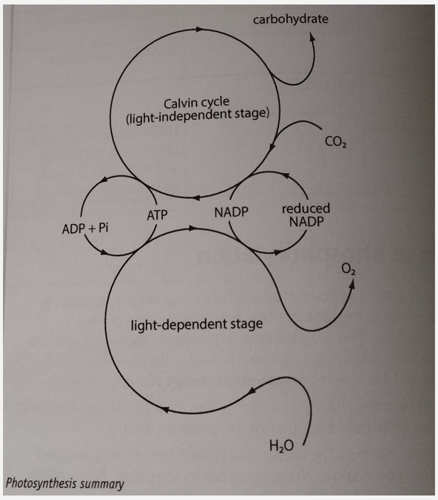
Photosynthesis involves two stages:

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

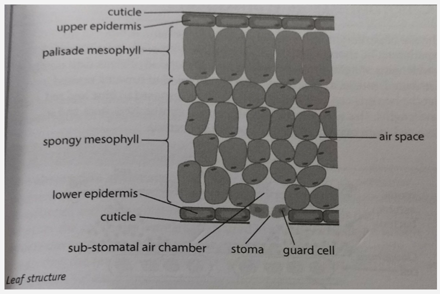
The leaf is **adapted** for **gas exchange** and **photosynthesis** by having a **large surface area** allowing the leaf to **capture light**, and having **pores** called **stomata** through which **gases diffuse.**

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 cell**s 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



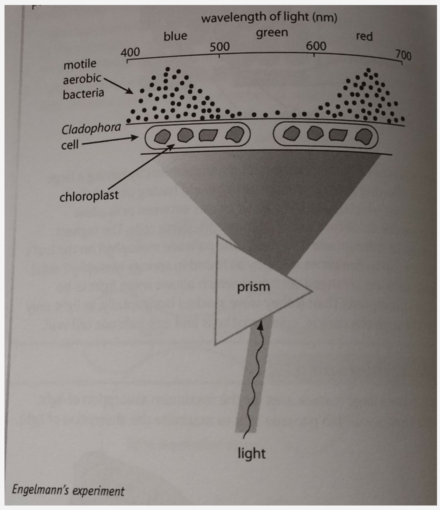
Chloroplasts as transducers

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

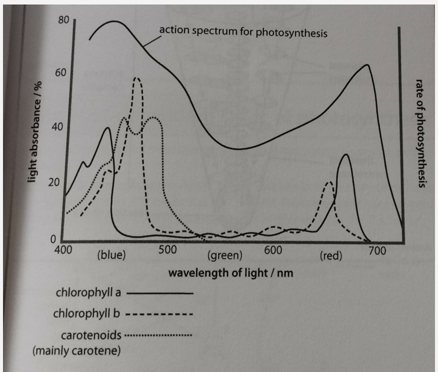
The **absorption spectrum** shows **how much** light energy a particular **pigment** absorbs at **different wavelengths**, for example **chlorophyll a** which absorbs **red and blue-violet** regions of the spectrum.

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



Graph showing the relationship between the absorption spectrum and the action spectrum

Light Harvesting

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

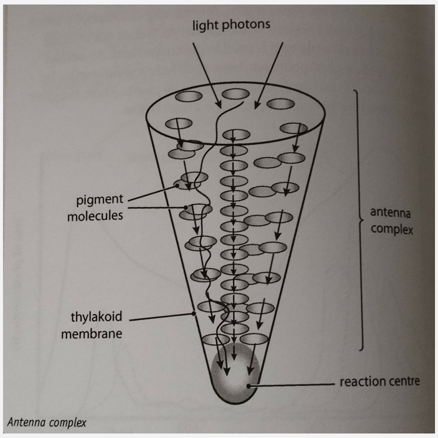
With the aid of **special proteins** associated with these **pigments**, **light energy** (photons) is funnelled towards the **reaction centre** at the base, containing **chlorophyll a.**

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



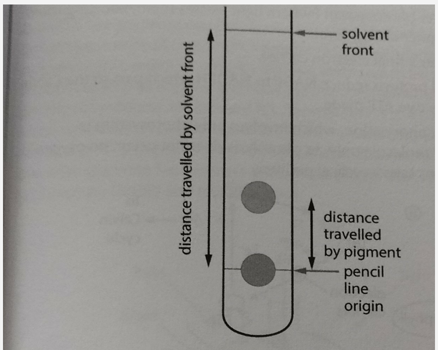
Antenna complex

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



Calculating R_f

The light-dependent stage of photosynthesis

Occurs on the **thylakoid membranes.**

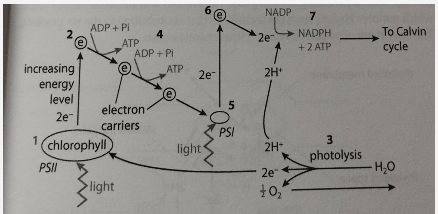
Photophosphorylation occurs via **2 pathways:**

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

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.**

Non-cyclic photophosphorylation (cont)

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

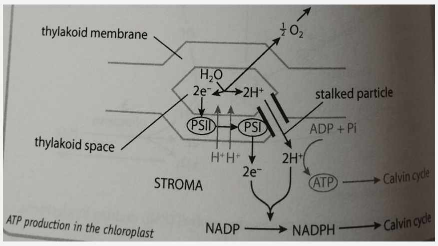
4. As **electrons** pass from **carrier to carrier**, electron **energy is lost**, which pumps **protons** from the **stroma** into the **thylakoid space.** As protons flow back through the **stalked particle**, **ADP** is **phosphorylated**; **2 ATP** are made in total.

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.**

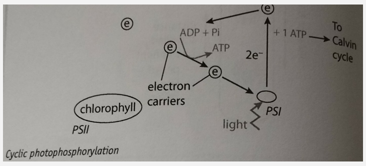
ATP is produced in the **chloroplast** when **protons** are **pumped** across the **thylakoid membrane** using **energy** from the **electrons** and **accumulate** with **protons** generated from **photolysis of water** in the **thylakoid space** generating an **electrochemical** (proton) **gradient.**

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.**

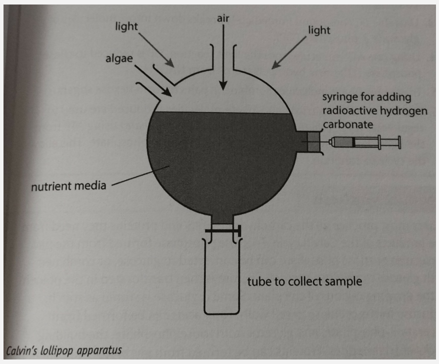
Calvin Cycle - light indep stage of photosynthesis (cont)

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

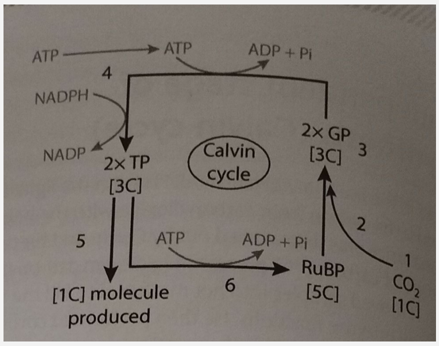
He exposed his **chromatogram** to piece of **x-ray film** which would **detect radiation** emitted from **14C** used.

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 bisphosphate** (RuBP) and finally **glucose.**

Calvin's lollipop apparatus



Calvin Cycle



Stages in the Calvin Cycle

1. **CO_2** diffuses into leaf via **stomata**, dissolving in the **water** surrounding **palisade mesophyll** cells before **diffusing into** the **cells.**

2. **CO_2** combines with the **5 carbon** compound **ribulose bisphosphate** (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.**

Stages in the Calvin Cycle

1. **CO_2** diffuses into leaf via **stomata**, dissolving in the **water** surrounding **palisade mesophyll** cells before **diffusing into** the **cells.**

2. **CO_2** combines with the **5 carbon** compound **ribulose bisphosphate** (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.**

Stages in the Calvin Cycle (cont)

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.**

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. **Mg^{2+}**, and the **middle lamella** of **cell walls** needs **Ca^{2+}.**

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 CO_2**, **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.**

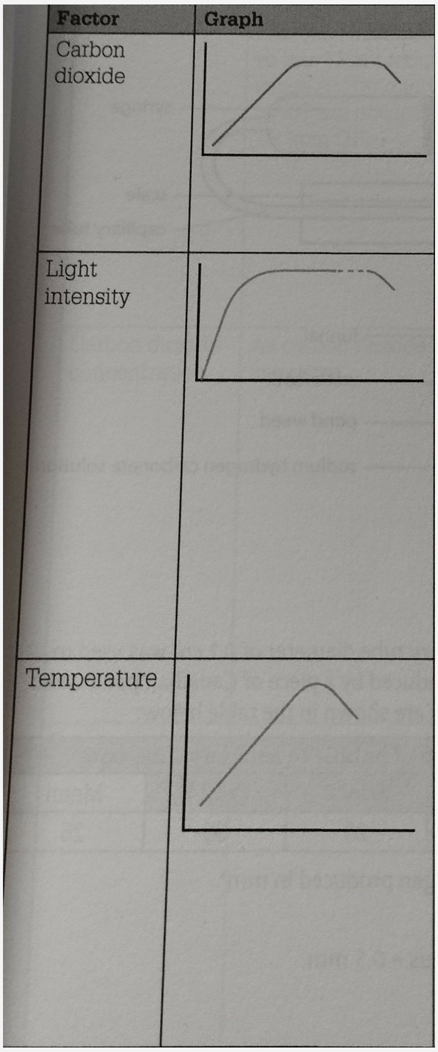
Limiting Factors Table

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 sone 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



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:

Volume = pi r2 x length of bubble

Where pi = 3.14 and r = radius or diameter/2