# Photosynthesis ( $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$)

## Light Dependent Reactions (on thylakoid membrane)

* **Primary** pigment: **special chl a** mlc, P680 & P700. P680 is found in the reaction centre (RC) of Photosystem II (PSII) & P700 in Photosystem I (PS I)
* **Accessory pigments**: other chl a, chl b mlcs & carotenoids (fd in the light harvesting complex (LHC)

### Non-cyclic photophosphorylation

* When a photon of **light** is **absorbed** by an **accessory pigment** molecule in the **light harvesting complex (LHC)** of PS II, one of its electrons is excited to a higher energy level. As the excited electron drops to its ground state, the energy released is passed on to the next pigment molecule. This **resonance transfer of energy** continues until **P680**, the **special chlorophyll a** molecule in the **reaction centre (RC)** is reached.

* When **P680** absorbs the energy from the accessory pigments of the light harvesting apparatus, it loses an **electron**, leaving an **electron hole** in PSII. The displaced electron is accepted by a **primary electron acceptor (X**) in the reaction centre.

* The electron hole in PSII is filled by an electron released from the **splitting of water** in an enzyme-catalysed reaction in the thylakoid space. During the splitting of water, the $H^+$ released contributes to a high concentration of $H^+$ in the thylakoid space while the O atom combines with another O atom, forming **molecular oxygen ($O_2$)** as a **by-product**

* The electron from the **primary $e^-$ acceptor (X)** is then passed down a **series of increasingly electronegative electron carriers** (of the 1st ETC) losing energy during the transfer. The **energy lost during this electron flow is** used to **actively pump $H^+$** from the **stroma to the thylakoid space**, generating a **proton gradient** across the membrane. **Chemiosmosis** occurs when **$H^+$ diffuse** down the proton gradient back into the stroma via **ATP synthase**, & **ADP is phosphorylated to ATP.**

* Meanwhile, PSI loses an electron in a manner similar to PSII. When **P700** absorbs the energy from the accessory pigments in the light harvesting apparatus, it **loses an electron**, leaving an **electron hole** in PSI. The displaced electron is accepted by a **primary electron acceptor (Y**) in the reaction centre. The electron hole in PSI is filled by the displaced electron from PSII when it reaches the end of the first electron transport chain.

* The electron from the **primary electron acceptor (Y)** is then is passed down a series of electron carriers of a 2nd ETC. (Energy is not released during electron transfer down this 2nd ETC.). The electron is finally accepted by **NADP** (the final electron acceptor) which is **reduced** to **NADPH** ($NADP + e^- + H^+ \rightarrow NADPH$) by **NADP reductase** which is found on the thylakoid membrane.

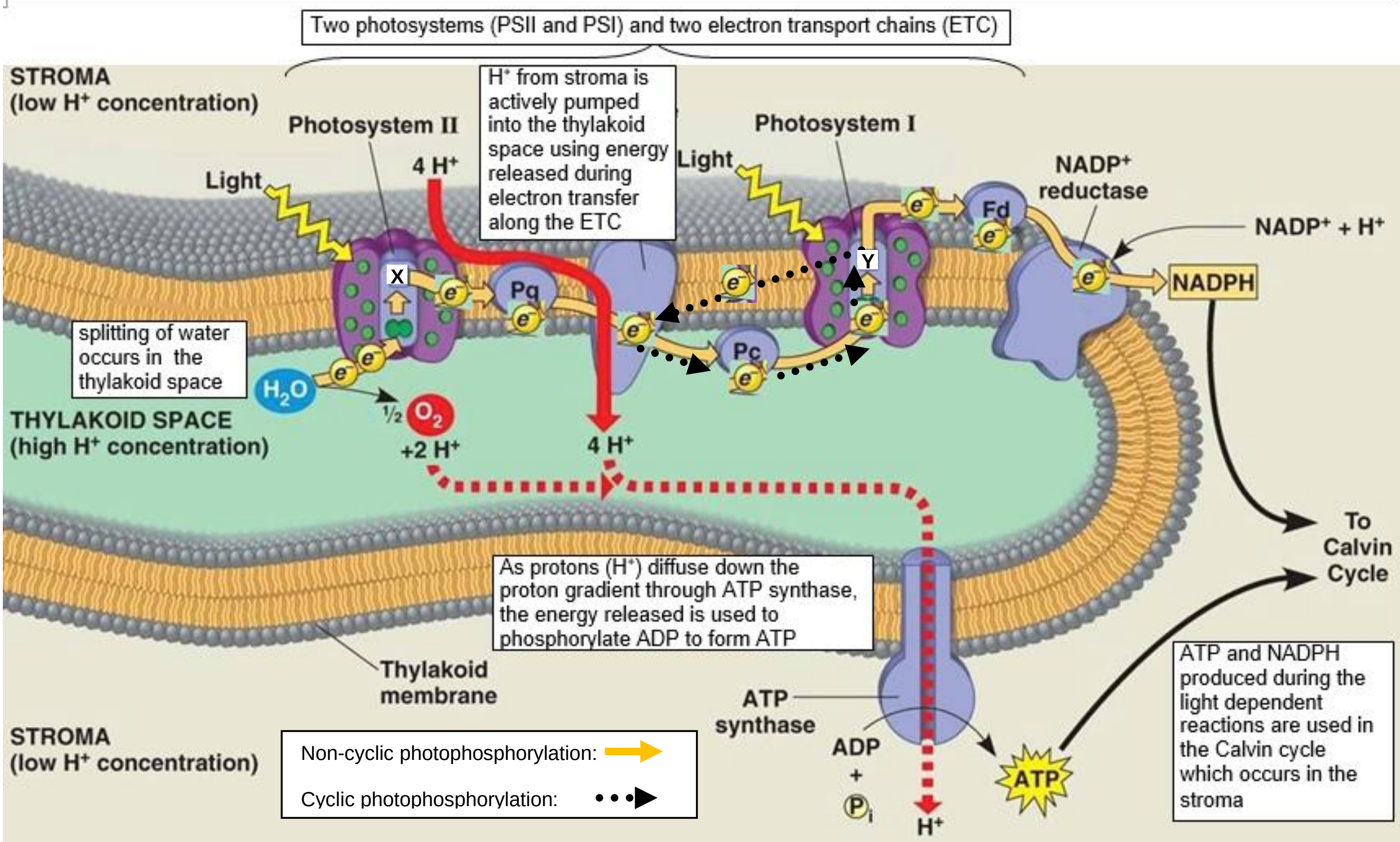
* The **ATP** & **NADPH** produced during non-cyclic photophosphorylation will be used in the Calvin cycle.

### Cyclic photophosphorylation

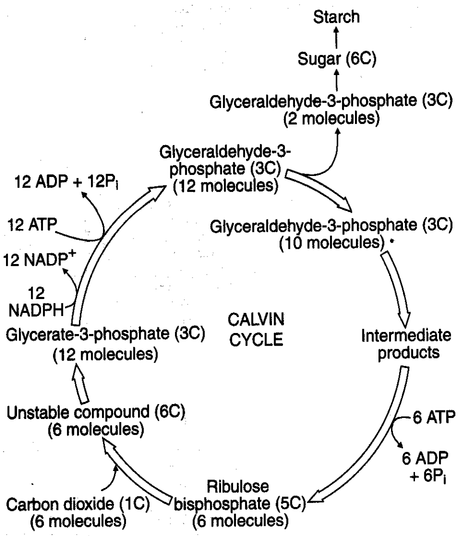
* In **cyclic photophosphorylation**, electrons displaced from **P700 of PSI** & accepted by the primary electron acceptor Y are transferred to the **middle of the 1st ETC**. The electron is transported down the ETC & is finally **recycled back to PSI.**

* **Energy lost during electron transfer** is **coupled to the formation of ATP** in a manner similar to non-cyclic photophosphorylation.

* **Only PSI is involved** & **only ATP is produced** during cyclic photophosphorylation. NADPH is not produced. The ATP produced is used in the Calvin cycle.



## Light Independent Reactions / Calvin Cycle (in stroma)




* Substances required from light reaction: **NADPH** & **ATP**

* **Carbon fixation**: $CO_2$ combines with RuBP (5C) in the presence of the enzyme ribulose bisphosphate carboxylase **(Rubisco)** to form an unstable 6C compound which breaks down into 2 molecules of GP/PGA (3C)

* **Reduction** and sugar formation: GP is reduced to G3P/TP/PGAL(3C). **ATP** and **NADPH** are needed for the reaction. NADPH provides the reducing power for the reaction

* **Regeneration of RUBP**: G3P molecules can either be converted to sugars and then polymerized to starch or enter a series of reactions driven by **ATP** to **regenerate RuBP** to allow $CO_2$ fixation to continue.

* C & O atoms of sugar ($C_6H_{12}O_6$) come from $CO_2$ & H atoms come from NADPH

* Products of light independent reaction : 1) **G3P** (a triose sugar)
2) **NADP** & **ADP** (which are recycled to the light reactions)

(Note: GP: Glycerate-3-phosphate / Glycerate phosphate;
G3P: Glyceraldehyde-3-phosphate; TP: Triose phosphate)

### Some terms:

**Phosphorylation =** addition of a phosphate group to a molecule [eg: ADP + $P_i$ (inorganic phosphate)➔ ATP]

**Photophosphorylation** = formation of ATP from ADP + $P_i$ using light energy in photosynthesis

**Non-cyclic photophosphorylation =** Electrons obtained from PS II ➔ Primary electron acceptor (X)➔ electron transport chain ➔ PSI ➔ Primary electron acceptor (Y) ➔ electron transport chain ➔NADP.
Electron from the photolysis of water replaces the electron lost form PSII.

**Cyclic photophosphorylation** = Electrons that are raised to a higher energy level are lost from PSI, but are recycled back to PSI through the 1st electron transport chain.

Together cyclic & non-cyclic photophosphorylation produce sufficient ATP & NADPH to drive the Calvin cycle.

**Chemiosmosis**: an energy coupling mechanism that uses energy stored in a proton gradient across a membrane to synthesise ATP.

**Photoactivation:** When a chlorophyll molecule absorbs light, the energy from this light raises one of its electrons to a higher energy level. That chlorophyll molecule is said to be photoactivated.

**Resonance transfer**: When a chlorophyll molecule absorbs light, the energy from light raises one of its electrons to a higher energy level. When the excited electron returns to its ground state, the energy released is transferred to another pigment molecule. This is called **resonance transfer**.

**Limiting factor**: Any environmental factor that - by its decrease or increase, absence or presence - alters the growth, metabolic processes or distribution of organisms and populations most significantly.

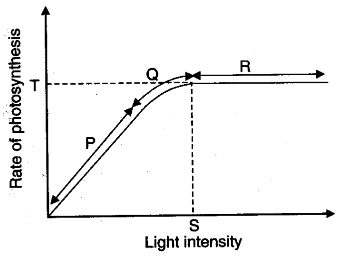
If you increase a particular variable and there continues to be a **proportional relationship** between the values on the x & y axes, it is referred to as the only limiting factor.

At P: light intensity is a limiting factor (note linear relationship between x and y values)

At Q: light intensity is not the only limiting factor. Some other factor is also limiting. (eg: $CO_2$ concentration)

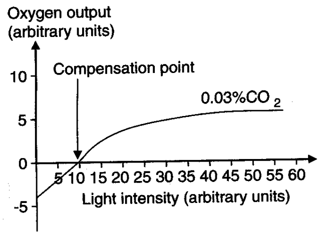
At R: light intensity is no longer limiting. (How do you know this? Even when light intensity is increased, there is no increase in the rate of reaction.) Some other factor is limiting.

S: **Light saturation point**: Light intensity beyond which an increase in light intensity will not increase the rate of photosynthesis

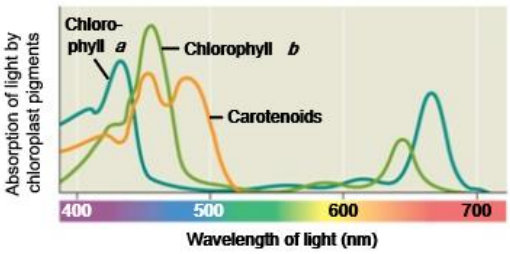



**Compensation point**: is the light intensity at which the rate of photosynthesis is equal to the rate of respiration.

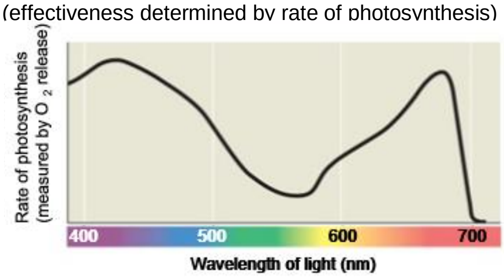
At compensation point, all the $CO_2$ produced during respiration is used in photosynthesis and all the oxygen produced in photosynthesis is used in respiration. Hence there is no net gain / loss of $CO_2$.




**Absorption spectrum**: a record of the amount of light absorbed by each pigment at each wavelength of light.




**Action spectrum**: graph showing the effectiveness of different wavelengths of light in stimulating photosynthesis (effectiveness determined by rate of photosynthesis)

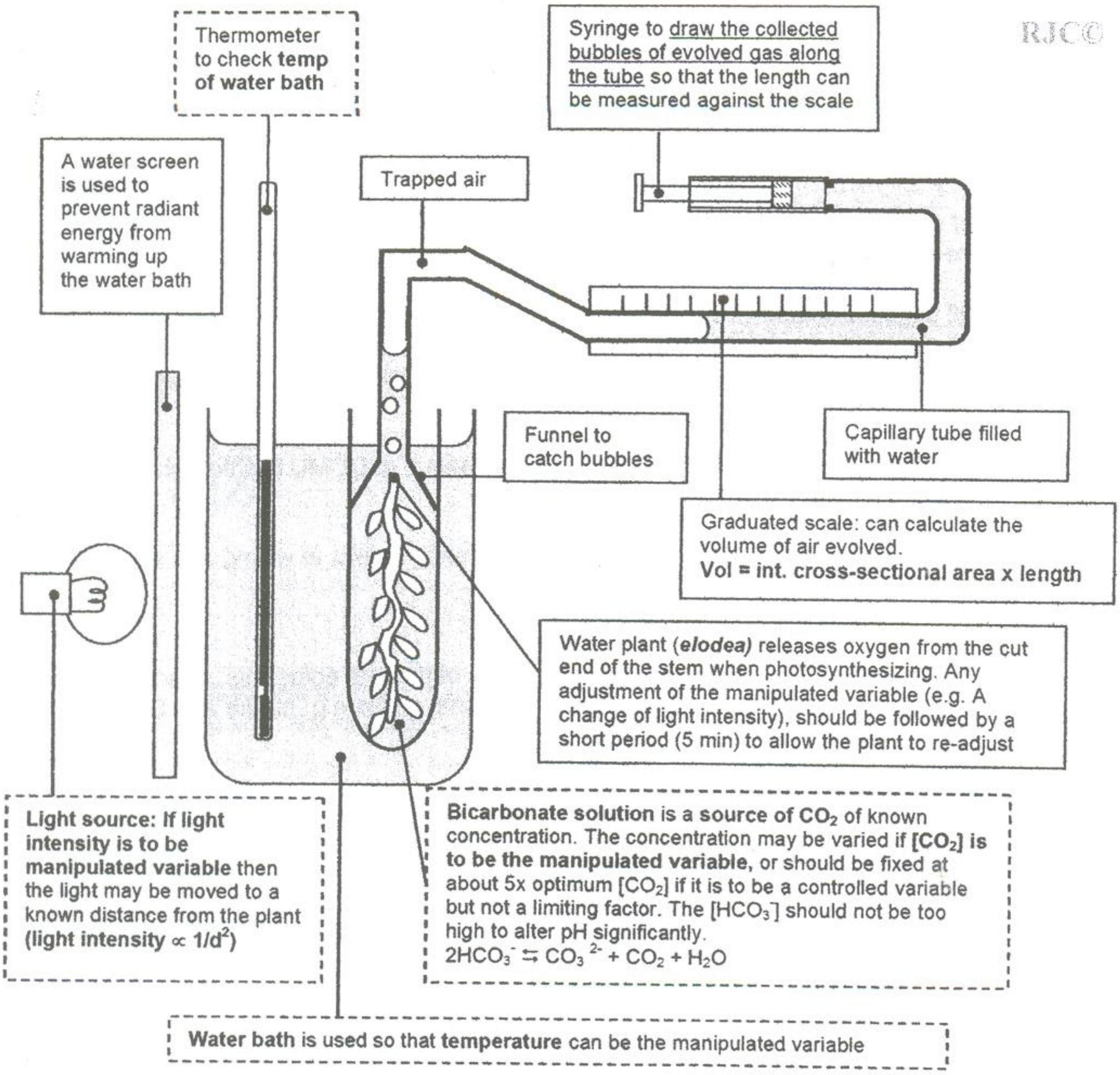



The **action spectrum** is **similar to** (wavelengths of peaks and troughs) but **does not exactly match** the **absorption spectrum of chlorophyll a**, because chlorophyll b and carotenoids, being **accessory pigments**, **broaden the spectrum of wavelength** over which photosynthesis can occur by channeling energy absorbed to chlorophyll a

## 3 KEY Factors Affecting The Rate Of Photosynthesis

1) light intensity 2) $CO_2$ concentration 3) temperature
(other factors which may limit rate of photosynthesis include chlorophyll or oxygen concentration, specific inhibitors like herbicides, water, pollution etc.)
Below is the setup to measure **rate of oxygen evolution by a water plant during photosynthesis**. Only 1 limiting factor should be tested at a time.

Rate of Photosynthesis is proportional to the volume of gas evolved. Since bubbles of evolved gas are collected over a fixed duration of time,
Rate of Photosynthesis = $\frac{\text{collected volume (mm}^3\text{)}}{\text{time (minutes)}}$ = ___ $mm^3$ of evolved $O_2$/min (at a known temperature, t°C)



## Distinguish between Light-Dependent and Light-Independent Reactions

| Feature | Light-Dependent Reaction | Light-Independent Reaction/ Calvin Cycle |
|---|---|---|
| **Location** | Thylakoid (thylakoid space, thylakoid membrane) & stroma | Stroma |
| **Conditions** | Requires light for photoactivation/ photoexcitation of electrons (both) and photolysis of water (non-cyclic photophosphorylation only) | Does not require light |
| | Less enzyme-dependent<br>Requires enzymes for photolysis of water and $NADP^+$ reductase for reduction of NADP (non-cyclic photophosphorylation only) | More enzyme-dependent<br>Requires RuBisCO for carbon fixation |
| **Reactions involved** | Cyclic and non-cyclic photophosphorylation<br>• Photoactivation<br>• Photophosphorylation (including chemiosmosis)<br>• Photolysis (non-cyclic only)<br>• Reduction of $NADP^+$ (non-cyclic only) | • Carbon fixation<br>• Reduction<br>• Regeneration of RuBP |
| **Reactants** | $H_2O$, $NADP^+$, ADP, $P_i$ | NADPH, ATP, $CO_2$ |
| **Products** | (NADPH, ATP) | G3P, ($NADP^+$, ADP) |
| **By-products** | $O_2$ | - |

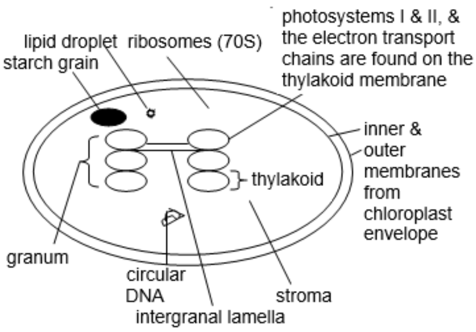
## Compare Non-cyclic and Cyclic Photophosphorylation

| Features | Non-Cyclic Photophosphorylation | Cyclic Photophosphorylation |
|---|---|---|
| **Similarities** | • <u>Energy lost</u> from the flow of electrons along an ETC is used to <u>actively pump</u> $H^+$ across membrane to generate a proton gradient<br>• <u>ADP is phosphorylated to ATP</u> via ATP synthase using energy directly from the flow of protons down their gradient via <u>chemiosmosis</u><br>• Both processes take place on <u>membranes</u> | |
| **Conditions**<br>*Calvin cycle requires 9 ATP & 6 NADPH → NADPH may be oxidized back but ATP insufficient* | When both ATP and NADPH are required<br>(too much $NADP^+$) | When only ATP is required<br>(i.e. when $NADP^+$ concentration is limiting, e.g. when there is a high NADPH to $NADP^+$ ratio) |
| **Pathway of electrons** | One direction from water through two ETC to $NADP^+$ via 2 photosystems | Cyclical passing from PSI to ETC back to PSI |
| **Photosystems involved** | PSII and PSI | PSI only |
| **First electron donor** | Water | P700 in PSI (no photolysis of water) |
| **Last electron acceptor** | $NADP^+$ | P700 in PSI |
| **Products** | ATP, NADPH, $O_2$ | ATP only |
| **High [$H^+$] in thylakoid space** | Active transport of $H^+$ ions by electron carriers of ETC; Photolysis of water<br>($H_2O \rightarrow 2e^- + 2H^+ + ½ O_2$) | Active transport of $H^+$ ions by electron carriers of ETC only |

## Describe the role of NADP in photosynthesis

1) $NADP^+$ is a **coenzyme** which **carries both protons and high energy electrons**
2) $NADP^+$ is the **final electron acceptor** in the **non-cyclic light dependent reaction** in the thylakoid membrane
3) Electrons carried in **reduced NADP (NADPH)** are used in the **Calvin cycle in the stroma** of the chloroplast to **reduce glycerate phosphate (GP) to glyceraldehyde-3-phosphate (G3P)**
4) When GP is reduced to G3P, **NADP is regenerated** to carry out its role as an electron carrier from the light dependent reactions

## Structure of chloroplast




## Some Questions:

**Q: What contributes to high $H^+$ concentration in the thylakoid space?**

1) **proton pump** (which actively pumps $H^+$ into the thylakoid space)
2) **photolysis of water** (catalysed by enzymes on inner thylakoid membrane)
3) **lack of permeability** of thylakoid membrane to $H^+$ (due to its hydrophobic core)
4) **reduction of NADP** to NADPH occurs in the stroma & hence reduces the $H^+$ concentration in the stroma thereby ensuring the steepness of the $H^+$ gradient across the membrane

**Q: Describe the function of the thylakoid membrane in photophosphorylation**.

1) Provides a **large surface area** to embed many **photosynthetic pigments** for light absorption
2) Maintains the **sequential arrangement of the electron carriers** of electron transport chain for the flow of electrons
3) Maintains **proton gradient for ATP synthesis** since the **hydrophobic core** of the membrane is **impermeable to protons** and this is essential for **chemiosmosis**
4) Allows of many **ATP synthase to be embedded** so ATP can be produced as protons flow down their gradient via **chemiosmosis** from thylakoid space to stroma