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Light Reaction: The First Step Toward Plant Life and Growth

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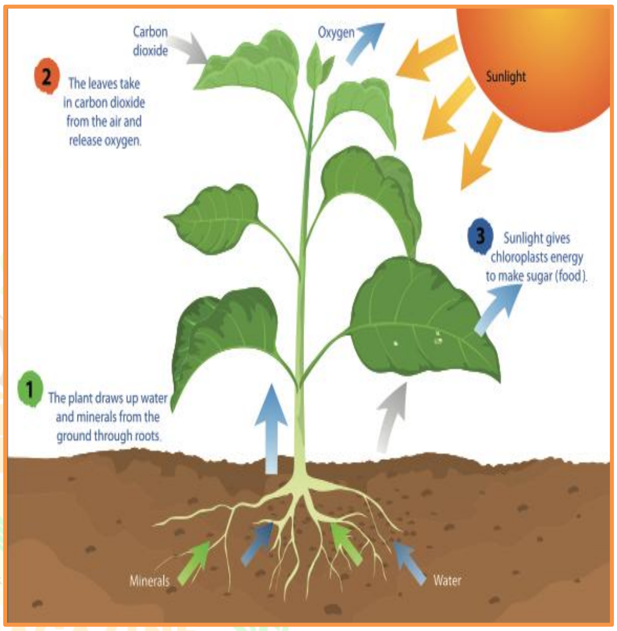
Photosynthesis is the process by which plants use sunlight, water, and carbon dioxide to create oxygen and energy in the form of sugar. When we're hungry, we eat something from the kitchen. But how do plants handle hunger? You likely know they need sunlight, water, and soil to grow but how do they get food? They produce it on their own? Plants are known as autotrophs because they make their own food using light energy. Some people think giving a plant to soil, water, or sunlight feeds it, but these aren't food. Instead, plants use sunlight, water, and air to create glucose (sugar) they need to live. This process, called photosynthesis, is done by all plants, algae, and some microorganisms. For photosynthesis, plants need carbon dioxide, water, and sunlight. Like animals, plants need gases to survive. Animals breathe in air through respiration, keeping only oxygen and exhaling the rest. Plants, on the other hand, use carbon dioxide for photosynthesis. This gas enters through small openings in their leaves, stems, flowers, and roots. Plants also need water to make food. All photosynthetic organisms have special features to gather water and most plants use roots to absorb it. The last key part of photosynthesis is sunlight it gives plants the energy to make food. But how do they turn carbon dioxide and water into sugar? With the Sun's help! Light energy starts a chemical reaction that breaks apart carbon dioxide and water molecules, then rearranges them into glucose (sugar) and oxygen. The plant's mitochondria later break down the glucose for energy used in growth and repair. The oxygen made in the process exits through the same tiny holes where carbon dioxide came in. That oxygen also helps animals and other organisms survive.

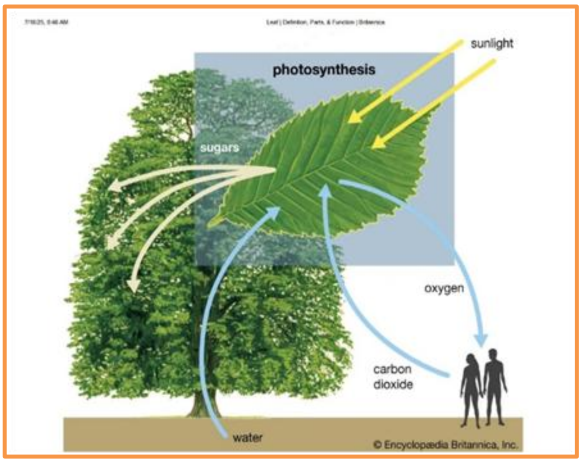


Plants absorb water (H_2O) through their roots, take in carbon dioxide (CO_2) from the air, and use sunlight to carry out photosynthesis. This process produces glucose (sugar) and releases oxygen (O_2).

If we were to write a formula for photosynthesis, it would look like this:

$$\textbf{Light energy} + 6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6\ \textbf{(sugar)} + 6O_2$$

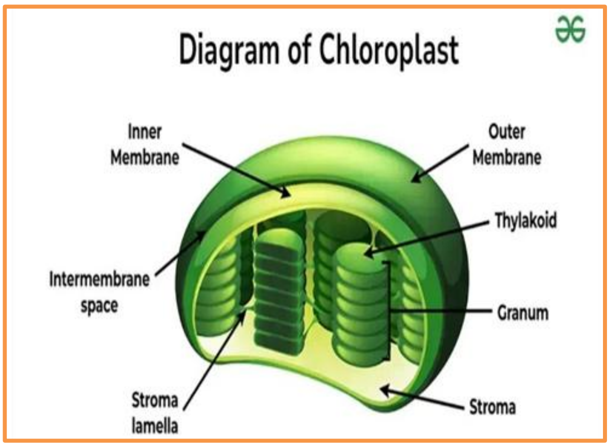
Where photosynthesis occurs?

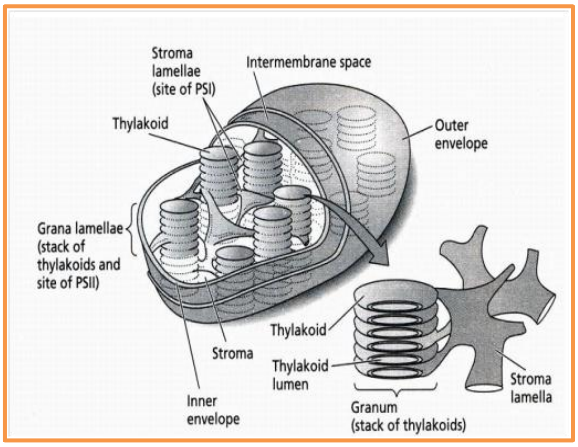


The Leaf: Photosynthetic organ: In higher plants, the mesophyll cells in leaves are the main site of photosynthesis. These cells have many chloroplasts, which hold green pigments called chlorophyll that absorb light. During photosynthesis, solar energy is used to split water, releasing oxygen, and to convert carbon dioxide into sugars. Leaves are specially adapted to carry out photosynthesis efficiently.

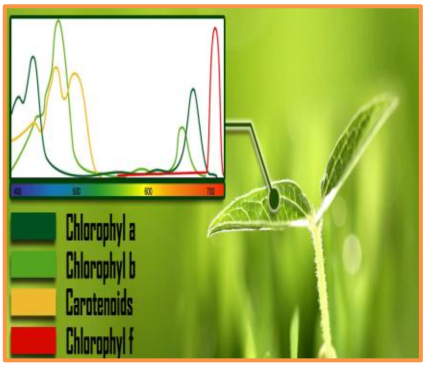
Chloroplast: The chloroplast is enclosed by a double membrane made of phospholipids an inner and an outer layer. Inside, it contains a complex system of membranes called thylakoids. On these thylakoids are small round structures called quantasomes, which help with photosynthesis. All chlorophyll is found in the thylakoid membranes, where the light reactions occur. The dark reactions, or carbon reduction reactions, happen in the stroma the fluid-filled space around the thylakoids. The stroma contains loosely arranged membranes called stroma lamellae and forms the main body of the chloroplast.

The chloroplast has a clear division of work. The membrane system captures light energy and produces ATP and NADPH. In the stroma, enzymes use carbon dioxide to make sugars, which later form starch. The reactions that need light are called light reactions. The ones that don't use light directly but rely on ATP and NADPH are called dark reactions. However, dark reactions don't happen only in the dark—they still depend on light indirectly.



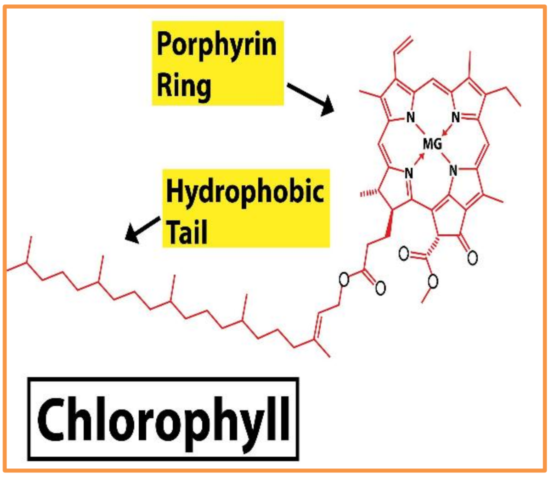


The nature of light: Photosynthesis gets its energy from sunlight. Light behaves both like waves and particles called photons. The energy in a photon is higher when its wavelength is shorter and lower when the wavelength is longer. To make carbohydrates, plants must change light energy into a usable form for building food. In the electromagnetic spectrum, the wavelengths between 400 and 700 nanometers are known as Photosynthetically Active Radiation (PAR).



Photosynthetic Pigments: Plants appear green because chlorophyll absorbs light primarily in the blue and red regions of the spectrum, while reflecting green light. This selective absorption can be represented by an absorption spectrum, which plots light absorbance against wavelength. The action spectrum of photosynthesis, which indicates the rate of photosynthetic activity at different wavelengths, closely corresponds to the absorption spectrum of chlorophyll. When chlorophyll absorbs a photon, one of its electrons becomes energized and jumps to a higher energy level. This excited electron may either take part in the photosynthetic process or return to its original state, releasing the excess energy as heat or as light of a longer wavelength.

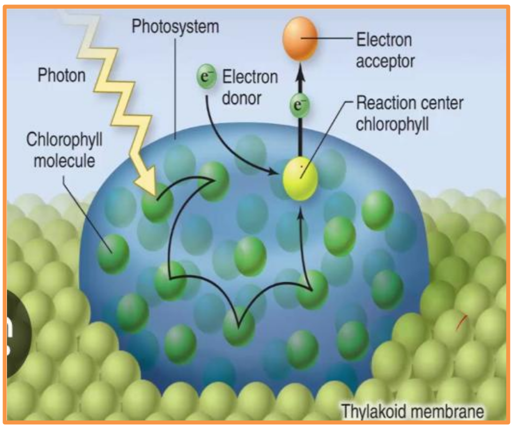
The primary pigments involved in photosynthesis are the chlorophylls. Pigments are substances that can absorb light at specific wavelengths. A chlorophyll molecule consists of two main parts: a "head" group, which is a nitrogen-containing porphyrin ring with a magnesium atom at its center, and a hydrocarbon "tail" that anchors the molecule to a membrane. Chlorophyll *a* is the main pigment responsible for capturing light energy in photosynthesis. In addition to chlorophyll *a*, most chloroplasts contain accessory pigments. These pigments extend the range of light wavelengths that can be absorbed and transfer the captured energy to chlorophyll *a*, or help protect the plant from light-induced damage. Examples of accessory pigments include chlorophyll *b*, carotenoids, and xanthophylls.



Chlorophyll b (C55H70O6N4Mg) differs from chlorophyll a (C55H72O5N4Mg) by the substitution of a CHO group for the CH3 marked at position A. Carotene/xanthophylls: Both are terpenoid pigments. Carotenes are hydrocarbons, xanthophylls are oxygenated. These pigments are orange and yellow in colour.

The reaction centre

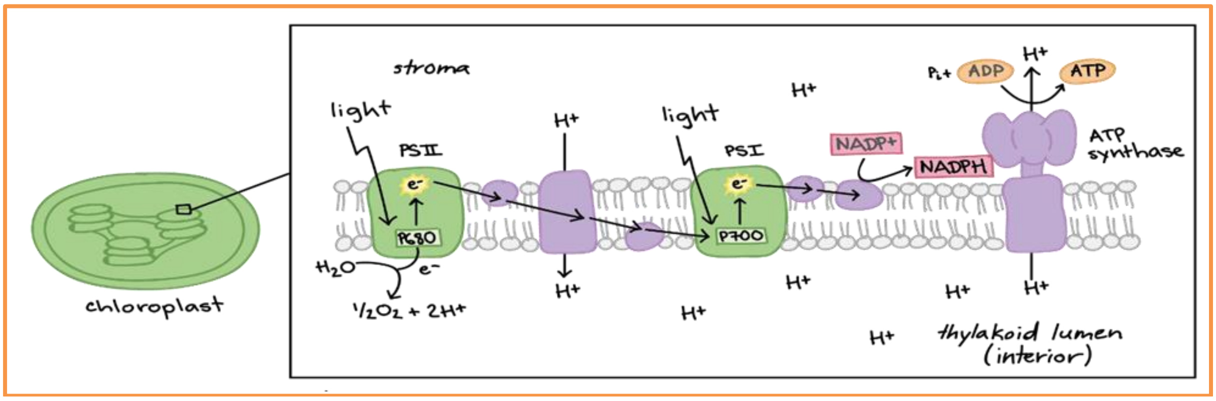
- Photosynthetic pigments are arranged to focus light energy onto reaction center chlorophylls via resonance energy transfer.
- The reaction center consists of a pair of chlorophyll a molecules, which transfer high-energy electrons to an electron acceptor.
- Pigments are arranged in flat sheets in the thylakoid membrane, optimized to capture light.
- Each reaction center is surrounded by 200–400 pigment molecules, forming the antenna complex.



- Together, the antenna complex and reaction center make up a photosystem.
- Thylakoids are stacked into grana, suspended in the stroma of chloroplasts.
- Two types of photosystems:
- Photosystem I (PS-I): Reaction center is P700, absorbs light at 700 nm.
- Photosystem II (PS-II): Reaction center is P680, absorbs light at 680 nm

PHOTOSYSTEM I & II

- PS-I has a reaction centre chlorophyll P700, which absorbs light maximally at 700 nm (in reduced state).
- PS-II has a reaction centre chlorophyll P680, absorbing maximally at 680 nm.
- PS-II is located mainly in the stacked regions of the grana lamellae.
- PS-I, along with ATP synthase and antenna pigments, is located in the stroma lamellae and grana edges.
- At wavelengths >680 nm, PS-II becomes inactive, causing a drop in quantum yield – a phenomenon called the red drop.
- PS-I composition: Large amount of chlorophyll a, small amount of chlorophyll b, and some β-carotene.
- PS-II composition: Contains chlorophyll a, large amount of chlorophyll b, and β-carotene



The light reaction

The light reactions, also known as the photochemical phase, involve processes such as light absorption, splitting of water, oxygen evolution, and the synthesis of ATP and NADPH, which are high-energy compounds. These reactions involve multiple protein–pigment complexes. The pigments are arranged into two distinct Light Harvesting Complexes (LHCs) located in Photosystem I (PS I) and Photosystem II (PS II). These photosystems are named based on the order in which they were discovered, not the order in which they operate during the light reaction. Each LHC consists of hundreds of pigment molecules that are attached to proteins. In both photosystems, all pigment molecules (except for a specific chlorophyll a) collectively form a light-harvesting system, also known as the antenna complex. These accessory pigments enhance photosynthetic efficiency by capturing light across a broader range of wavelengths. At the core of each photosystem is a unique reaction centre, containing a single chlorophyll a molecule. The reaction cenetrs differ between the two photosystems: in PS I, this chlorophyll a absorbs light most efficiently at 700 nm, and is therefore called P700; in PS II, it absorbs maximally at 680 nm, and is known as P680.

Sequence of light reactions

Water is oxidized to oxygen by Photo system II:
The chemical reaction by which water is oxidized is given by the following equation.

Equation:

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

(Water is split to release electrons, protons, and oxygen.)

Discovery: Robert Hill showed that isolated chloroplasts release O_2 when illuminated in the presence of an artificial electron acceptor like ferricyanide, which gets reduced to ferrocyanide.

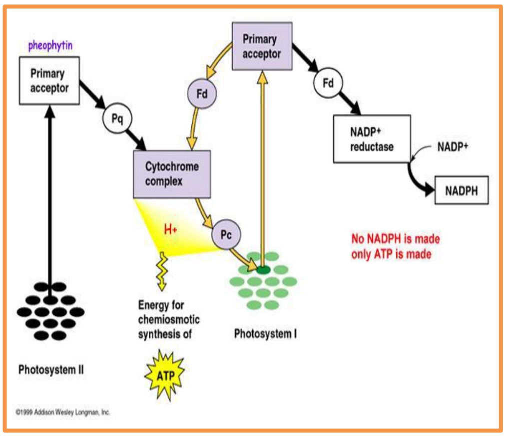
Significance: This process, known as the Hill Reaction, proved that:

- Water is the source of electrons for photosynthesis.
- Oxygen is released as a byproduct of water photolysis.
- CO_2 fixation is separate from oxygen evolution.

Electron Transport System: In Photosystem II (PS II), chlorophyll *a* absorbs 680 nm red light, exciting electrons that jump to higher orbits. These electrons are captured by an electron acceptor and passed through an electron transport chain (including cytochromes) in a downhill redox flow. The electrons are then transferred to Photosystem I (PS I) pigments. Meanwhile, in PS I, chlorophyll *a* absorbs 700 nm light, exciting its electrons, which are accepted by a molecule with higher redox potential. These electrons also move downhill to NADP+, reducing it to NADPH + H^{+}. This entire flow—from PS II excitation to PS I and final electron transfer to NADP+—forms the Z scheme, named for its zigzag shape on a redox potential scale

Summary of the Light Reaction: Absorption of light energy by pigments, Activation of chlorophyll molecule, Photolysis of water, Electron transport chain and Synthesis of assimilatory power (ATP and NADH).

CYCLIC AND NON-CYCLIC PHOTO-PHOSPHORYLATION: Photophosphorylation refers to the formation of ATP from ADP and inorganic phosphate using light energy.

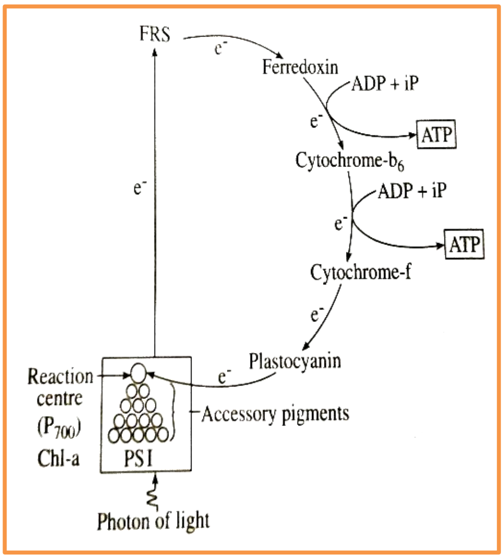


Non cyclic photophosphorylation: involves integration of two photo systems (PS-I and PSII).

Non-Cyclic: Electrons follows a noncyclic track.

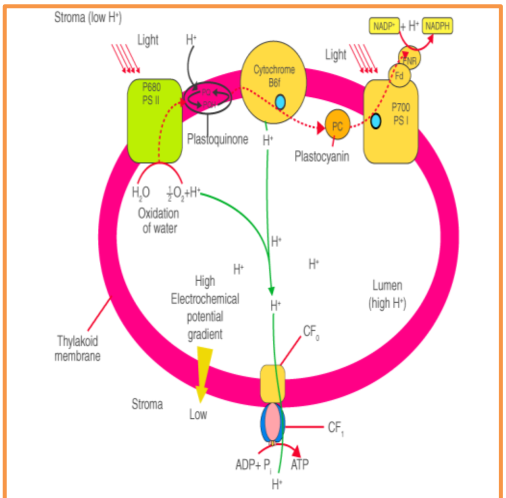
Photo: It is the light energy that drives electrons

Phosphorylation: ADP is phosphorylated to yield ATP. The excited P680 of PS II transfers electrons to pheophytin, plastoquinones (Pq), and cyt b6-f complex. Cytochrome b6-f complex transfers electrons to plastocyanin (PC), which in turn reduces P700* (excited P700). The electron deficit created in photo system II is filled by-electrons that are derived from the oxidation of water. In addition to the energy stored as redox equivalents (NADPH) by the light reactions a portion of the photons energy is utilized for the synthesis of ATP during the transfer of electrons between plaotoquinone and cyt b6-f complex. This phenomenon of synthesis of ATP in light reactions of photosynthesis is known as non-cyclic photophosphorylation.



Cyclic photophosphorylation: Cyclic photophosphorylation takes place when chloroplasts are exposed to light with wavelengths longer than 680 nm. In this condition, only Photosystem I is activated, and electrons are not extracted from H_2O molecules. Since water no longer donates electrons, the non-cyclic electron flow is inhibited and $NADP^+$, in its oxidized form, is not available to accept electrons**. When Photosystem I is stimulated by light of wavelengths above 680 nm,** electrons are transferred from the P700 reaction center to a chlorophyll molecule and then to ferredoxin. Instead of reducing $NADP^+$, these electrons cycle back to P700 through a series of carriers including the cytochrome b6-f complex, plastoquinone, and plastocyanin. This cyclic pathway of electron flow leads to ATP production at two specific points: one site is between the iron-sulfur (Fe-S) protein and the cytochrome b6 complex, and the other is between cytochrome b6 and cytochrome f.

MECHANISM OF ATP SYNTHESIS: The phenomenon of synthesis of ATP in light reactions of photosynthesis is known as photophosphorylation. The mechanism of ATP synthesis is explained by the chemi-osmotic mechanism first proposed in 1960 by **Peter Mitchell**. During photosynthesis, plants produce ATP with the help of the enzyme ATP synthase. This process, known as chemiosmosis, relies on the formation of a proton gradient across the thylakoid membrane. In this case, protons gather inside the thylakoid lumen, unlike in mitochondria where they build up in the intermembrane space.



ATP synthesis through chemiosmosis

A proton gradient is created by the following steps:

- Water molecules are split in Photosystem II, resulting in the release of protons into the thylakoid lumen.
- The transfer of electrons through the photosystems also drives protons from the stroma into the lumen across the membrane.
- Additionally, protons from the stroma are consumed during the reduction of $NADP^+$ to NADPH by the enzyme $NADP^+$ reductase, which is located on the stroma side of the thylakoid membrane. The steps generate a proton gradient across the thylakoid membrane, which powers ATP synthesis. Protons move from the lumen to the stroma through the CF_0 channel of ATP synthase by facilitated diffusion. The CF_1 unit on the stroma side undergoes conformational changes, leading to ATP formation. This ATP is then used in the dark reactions to produce sugars

Reference

1. NCERT. (2014). Biology: Textbook for Class XI. New Delhi: National Council of Educational Research and Training. Chapter 11: Photosynthesis in Higher Plants, pp. 133–152.