

11th class

PHOTOSYNTHESIS IN HIGHER PLANTS

Chapter: - 13th



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PHOTOSYNTHESIS IN HIGHER PLANTS

Plants are the primary producers of food on Earth, synthesizing their nutrients through a process called photosynthesis, making them autotrophs. Unlike animals and other organisms, which are heterotrophs, plants don't rely on other organisms for food. Instead, they use light energy from the sun to create organic compounds. This process not only provides the basis for the food chain but also releases oxygen into the atmosphere, which is essential for the survival of many organisms, including humans. Without photosynthesis, there would be no primary food source and no oxygen to breathe, emphasizing its significance in sustaining life on Earth. The details of this process, including the machinery and reactions involved, are the focus of further study.

I. WHAT DO WE KNOW?

1. Necessities for Photosynthesis:

- **Chlorophyll:** Green pigment in plants that captures light energy.
- **Light:** Essential for the photosynthesis process.
- **CO₂ (Carbon Dioxide):** An important ingredient for plants to synthesize food.

2. Starch Formation Experiment:

- **Procedure:**
 - Used two leaves for the experiment.
 - One leaf was variegated (partly green and partly white) or partially covered with black paper.
 - Exposed the leaves to light.
 - Tested the leaves for starch presence.
- **Observations:**
 - Photosynthesis occurred only in the green parts of the leaves.
 - The areas exposed to light showed the presence of starch.
 - Areas covered or not green did not show the presence of starch.

3. CO₂ Requirement Experiment:

- **Procedure:**
 - A part of a leaf enclosed in a test tube.
 - The test tube contained KOH-soaked cotton, which absorbs CO₂.
 - The other half of the leaf was left exposed to air.
 - The setup was exposed to light for a duration.
 - Later, both parts of the leaf were tested for starch.
- **Observations:**
 - The leaf section exposed to air tested positive for starch.
 - The leaf section in the test tube with KOH tested negative for starch.

- **Conclusion:**

- The section of the leaf without access to CO_2 (because of the KOH) did not undergo photosynthesis, indicating the importance of CO_2 for the process.

II. EARLY EXPERIMENTS

1. Joseph Priestley (1733-1804):

- *Key Experiments:*
 - Discovered oxygen in 1774.
 - Found that a candle extinguishes in a closed space, and a mouse suffocates.
 - A mint plant restored the "damaged" air, allowing the candle to burn and the mouse to breathe.
- *Conclusion:* Plants restore the air consumed by breathing animals and burning candles.

2. Jan Ingenhousz (1730-1799):

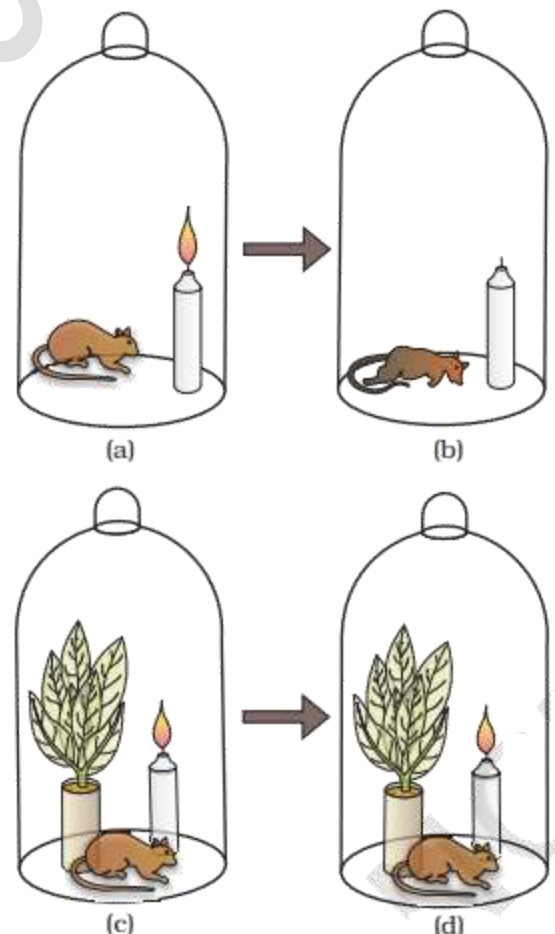
- *Key Experiments:*
 - Repeated Priestley's experiment in sunlight and darkness.
 - Observed bubbles (later identified as oxygen) forming around an aquatic plant in sunlight, but not in the dark.
- *Conclusion:* Only the green parts of plants release oxygen, and sunlight is vital for this process.

3. Julius von Sachs (1854):

- *Key Findings:*
 - Provided evidence for glucose production in plants, which is stored as starch.
 - Located chlorophyll within special bodies inside plant cells, later termed chloroplasts.
 - Identified the green parts of plants as the glucose production site.

4. T.W Engelmann (1843–1909):

- *Key Experiments:*
 - Used a prism to split light and shone it on a green alga in a bacteria suspension.
 - Bacteria accumulated mainly around blue and red-light regions,



Priestley's experiment

indicating these were where O₂ was being evolved.

- **Conclusion:** First action spectrum of photosynthesis, resembling chlorophyll a and b absorption spectra.

5. Cornelius van Niel (1897-1985):

- **Key Discoveries:**
 - Photosynthesis is a light-dependent reaction.
 - In green plants, H₂O is the hydrogen donor, which is oxidized to O₂.
 - Certain organisms use H₂S as a hydrogen donor, releasing Sulphur/sulphate instead of O₂.
 - O₂ released by green plants is derived from H₂O, not CO₂.

6. Overall Photosynthesis Equation:

- Traditional understanding: $\text{CO}_2 + \text{H}_2\text{O} \xrightarrow{\text{light}} [\text{CH}_2\text{O}] + \text{O}_2$ (with light).
- **Corrected equation by van Niel:**
 - $6\text{CO}_2 + 12\text{H}_2\text{O} \xrightarrow{\text{light}} \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{H}_2\text{O} + 6\text{O}_2$ (with light).
 - 12 molecules of water are used because 6 are consumed in the photosynthesis process, and 6 are produced as a byproduct.

These early experiments laid the foundational understanding of photosynthesis, illuminating the role of light, water, and CO₂ in the process.

III. WHERE DOES PHOTOSYNTHESIS TAKE PLACE?

1. Location:

- **Primary Location:** Photosynthesis primarily takes place in the chloroplasts found in the green leaves of plants.
- **Other Locations:** Apart from green leaves, photosynthesis can also occur in other green parts of plants. This might include stems (especially in young plants), green fruits, and in some cases, even green roots.

2. Mesophyll Cells:

- The mesophyll cells in leaves contain a significant number of chloroplasts.
- These chloroplasts usually position themselves along the walls of the mesophyll cells to capture the maximum amount of incident light.

3. Orientation of Chloroplasts:

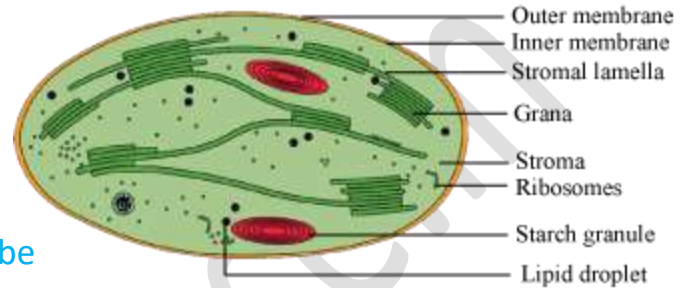
- **Parallel Alignment:** Chloroplasts will align with their flat surfaces parallel to the cell walls when they aim to capture the maximum amount of light.
- **Perpendicular Alignment:** In conditions of excessive light that might damage the chloroplast, they might position themselves perpendicular to reduce light capture.

4. Chloroplast Structure:

- **Comprised of a membranous system including:**
 - **Grana:** Stacks of thylakoid membranes where light reactions take place.
 - **Stroma Lamellae:** Connect grana.
 - **Matrix Stroma:** Where the dark reactions of photosynthesis occur.

5. Division of Labor within the Chloroplast:

- **Membrane System:**
 - Captures light energy.
 - Synthesizes ATP and NADPH.
- **Stroma:**
 - Enzymatic reactions here produce sugar, which can later be transformed into starch.



6. Types of Reactions:

- **Light Reactions (Photochemical Reactions):**
 - Occur in the grana.
 - Directly driven by light.
 - Produce ATP and NADPH.
- **Dark Reactions (Carbon Reactions):**
 - Occur in the stroma.
 - Though termed 'dark', these reactions are still dependent on the products of the light reactions (ATP and NADPH). They don't necessarily occur in the absence of light, but are termed so because they aren't directly driven by light.

IV. HOW MANY TYPES OF PIGMENTS ARE INVOLVED IN PHOTOSYNTHESIS?

1. Variety of Greens:

- The numerous shades of green observed in plant leaves are not due to a single pigment. Instead, a mix of various pigments contributes to the coloration.

2. Identification of Pigments through Chromatography:

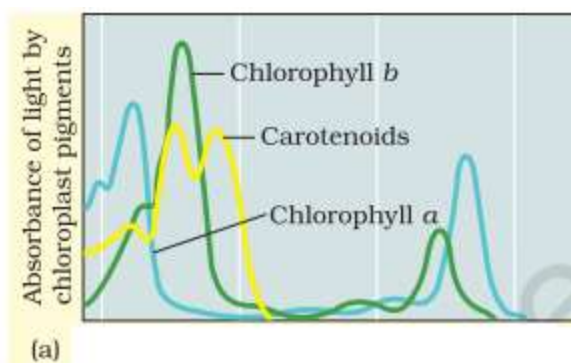
- Chromatographic separation reveals the presence of multiple pigments in leaves:
 - **Chlorophyll a:** Bright or blue-green
 - **Chlorophyll b:** Yellow-green
 - **Xanthophylls:** Yellow
 - **Carotenoids:** Yellow to yellow-orange

3. Role of Pigments:

- Pigments absorb light at specific wavelengths, enabling the capture of solar energy for photosynthesis.

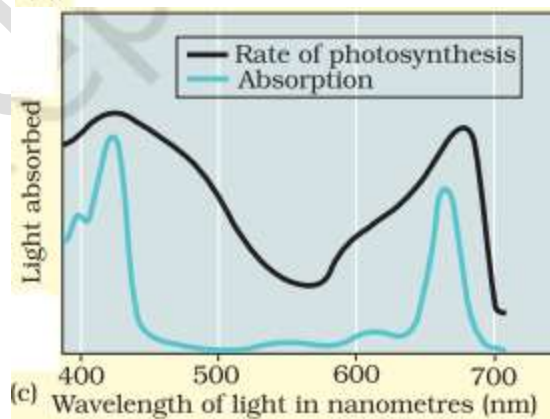
4. Chlorophyll a:

- Most abundant plant pigment globally.
- A graph, denoted as Figure a, would show the wavelengths at which chlorophyll a absorbs light.
- It primarily absorbs light in the blue and red regions of the spectrum.
- Figure b would show the wavelengths at which photosynthesis is most efficient, confirming that regions with high chlorophyll an absorption coincide with higher photosynthetic rates.



5. Overlap between Absorption and Action Spectrum:

- Figure c would demonstrate that while there's a strong overlap between chlorophyll a's absorption and photosynthesis's action spectrum, they don't match perfectly. This indicates that other pigments also play roles in photosynthesis.



6. Importance of Accessory Pigments:

- Apart from chlorophyll a, other pigments like chlorophyll b, xanthophylls, and carotenoids serve vital roles:
 - They expand the range of light wavelengths that can be used for photosynthesis, ensuring the plant can harness energy even outside of chlorophyll a's primary absorption peaks.
 - They protect chlorophyll a from photo-oxidation, a damaging process that can occur when chlorophyll a absorbs too much energy.

In summary, while chlorophyll a is the primary pigment driving photosynthesis, other pigments like chlorophyll b, xanthophylls, and carotenoids play supportive roles, ensuring efficient energy capture and protection against damage.

V. WHAT IS LIGHT REACTION?

1. Overview:

- The light reactions, also known as the 'Photochemical' phase, are the initial stages of photosynthesis that absorb sunlight and convert it into chemical energy in the form of ATP and NADPH. This phase also involves the splitting of water molecules, leading to the release of oxygen.

2. Protein Complexes:

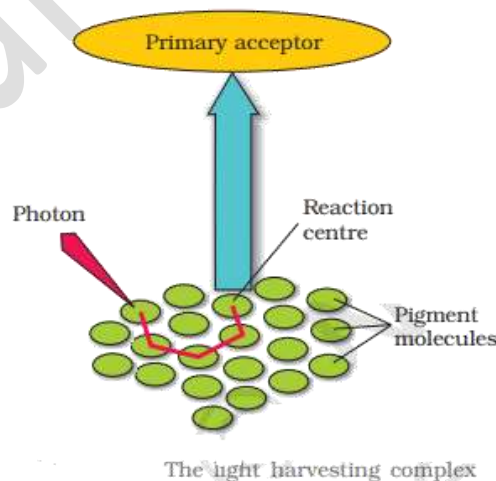
- The process involves various protein complexes. These proteins, along with pigments, are responsible for capturing and transferring light energy.

3. Photochemical Light Harvesting Complexes (LHC):

- Pigments are organized into two discrete complexes: Photosystem I (PS I) and Photosystem II (PS II).
- Despite their names, PS II acts before PS I in the sequence of the light reaction. They're named based on the order of their discovery.

4. Composition of LHC:

- Each photosystem (PS I and PS II) is composed of hundreds of pigment molecules that are attached to proteins. This entire ensemble (except for a singular chlorophyll a molecule) functions as a light-harvesting system or antennae, as depicted in Figure.
- The purpose of these pigments is to enhance the efficiency of photosynthesis by capturing a diverse range of light wavelengths.



5. Reaction Centre:

- At the core of each photosystem is the reaction center, composed of a single molecule of chlorophyll a. This molecule is pivotal in initiating the photochemical reactions.
- The reaction centers in PS I and PS II are distinguishable based on their light absorption peaks:
 - PS I:** The chlorophyll a in the reaction center has a peak absorption at 700 nm, and is therefore named P700.
 - PS II:** The chlorophyll a here has a peak absorption at 680 nm, leading it to be termed P680.

In essence, the light reactions are the starting steps of photosynthesis where light energy is absorbed and converted into chemical energy (ATP and NADPH) while splitting water to release oxygen. This process is facilitated by intricate complexes of proteins and pigments within the chloroplasts.

VI. THE ELECTRON TRANSPORT

1. Initiation at Photosystem II (PS II):

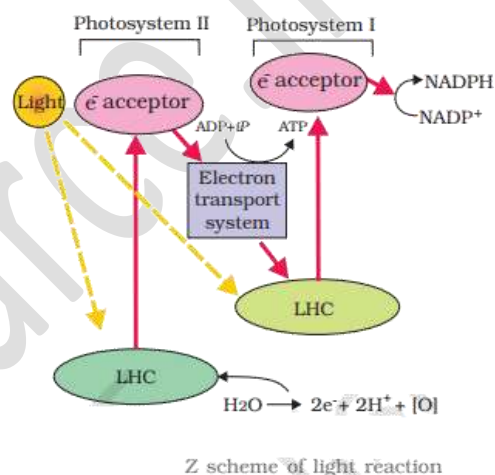
- Within PS II, the reaction center's chlorophyll a molecule absorbs light at **680 nm** (red light). This absorption energizes the electrons, prompting them to jump to a higher energy orbit.
- An electron acceptor molecule then captures these high-energy electrons, initiating the electron transport process.

2. Electron Transport Chain:

- The energized electrons are passed through a series of molecules, primarily cytochromes, in a sequence often depicted in Figure
- This flow of electrons is essentially "downhill", meaning it moves from a higher to a lower energy state or redox potential.

3. Transition to Photosystem I (PS I):

- As electrons traverse the transport chain, they are eventually transferred to the pigments of PS I.
- Here, they are re-energized. When PS I's chlorophyll a absorbs light at 700 nm, the electrons gain energy again.



4. Final Acceptance and NADPH Formation:

- The excited electrons from PS I are taken up by another electron acceptor with a greater redox potential.
- These electrons then travel "downhill" again and are eventually added to NADP⁺ (a molecule waiting to receive these electrons).
- Upon receiving the electrons (and a proton), NADP⁺ is reduced to form NADPH + H⁺.

5. The Z-Scheme:

- This entire intricate flow of electrons, from PS II through the electron transport chain to PS I, and finally to NADP⁺, forming NADPH, is often visualized as the Z scheme.
- The name "Z scheme" arises from the characteristic shape the process takes when depicted on a graph that plots redox potential. It resembles the letter Z.

To summarize, the electron transport process in photosynthesis is a systematic flow of electrons through protein complexes and molecules within the thylakoid membrane of chloroplasts. This flow helps convert light energy into a chemical form, ultimately producing the energy-rich molecule NADPH, which is crucial for the subsequent stages of photosynthesis.

➤ **Splitting of Water: -**

1. Purpose of Photosystem II (PS II):

- PS II continuously supplies electrons during photosynthesis.
- When electrons are moved from PS II, they must be replaced to ensure the continuity of the process.

2. Role of Water Splitting:

- To replace the electrons moved from PS II, water is split to provide the necessary electrons.
- This process is associated specifically with PS II.

3. Process of Water Splitting:

- Water (H₂O) is split into:
 - 2H⁺ (protons)
 - [O] (oxygen atoms which will eventually form O₂)
 - Electrons (e⁻)
- The given equation for this process is:



4. Products of Water Splitting:

- Oxygen (O₂) is one of the net products of photosynthesis, resulting from the joining of two [O] atoms.
- The electrons produced by water splitting replace those removed from photosystem I.

5. Location of PS II:

- PS II, with the water-splitting complex, is located on the inner side of the thylakoid membrane.

6. Release of Products:

- Given the physical location of PS II on the inner side of the thylakoid membrane, the protons (H⁺) and oxygen (O₂) formed from water splitting are most likely to be released in the lumen of the thylakoid.

In summary, the splitting of water in photosynthesis ensures the continuous supply of electrons for PS II. This process produces oxygen as a byproduct and occurs on the inner side of the thylakoid membrane, releasing protons and oxygen into the thylakoid lumen.

➤ Cyclic and Non-cyclic Photo-phosphorylation

1. Energy Storage in Organisms:

- Living organisms can extract energy from oxidizable substances.
- This energy is stored as bond energy, particularly in molecules like ATP.

2. Phosphorylation:

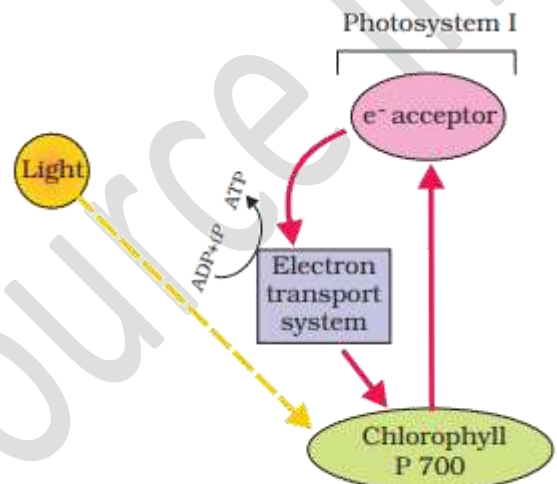
- Refers to the process where ATP is synthesized by cells.
- Occurs in both mitochondria (for cellular respiration) and chloroplasts (for photosynthesis).

3. Photo-phosphorylation:

- It is the synthesis of ATP from ADP and inorganic phosphate, but this process happens in the presence of light.

4. Non-cyclic Photo-phosphorylation:

- Involves both photosystems working sequentially: PS II followed by PS I.
- This process can be visualized in the Z-scheme.
- The electron flow in this process leads to the synthesis of both ATP and $\text{NADPH} + \text{H}^+$.



5. Cyclic Photo-phosphorylation:

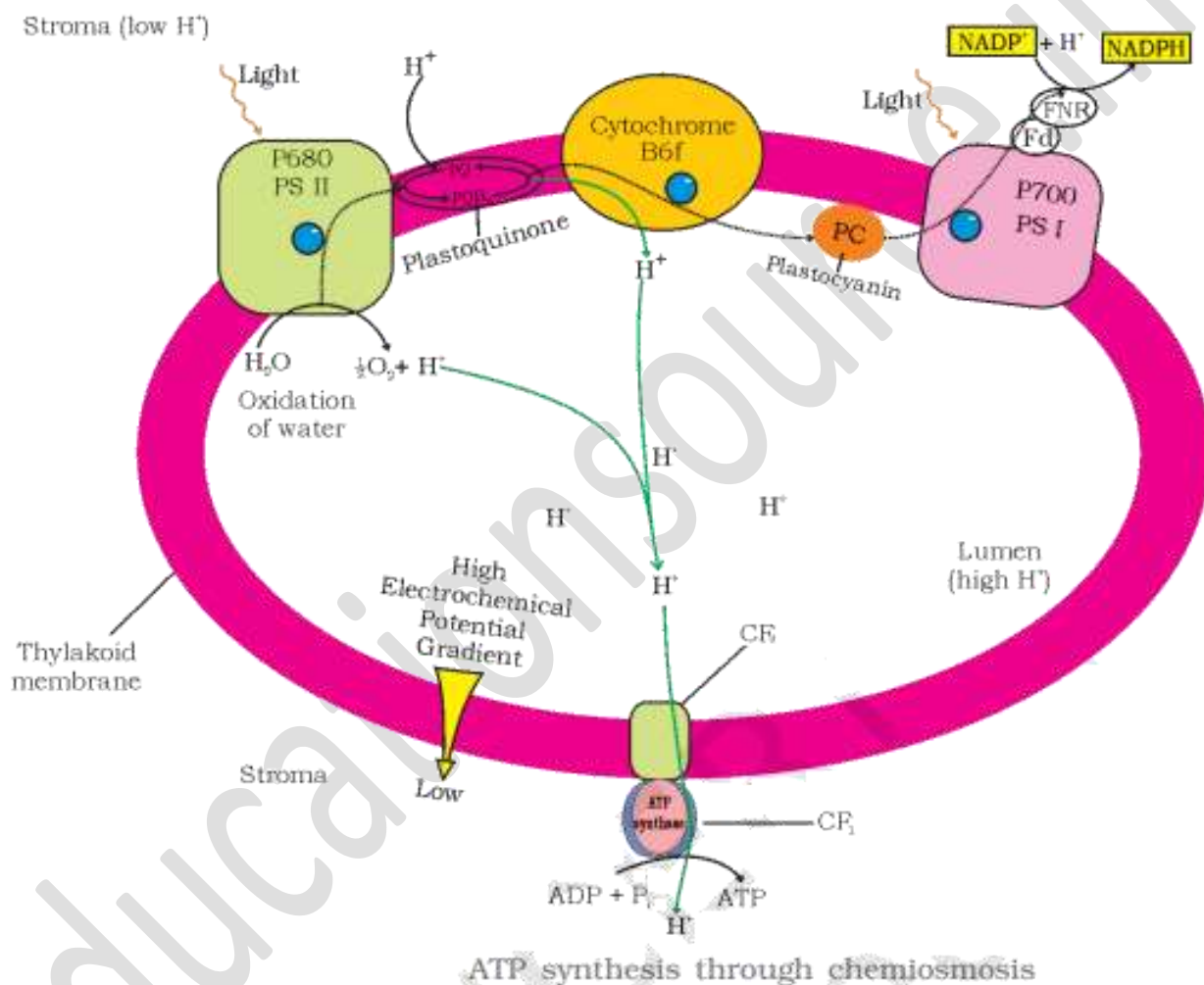
- Occurs when only PS I is functional.
- Here, the electron is circulated within the PS I, leading to the formation of ATP.
- This electron flow is termed 'cyclic' because the electron doesn't get transferred to NADP^+ but instead cycles back into the PS I through an electron transport chain.
- A significant location for this process might be in the stroma lamellae.
- The stroma lamellae membranes possess PS I but lack PS II and the NADP reductase enzyme.
- The outcome of cyclic photo-phosphorylation is only the synthesis of ATP, without the production of $\text{NADPH} + \text{H}^+$.
- This cyclic process is also prominent when light of wavelengths beyond 680 nm is available for excitation.

Summary: While non-cyclic photo-phosphorylation involves both PS I and PS II and results in the production of ATP and $\text{NADPH} + \text{H}^+$, cyclic photo-phosphorylation only involves PS I and solely results in the production of ATP. The former represents a series flow of electrons while the latter exhibits a cyclic flow.

➤ Chemiosmotic Hypothesis

1. Basics of Chemiosmotic Hypothesis:

- Explains the mechanism of ATP synthesis in chloroplasts.
- In both respiration and photosynthesis, ATP synthesis is tied to a proton gradient across a membrane.



2. Location and Direction:

- In photosynthesis: the membrane involved is the thylakoid membrane, and protons accumulate inside the membrane, in the lumen.
- In respiration: protons accumulate in the intermembrane space of the mitochondria.

3. Creation of Proton Gradient:

- (a) Splitting of water on the inner side of the membrane leads to proton accumulation within the thylakoid's lumen.

- (b) As electrons traverse through the photosystems, protons get transported across the membrane. This is due to the primary electron acceptor, which takes up a proton from the stroma and releases it into the lumen when transferring an electron.
- (c) The NADP reductase enzyme on the stroma side uses protons (from the stroma) for the conversion of NADP^+ to $\text{NADPH} + \text{H}^+$.

4. Proton Gradient Importance:

- The difference in proton concentration (or the gradient) is crucial because its dissipation or breakdown results in ATP synthesis.

5. Breaking the Proton Gradient:

- Protons move back to the stroma via the CF_0 part of the ATP synthase, which spans the thylakoid membrane.
- ATP synthase has two parts:
 - F_0 : embedded in the thylakoid membrane, facilitates proton movement across the membrane.
 - F_1 : protrudes towards the stroma side. When the gradient breaks down, it drives a conformational change in CF_1 , enabling ATP synthesis.

6. Essentials for Chemiosmosis:

- A membrane, a proton pump, a proton gradient, and ATP synthase are necessary.
- Energy is utilized to move protons across a membrane, creating a gradient within the thylakoid lumen.
- The ATP synthase channel allows proton diffusion back across, releasing energy that activates ATP synthesis.

7. Purpose of Produced ATP and NADPH:

- Both are immediately used for reactions in the stroma, which are involved in CO_2 fixation and sugar synthesis.

Summary: Chemiosmotic hypothesis explains how ATP is generated in chloroplasts. A proton gradient is formed across the thylakoid membrane, with protons accumulating in the lumen. This gradient's breakdown via the ATP synthase leads to the synthesis of ATP, which, along with NADPH, gets utilized for CO_2 fixation and sugar synthesis in the stroma.

VII. WHERE ARE THE ATP AND NADPH USED?

1. Products of Light Reaction:

- ATP, NADPH, and O_2 are the products of the light reaction of photosynthesis.

- O_2 diffuses out of the chloroplast.
- ATP and NADPH are used in the biosynthetic phase for the synthesis of sugars.

2. Biosynthetic Phase of Photosynthesis:

- Also known as the Calvin cycle or dark reaction.
- Does not directly rely on light but depends on products of the light reaction, specifically ATP and NADPH.
- Even if light becomes unavailable, the biosynthetic process continues for a while before ceasing. If light is reintroduced, synthesis resumes.
- The term "dark reaction" might be misleading, as it doesn't require darkness but is independent of direct light.

3. Discovery of the First Product of CO_2 Fixation:

- Post World War II, Melvin Calvin utilized radioactive ^{14}C in algal photosynthesis studies.
- He discovered that the initial CO_2 fixation product is a 3-carbon organic acid.
- This discovery led to the identification of the Calvin cycle.
- The first identified product was 3-phosphoglyceric acid (PGA), which has three carbon atoms.

4. Diversity in CO_2 Fixation:

- Studies across various plants revealed another group where the initial stable CO_2 fixation product is a 4-carbon organic acid.
- This acid was identified as oxaloacetic acid (OAA).
- Based on this discovery, CO_2 assimilation during photosynthesis is classified into two main types:
 - **C_3 Pathway:** Plants where the initial product of CO_2 fixation is a C_3 acid, i.e., PGA.
 - **C_4 Pathway:** Plants where the initial product is a C_4 acid, i.e., OAA.

5. Significance of ATP and NADPH:

- Both ATP and NADPH provide the necessary energy and reducing power, respectively, for the Calvin cycle.
- They assist in the conversion of CO_2 and H_2O into glucose, which stores energy for plant cells.

Summary: The products of the light reaction, ATP and NADPH, play pivotal roles in the Calvin cycle, helping convert CO_2 into sugars. Different plants follow different pathways (C_3 and C_4) based on the initial product of CO_2 fixation.

(a) The Primary Acceptor of CO_2

1. Main Inquiry:

- Scientists aimed to understand the "dark reaction" by identifying the molecule that, after accepting CO_2 , would result in the 3-carbon molecule, PGA.
- 2. Assumptions and Results:**
- Given that PGA is a 3-carbon molecule, the assumption was that a 2-carbon molecule would serve as the primary CO_2 acceptor.
 - However, the actual primary acceptor turned out to be a 5-carbon molecule.
- 3. Primary Acceptor Identified:**
- The molecule that serves as the primary acceptor of CO_2 is a 5-carbon ketose sugar known as ribulose biphosphate (RuBP).
- 4. Scientific Challenges:**
- The discovery of RuBP as the primary acceptor was unexpected.
 - Scientists initially sought a 2-carbon compound, based on their assumptions.
 - They conducted numerous experiments over several years before arriving at the 5-carbon RuBP as the primary acceptor.

Summary: In the quest to understand the dark reaction of photosynthesis, scientists aimed to identify the primary CO_2 acceptor. Initially expecting a 2-carbon compound due to the 3-carbon nature of PGA, they were surprised to find that the 5-carbon molecule, ribulose biphosphate (RuBP), was the primary acceptor.

(b) The Calvin Cycle

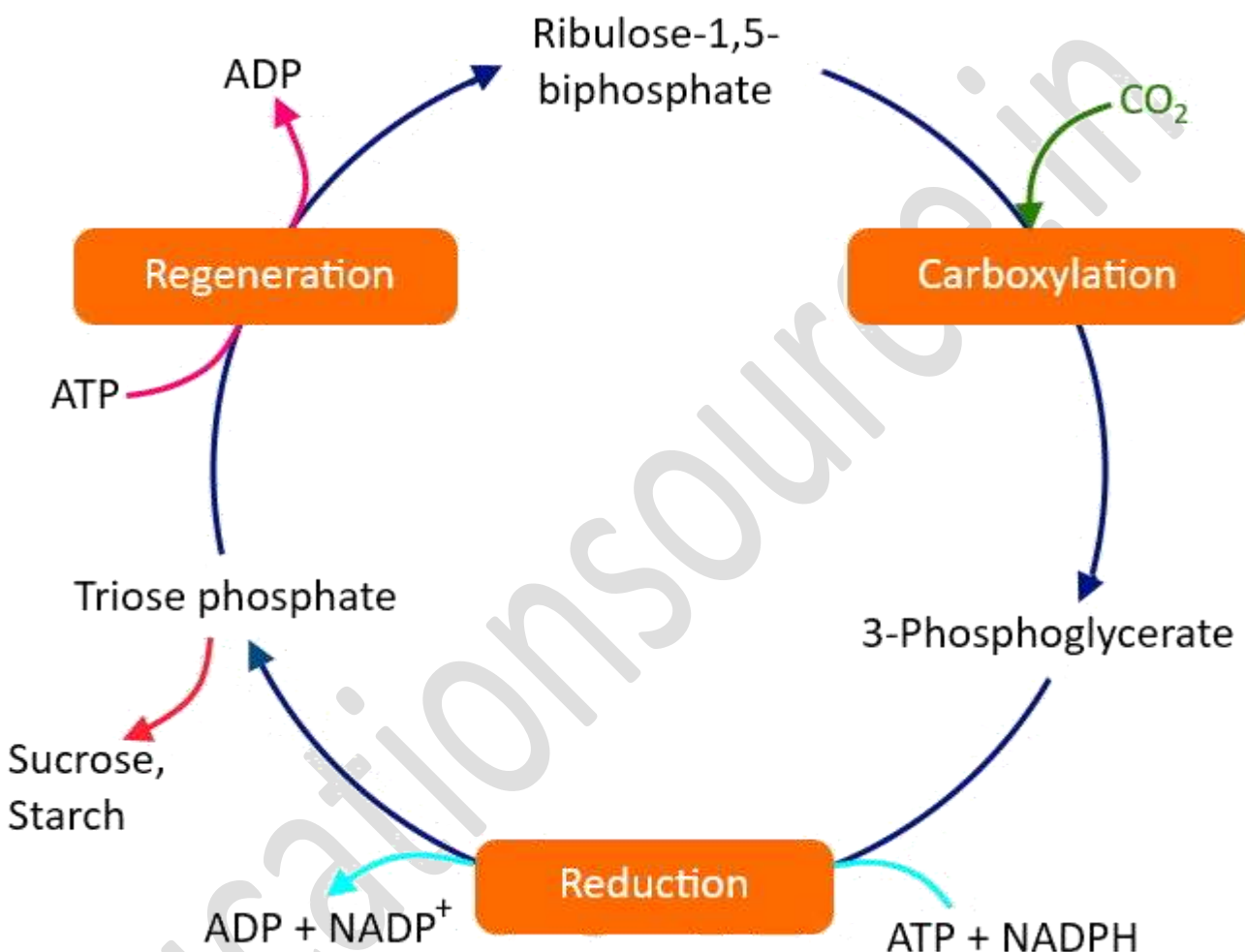
1. Introduction:

- Calvin and his colleagues identified the Calvin cycle as a cyclic pathway where the CO_2 acceptor, RuBP, is regenerated.
- This pathway operates in all photosynthetic plants regardless of whether they use the C_3 or C_4 pathways.

2. Three Stages of the Calvin Cycle:

- **Carboxylation:**
 - CO_2 is fixed into a stable organic intermediate.
 - RuBP, a 5-carbon molecule, accepts CO_2 , leading to the formation of two molecules of 3-PGA.
 - The reaction is catalyzed by the enzyme RuBisCO (RuBP carboxylase-oxygenase).
- **Reduction:**
 - These reactions ultimately lead to glucose formation.
 - Requires 2 ATP molecules for phosphorylation and 2 NADPH molecules for reduction for every CO_2 molecule fixed.

- For one glucose molecule to be synthesized, 6 CO₂ molecules need to be fixed, implying 6 turns of the Calvin cycle.
- **Regeneration:**
 - RuBP, the CO₂ acceptor molecule, is regenerated.
 - Regeneration requires 1 ATP molecule to phosphorylate and form RuBP.



3. Energy Requirements:

- For every CO₂ molecule processed by the Calvin cycle, 3 ATP and 2 NADPH molecules are required.
- Cyclic phosphorylation possibly occurs to balance the difference in the number of ATP and NADPH molecules used in the cycle.

4. Glucose Formation:

- To form one glucose molecule, 6 turns of the Calvin cycle are needed.
- This means 18 ATP (3 ATP x 6) and 12 NADPH (2 NADPH x 6) molecules are required to produce

In	Out
Six CO ₂	One glucose
18 ATP	18 ADP
12 NADPH	12 NADP

one glucose molecule via the Calvin pathway.

Summary: The Calvin cycle, identified by Calvin and his team, operates cyclically and involves three main stages: carboxylation, reduction, and regeneration. It's the primary method plants use to convert atmospheric CO₂ into glucose. Both ATP and NADPH are essential energy molecules used in this cycle, and for one glucose molecule to be formed, the cycle must complete 6 turns.

VIII. THE C₄ PATHWAY

1. Introduction to C₄ Plants:

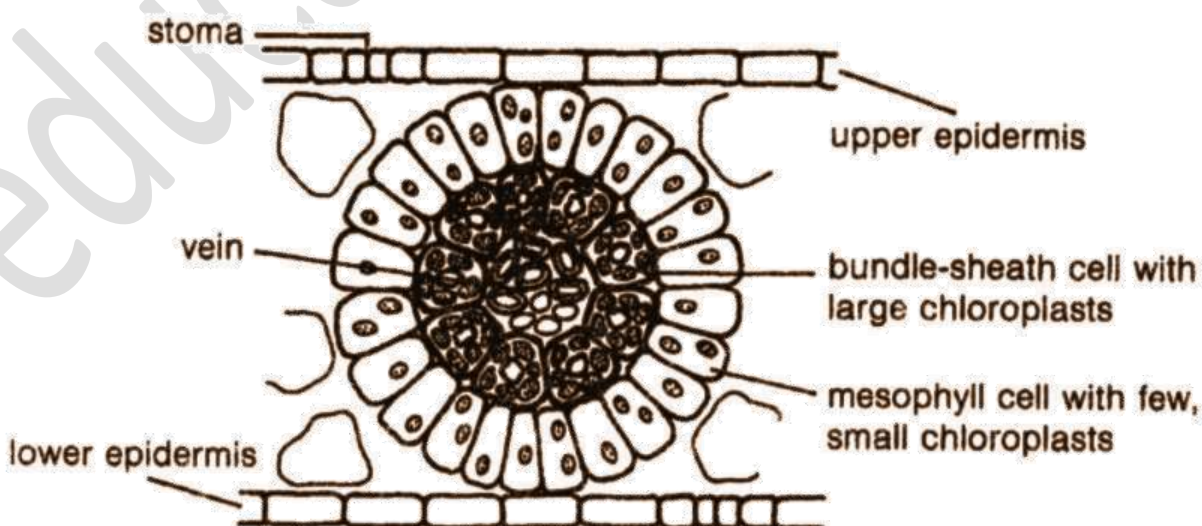
- C₄ plants are adapted to dry tropical regions.
- Despite having oxaloacetic acid (OAA) as their first CO₂ fixation product, they utilize the Calvin cycle (C₃ pathway) for the primary biosynthetic process.

2. Distinctive Features of C₄ Plants:

- They possess a specific leaf anatomy suitable for their environment.
- These plants can tolerate higher temperatures.
- They respond efficiently to high light intensities.
- They lack photorespiration, which is a wasteful process.
- They exhibit greater productivity in terms of biomass.

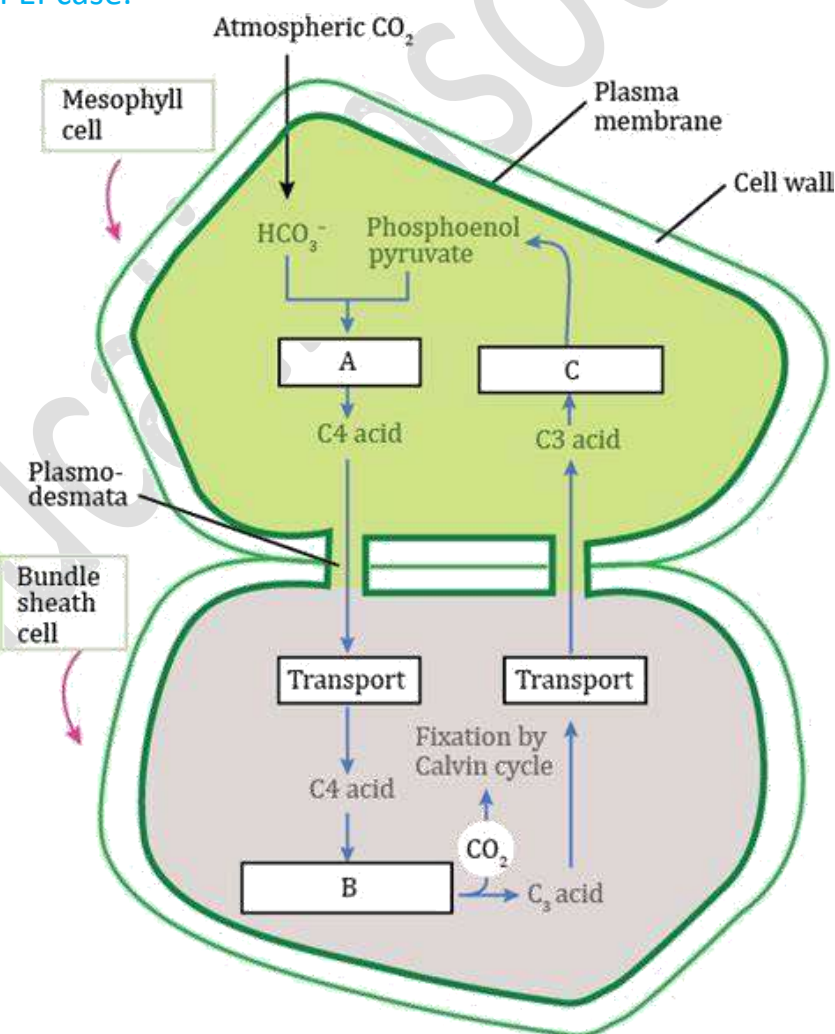
3. Kranz Anatomy:

- C₄ plants possess large cells around their vascular bundles, termed bundle sheath cells, leading to the "Kranz" anatomy.
- "Kranz" means "wreath", mirroring the arrangement of these cells.
- These cells have multiple layers around the vascular bundles, characterized by numerous chloroplasts, thick walls, and no intercellular spaces.



4. Hatch and Slack Pathway:

- This cyclic process is named after the scientists who identified it.
- Steps involved:
 - The primary CO_2 acceptor in mesophyll cells is a 3-carbon molecule, phosphoenol pyruvate (PEP).
 - PEP carboxylase (PEPcase) facilitates this CO_2 fixation.
 - Mesophyll cells don't possess the RuBisCO enzyme.
 - The C_4 acid (like OAA) forms in mesophyll cells and can be transformed into other C_4 compounds, e.g., malic acid.
 - These C_4 compounds move to the bundle sheath cells where they break down, releasing CO_2 and a 3-carbon molecule.
 - The 3-carbon molecule goes back to the mesophyll cells and is converted back to PEP, completing the cycle.
 - The CO_2 released in the bundle sheath cells enters the Calvin cycle (C_3 pathway).
 - Notably, bundle sheath cells are rich in the RuBisCO enzyme but lack PEPcase.



5. Distribution of Calvin Pathway:

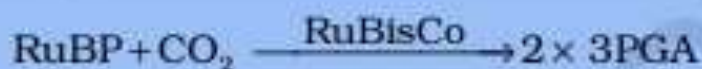
- In C_3 plants, the Calvin cycle occurs in all mesophyll cells.
- For C_4 plants, this cycle doesn't happen in mesophyll cells but is restricted to bundle sheath cells.

Summary: C_4 plants, adapted to dry tropical climates, have a distinct mechanism of CO_2 fixation called the C_4 pathway or Hatch and Slack Pathway. This involves the preliminary fixation of CO_2 in mesophyll cells followed by the release of CO_2 in bundle sheath cells where the Calvin cycle operates. The unique Kranz anatomy of C_4 plants aids in this dual system of CO_2 fixation.

IX. PHOTORESPIRATION

1. Overview:

- Photorespiration is a process that distinguishes C_3 plants from C_4 plants. It reduces the efficiency of photosynthesis in C_3 plants by consuming oxygen and releasing carbon dioxide.



2. RuBisCO's Dual Function:

- RuBisCO is the world's most abundant enzyme, playing a pivotal role in the Calvin cycle.
- Its active site can bind to both CO_2 and O_2 . This makes RuBisCO unique.
- When CO_2 levels are equivalent to O_2 levels, RuBisCO shows a stronger affinity for CO_2 .

3. Photorespiration in C_3 Plants:

- In C_3 plants, O_2 competes with CO_2 to bind to RuBisCO, decreasing CO_2 fixation efficiency.
- RuBP binds with O_2 to produce one molecule of phosphoglycerate and one molecule of phosphoglycolate (a 2-carbon molecule), initiating the photorespiratory pathway.
- This pathway neither produces sugars nor ATP. In fact, it consumes ATP and releases CO_2 .
- The exact biological role of photorespiration remains unclear.

4. Absence of Photorespiration in C₄ Plants:

- C₄ plants do not exhibit photorespiration. They have a mechanism that elevates the CO₂ concentration at the RuBisCO enzyme site.
- Breaking down the C₄ acid in the bundle sheath cells releases CO₂, which amplifies the intracellular CO₂ concentration.
- This high concentration ensures that RuBisCO acts primarily as a carboxylase, minimizing its oxygenase activity.

5. Advantages of C₄ Plants:

- Due to the absence of photorespiration, C₄ plants are more productive and have higher yields.
- C₄ plants are also more tolerant to higher temperatures.

Comparison of C₃ and C₄ Plants (based on the above discussion):

Feature	C ₃ Plants	C ₄ Plants
Photorespiration	Present	Absent
RuBisCO's Primary Function	Both carboxylase and oxygenase	Primarily carboxylase
Carbon Fixation Product	3-phosphoglycerate (3-carbon)	Oxaloacetic acid (4-carbon)
Efficiency & Yield	Reduced due to photorespiration	Higher, as there's no energy wastage in photorespiration
Temperature Tolerance	Lesser compared to C ₄ plants	Higher tolerance to elevated temperatures
CO ₂ Concentration Mechanism	Absent	Mechanism present to increase CO ₂ concentration

This comparison helps highlight the major differences between C₃ and C₄ plants, especially with regard to their photosynthetic efficiency and adaptability to environmental conditions.

X. FACTORS AFFECTING PHOTOSYNTHESIS

1. Introduction

- Photosynthesis is crucial for plant yield.
- It is influenced by both internal (plant-specific) and external factors.

2. Internal Factors (Plant Factors)

- **Number of Leaves:** More leaves generally mean increased photosynthesis.
- **Size of Leaves:** Larger leaves can absorb more sunlight, aiding in photosynthesis.
- **Age of Leaves:** Younger leaves may be more efficient at photosynthesis than older, possibly damaged or deteriorated ones.
- **Orientation of Leaves:** Leaves oriented towards the light source can absorb more light.
- **Mesophyll Cells and Chloroplasts:** These are where photosynthesis occurs; their number and efficiency are crucial.
- **Internal CO₂ Concentration:** Affects the rate of photosynthesis as it's a key reactant.
- **Chlorophyll Amount:** Chlorophyll captures light energy, so its amount directly influences the photosynthesis rate.
- The internal factors are largely influenced by the plant's genetics and growth.

3. External Factors

- **Sunlight Availability:** Directly correlates with the photosynthesis rate; without light, photosynthesis can't proceed.
- **Temperature:** Extremely important. Even with optimal light and CO₂, very low temperatures can halt photosynthesis.
- **CO₂ Concentration:** Essential reactant for photosynthesis. Higher concentrations usually enhance the photosynthesis rate up to a certain limit.
- **Water Availability:** Water is a reactant in the photosynthesis process. Without it, the process slows down or stops.

4. Interplay of Factors

- While many factors influence photosynthesis, typically one factor is the "limiting factor."
- This limiting factor determines the rate of photosynthesis at any given point.

5. Blackman's Law of Limiting Factors (1905)

- If multiple factors influence a chemical process, its rate is determined by the factor closest to its minimal value.
- In other words, the factor in shortest supply or most away from its optimal level usually limits the rate.
- Example: A plant with sufficient light and CO₂ might not photosynthesize in very low temperatures. Optimal temperature can restart the photosynthesis process.

Understanding these factors provides insight into optimizing conditions for better plant growth and yield. It highlights the importance of creating a balanced environment where no single factor becomes the limiting constraint for photosynthesis.

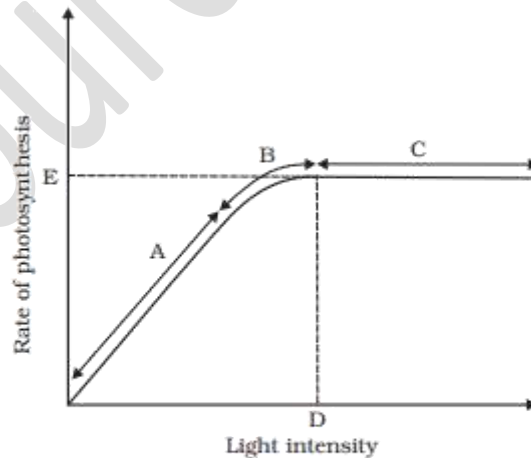
(a) Light

1. Different Aspects of Light:

- **Light Quality:** Refers to the color (or wavelength) of light. Different pigments in plants absorb different wavelengths.
- **Light Intensity:** Refers to the brightness or amount of light. It can influence the rate of photosynthesis.
- **Duration:** Refers to how long the plant is exposed to light.

2. Relationship between Light and Photosynthesis:

- At **low light intensities**, there's a linear relationship between the amount of incoming light and the rate of CO₂ fixation (photosynthesis).
- As light intensity increases, this relationship changes. At **higher light intensities**, the photosynthesis rate plateaus as other factors start to become limiting.
- An important observation is that light saturation (where increased light doesn't lead to an increase in photosynthesis) can occur at just 10% of full sunlight.



Graph of light intensity on the rate of photosynthesis

3. Implications in Nature:

- Given the above observation, for most plants that are directly under sunlight or in open areas, light is usually not the limiting factor.
- However, plants in shaded areas or dense forests might experience light as a limiting factor.

4. High Light Intensity and Plant Health:

- Intensities of light beyond a certain threshold can be harmful.
- Excessive light can lead to the breakdown of chlorophyll, which can consequently decrease the rate of photosynthesis.
- This is a protective mechanism for plants, as overly intense light can damage their photosynthetic machinery.

In essence, while light is crucial for photosynthesis, its quality, intensity, and duration all play roles in determining the rate at which photosynthesis occurs. Just as too little light can limit photosynthesis, so can too much light. Therefore, understanding the optimal light conditions for specific plants can be key for agricultural and botanical endeavors.

(b) Carbon dioxide Concentration

1. Importance of CO₂:

- CO₂ is a crucial substrate in photosynthesis and often becomes the major limiting factor.

2. Current Atmospheric CO₂ Concentration:

- The CO₂ concentration in the atmosphere is quite low, usually between 0.03% and 0.04%.

3. Effect of Increased CO₂ Concentration:

- A slight increase in the concentration of CO₂ (up to 0.05%) can enhance CO₂ fixation rates.
- However, levels beyond this can be harmful over extended durations.

4. Response of Different Plants to CO₂ Concentration:

- **C₃ Plants vs. C₄ Plants:**
 - Both types of plants have different responses to variations in CO₂ concentration.
 - Under low light conditions, neither C₃ nor C₄ plants show a significant response to increased CO₂ levels.
 - At high light intensities, both C₃ and C₄ plants exhibit an increase in photosynthesis rates.
- **Saturation Points:**
 - C₄ plants reach a saturation point at around 360 μL^{-1} .
 - C₃ plants continue to respond positively to rising CO₂ levels and only show saturation beyond 450 μL^{-1} .
- Given the current atmospheric CO₂ levels, C₃ plants are especially limited.

5. Agricultural Implications and Techniques:

- The response of C₃ plants to elevated CO₂ concentrations can be exploited in agriculture.
- Some greenhouse crops, like tomatoes and bell peppers, are grown in CO₂-enriched atmospheres.
- This controlled environment results in increased photosynthesis rates, which subsequently lead to higher crop yields.

In conclusion, understanding the influence of CO₂ concentration on photosynthesis, and the differing responses of C₃ and C₄ plants, can be pivotal for agricultural strategies, especially in controlled environments like greenhouses.

(c) Temperature

1. Role of Temperature in Photosynthesis:

- Photosynthesis involves both light-driven and enzymatic (dark) reactions.
- While both types of reactions are influenced by temperature, it's the dark, enzymatic reactions that are predominantly temperature-regulated.

2. Comparing Light and Dark Reactions:

- **Light Reactions:** Although these reactions can be influenced by temperature, their sensitivity is comparatively lower.
- **Dark Reactions:** Due to their enzymatic nature, dark reactions are more acutely responsive to temperature fluctuations.

3. C₃ and C₄ Plants' Temperature Responses:

- **C₄ Plants:** These are more adaptable to warmer conditions, exhibiting enhanced photosynthetic rates with rising temperatures.
- **C₃ Plants:** They have a preference for cooler temperatures, with their photosynthetic rates peaking at much lower temperature ranges than C₄ plants.

4. Adaptation to Local Habitats:

- The ideal temperature for photosynthesis is largely dictated by a plant's native environment.
- **Tropical Plants:** Accustomed to warmer environments, they naturally have a higher optimal temperature for photosynthesis.
- **Temperate Plants:** Adapted to milder climates, these plants thrive best and photosynthesize optimally at cooler temperatures.

In a nutshell, while temperature influences all aspects of photosynthesis, its most pronounced effect is on the enzymatic dark reactions. Additionally, plants have evolved to optimize their photosynthetic response according to the typical temperatures of their native habitats.

(d) Water

1. Water's Direct Role:

- Water is directly involved in the light reactions of photosynthesis. It is split to release oxygen, electrons, and protons during these reactions.

2. Indirect Impact on Photosynthesis:

- The influence of water on photosynthesis extends beyond its role as a direct reactant. Its availability primarily affects the plant's physiology, which in turn impacts photosynthesis.

3. Water Stress & Stomatal Behavior:

- When a plant experiences water stress, its stomata (tiny pores on the leaf surface) tend to close to reduce water loss through transpiration.
- Closed stomata limit the intake of CO_2 from the atmosphere, which can curtail the rate of photosynthesis since CO_2 is a vital reactant in the Calvin cycle (dark reactions).

4. Impact on Leaf Morphology & Metabolism:

- Water stress can cause leaves to wilt.
- Wilting not only reduces the surface area available for light absorption but also can diminish the overall metabolic activity of the leaf. A wilted leaf may not be as efficient in capturing light or facilitating gas exchange, both critical for photosynthesis.

In summary, while water is a direct participant in photosynthesis, its primary influence on the process is through its effect on plant health, stomatal behavior, and leaf morphology. Ensuring adequate water availability is crucial for maintaining optimal photosynthetic rates and overall plant health.