# Photosynthesis in Higher Plants

**Chapter 10**

## 1 INTRODUCTION

- Green plants synthesise the food they need, by photosynthesis and all other organisms depend on them for their needs.
- Photosynthesis is a physico-chemical process by which plants use light energy to drive the synthesis of organic compounds.
- The use of energy from sunlight by plants doing photosynthesis is the basis of life on earth.
- Photosynthesis is important due to two reasons : (a) It is the primary source of all food on earth and (b) It is also responsible for the release of oxygen into the atmosphere.

## 2 WHAT DO WE KNOW?

- Experiment for starch formation on variegated leaf or a leaf that was partially covered with black paper & exposed to light showed that photosynthesis occurred only in green part of leaves in the presence of light.
- Experiment where a part of leaf is enclosed in a test-tube with some KOH soaked cotton (which absorbs $CO_2$), while other half is exposed to air and set-up kept in light proved that $CO_2$ is needed for photosynthesis.

## 3 EARLY EXPERIMENTS

(1) Joseph Priestley
Using a burning candle, a mouse, mint plant and a bell jar for closed space, hypothesised that plants restore to the air whatever burning candles or breathing animals remove.

(2) Jan Ingenhousz
In an elegant experiment with an aquatic plant, showed that in bright sunlight plants produce oxygen.

(3) Julius von Sachs
Found that glucose is made in green plant parts and stored as starch.

(4) T. W. Engelmann
Using a prism, green alga *Cladophora* and aerobic bacteria, described the action spectrum of photosynthesis, which roughly resembles the absorption spectrum of chlorophyll- a and b.

(5) Cornelius van Niel
- Demonstrated that photosynthesis is essentially a light dependent reaction in which hydrogen from suitable oxidisable compound reduces $CO_2$ to carbohydrates.
- $H_2S$ is hydrogen donor for purple & green sulphur bacteria. $H_2O$, the hydrogen donor in green plants is oxidised to $O_2$.
- The oxidation product is sulphur or sulphate in purple & green sulphur bacteria and not $O_2$. Hence it was inferred that $O_2$ evolved by green plants comes from $H_2O$ and not from $CO_2$. This was later proved by using radioisotopic techniques. The correct equation, for the overall process:

$$6CO_2 + 12H_2O \xrightarrow{Light} C_6H_{12}O_6 + 6H_2O + 6O_2$$

## 4 WHERE DOES PHOTOSYNTHESIS TAKE PLACE

- In green parts of the plants, mainly in the mesophyll cells in the leaves, which have large number of chloroplasts.
- Usually the chloroplasts align themselves along the walls of mesophyll cells to get optimum quantity of the incident light.

**CHLOROPLAST ALIGNMENT**

**PARALLEL**
- In low or optimum light intensity to get maximum incident light

**PERPENDICULAR**
- In extremely high light intensity to avoid photo-oxidation.

There is a clear DIVISION OF LABOUR within the chloroplast.

**CHLOROPLAST**

**MEMBRANOUS SYSTEM**
- (Grana + Stroma lamellae)
- Responsible for trapping light & synthesis of ATP and NADPH.
- Directly light driven, called LIGHT REACTION (photochemical reactions)

**STROMA**
- Enzymatic reactions to synthesise sugar, which in turn forms starch, takes place
- Dependent on products of light reactions (ATP & NADPH)
- By convention called DARK REACTIONS (Carbon reactions)

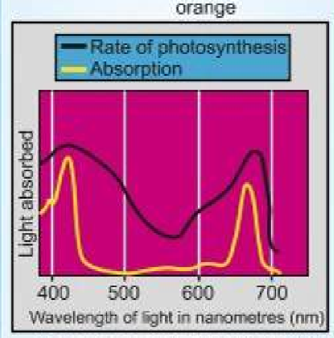
- However, this should not be construed to mean that the dark reaction occur in darkness or that they are not light-dependent.

## 5 HOW MANY TYPES OF PIGMENTS ARE INVOLVED IN PHOTOSYNTHESIS

- Leaf-pigments of any green plant can be separated through paper chromatography
- The colour in leaves is due to four pigments, that have the ability to absorb light, at specific wavelengths.

### COLOUR OF THE PIGMENTS IN THE CHROMATOGRAM

i. Chlorophyll-a = Bright or blue green
ii. Chlorophyll-b = Yellow-green
iii. Xanthophyll = Yellow
iv. Carotenoids = Yellow to yellow-orange




- The wavelength of light at which there is maximum absorption by chlorophyll-a i.e., in blue and red regions, also shows higher rate of photosynthesis.
- Hence, we can conclude that Chl-a is the chief pigment associated with photosynthesis.

- Chl-b, carotenoids and xanthophyll are accessory pigments. They absorb light and transfer the energy to Chl-a. They enable a wider range of wavelength of incoming light to be utilised for photosynthesis and also protect chlorophyll-a from photo-oxidation.

## 6 WHAT IS LIGHT REACTION?

- Light reactions or the photochemical phase include:
  - (a) Light absorption
  - (b) Water splitting
  - (c) Oxygen release, and
  - (d) ATP and NADPH formation
- Several protein complexes are involved in the process.
- The pigments are organised into two photosystems

**PHOTOSYSTEM**

- **PS-I**: LHC-I (Hundreds of pigments); Reaction centre (One molecule of Chl-a)
  - Absorption peak at 700 nm (P700)
- **PS-II**: LHC-II (Hundreds of pigments); Reaction centre (One molecule of Chl-a)
  - Absorption peak at 680 nm (P680)
- Named in the sequence of their discovery and not in the sequence of their function.

## 7 THE ELECTRON TRANSPORT

- The whole scheme of transfer of electrons starting from PS-II → uphill to the acceptor → down the ETC to PS-I → Excitation of electrons → transfer to another acceptor → finally downhill → to $NADP^+$ → reducing it to NADPH + $H^+$ is called the z-scheme, due to its characteristic shape.
- This shape is formed when all the carriers are placed in a sequence on a redox potential scale.

## 8 SPLITTING OF WATER

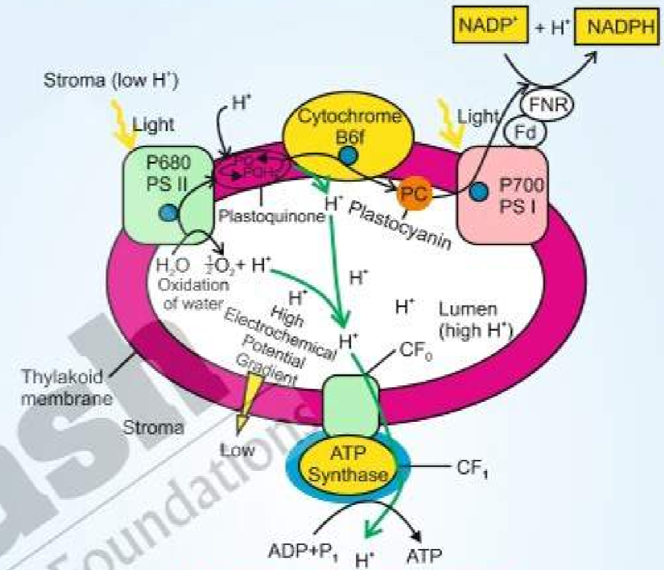
- PS-II continuously supplies electrons which becomes available by splitting of water.
- Water splitting complex is associated with PS-II, which itself is physically located on inner side of membrane of thylakoid.
- Water split into $2H^+$, [O] & electrons.
- This creates oxygen, one of the net products of photosynthesis.

## 9 CYCLIC AND NON-CYCLIC PHOTO-PHOSPHORYLATION

- When both PS-I and PS-II are involved, the process is non-cyclic, producing ATP, NADPH + $H^+$ and oxygen.
- When only PS-I is functional, cyclic flow takes place to produce only ATP.
- A possible location for cyclic flow is the stroma lamellae membranes which lack PS-II and NADP reductase enzyme.
  - Cyclic photo-phosphorylation also occurs when only light of wavelengths beyond 680 nm are available for excitation.
  - The membrane or lamellae of the grana have both PS-I and PS-II

## 10 CHEMIOSMOTIC HYPOTHESIS

- ATP synthesis in photosynthesis is linked to the development of a proton gradient across the membranes of thylakoid and protons accumulate in the lumen of thylakoids.
- The proton gradient is caused by:
  - (a) Protons or hydrogen ions produced by splitting of water, accumulate in the lumen of the thylakoids.
  - (b) The primary acceptor of electron located towards outer side of membrane transfers its electron to an H carrier, which removes a proton from stroma while transporting an electron to thylakoid lumen.
  - (c) The NADP reductase enzyme located on stroma side of membrane, removes protons from stroma, while reducing $NADP^+$ to NADPH + $H^+$.




**ATP synthesis through chemiosmosis**

- Within chloroplast, protons decrease in stroma and accumulate in lumen. This creates a proton-gradient across thylakoid membrane as well as a measurable decrease in pH in the lumen.
- Breakdown of this gradient leads to synthesis of ATP, when protons move across the membrane to the stroma through transmembrane channel of the $CF_0$ of the ATP synthase.

ATP synthase (Two parts)

- $CF_0$ = Embedded in the thylakoid membrane. A transmembrane channel for facilitated diffusion of protons
- $CF_1$ = Protrudes on outer surface of thylakoid membrane on the side that faces stroma. It synthesise ATP

- Chemiosmosis requires - a membrane, a proton pump, a proton gradient and ATP synthase.

## (11) WHERE ARE THE ATP AND NADPH USED?

- Of the products of light reaction- ATP, NADPH and $O_2$. $O_2$ diffuses out of chloroplast while ATP and NADPH are used to synthesise sugars in the biosynthetic phase of photosynthesis. Melvin Calvin used radioactive $^{14}C$ in algal photosynthesis studies to discover the first $CO_2$ fixation product, the 3-C organic acid (3-PGA) ($C_3$ – pathway).
- In another group of plants, the first stable product was 4 carbon, oxaloacetic acid OAA ($C_4$-pathway).

## (12) THE CALVIN CYCLE

- The Calvin cycle occurs in all photosynthetic plants; whether they have $C_3$ or $C_4$ (or any other) pathways.
- Calvin cycle can be described under three stages:

(1) CARBOXYLATION: Most crucial step.

$$\underset{(5C)}{RuBP} \xrightarrow[CO_2 + H_2O]{RuBisCO} \underset{(3C)}{2 \times 3-PGA}$$

(2) REDUCTION: A series of reactions that lead to formation of glucose. Utilises 2 ATP and 2 NADPH per $CO_2$. (The fixation of $6CO_2$ and 6 turns of the cycle are needed to form one molecule of glucose from the pathway).

(3) REGENERATION: Regeneration of RUBP is crucial for the cycle to continue. This step require one ATP. So, to produce one molecule of glucose in Calvin cycle an input of $6CO_2$ 18 ATP & 12 NADPH are required

## (13) THE $C_4$-PATHWAY

- Plants adapted to dry tropical regions have the $C_4$-pathway.
- $C_4$-plants are special: They have special type of leaf anatomy, tolerate higher temperatures, show response to high light intensities, lack photorespiration and have greater biomass productivity
- $C_4$-plants have leaves showing KRANZ ANATOMY the particularly large cells around the vascular bundles, which may form several layers and are called bundle sheath cells, characterised by having a large number of chloroplasts, thick walls impervious to gaseous exchange and no intercellular spaces.
- The pathway is cyclic & called the Hatch and Slack Pathway. It is partly completed in mesophyll & partly in bundle sheath cell.

| MESOPHYLL CELL | BUNDLE-SHEATH CELLS |
|---|---|
| (1) Primary $CO_2$ acceptor is a 3-C compound PEP.<br>(2) Enzyme for this fixation is PEPcase.<br>(3) Lacks RuBisCO<br>(4) $C_4$-acid formed is OAA; which forms malic acid or aspartic acid and transported to bundle sheath cells. | (1) Malic Acid/Aspartic Acid → $CO_2$ + 3-Carbon molecule<br>3-Carbon molecule → Transported to mesophyll & converted to PEP<br>$CO_2$ → Enters – Calvin cycle a pathway common to all plants.<br>(2) Rich in RuBisCO, but lack PEPcase. |

## (14) PHOTORESPIRATION

- RuBisCo, the most abundant enzyme in the world, has the active site that can bind to both $CO_2$ and $O_2$. This binding is competitive. It is the relative concentration of $O_2$ and $CO_2$ that determines which of the two will bind to the enzyme.
- RuBisCo, has a much greater affinity for $CO_2$, when the $CO_2$: $O_2$ is nearly equal than for $O_2$.
- In $C_3$-plants some $O_2$ does bind to RuBisCO, and hence $CO_2$ fixation is decreased, due to the following reaction.

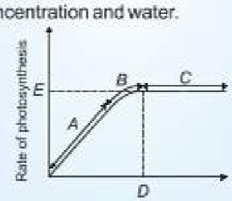
$$RuBP + O_2 \xrightarrow{RuBisCo} 3\ PGA\ (3C) + 2\ phosphoglycolate\ (2C)$$

This is called photo-respiration
- In photo-respiration there is neither synthesis of sugars, nor of ATP. It results in release of $CO_2$ with utilisation of ATP.
- The biological function of photorespiration is not known yet.
- In $C_4$-plants photo-respiration does not occur, as they have a mechanism that increases the concentration of $CO_2$ at the enzyme site. This ensures that the RuBisCO functions as a carboxylase minimising the oxygenase activity.

## (15) FACTORS AFFECTING PHOTOSYNTHESIS

- Photosynthesis is under the influence of several factors, both internal (plant) & external.

**Internal Factors:**
- The plant factors include the number, size, age & orientation of leaves, mesophyll cells and chloroplasts, internal $CO_2$ concentration & the amount of chlorophyll.
- The plant or internal factors are dependent on the genetic predisposition & growth of the plant.
- **External factors:** include availability of sunlight, temperature, $CO_2$ concentration and water.




- **Blackman's Law of Limiting Factor**
  If a chemical process is affected by more than one factor, then its rate will be determined by the factor which is nearest to its minimal value. It is the factor which directly affects the process if its quality is changed.

(i) Light: Light saturation occurs at 10% of the full sunlight. Except for plants in shade or in dense forests, light is rarely a limiting factor in nature.
- There is a linear relationship between incident light & $CO_2$ fixation rates at low light intensities. At higher light intensities, gradually the rate does not show further, increase as other factors become limiting.

(ii) $CO_2$ concentration: Major limiting factor. The concentration of $CO_2$ is very low in the atmosphere (0.03 & 0.04%), so increase in concentration upto 0.05% can cause increase in $CO_2$ fixation rates, beyond this levels it can become damaging over longer periods.
- At low light conditions neither group responds to high $CO_2$ conditions $C_4$-plants show saturation at $360\mu 1L^{-1}$ $C_3$-saturation is seen at $450\mu 1L^{-1}$. Some greenhouse crops like tomatoes and bell pepper show higher yields in $CO_2$ enriched atmosphere.

(iii) Temperature: Dark reactions being enzymatic are temperature controlled. Light reactions are also temperature sensitivie. $C_4$-plants show higher yield at high temperature while $C_3$-plants have a much lower temperature optimum.

(iv) Water: Effect of water as a factor is more through its effect on the plant rather than directly on photosynthesis. Water stress causes the stomata to close hence reducing $CO_2$ availability. Water stress also makes leaves wilt, thus, reducing the surface area of leaves and their metabolic activity as well.

## Sharpen Your Understanding — NCERT Based MCQs

1. The carbon reactions of photosynthesis takes place in the - [NCERT Pg. 209]
   (1) Stroma lamellae
   (2) Membrane system of grana
   (3) Stroma
   (4) Thylakoid system

2. The green parts in plants synthesise glucose which is stored as starch was found first by: [NCERT Pg. 208]
   (1) Julius von Sachs (2) T.W. Engelmann
   (3) Cornelius van Niel (4) Joseph Priestley

3. Who first inferred that the $O_2$ evolved by the green plants during photosynthesis comes from $H_2O$ and not from $CO_2$? [NCERT Pg. 208]
   (1) T.W. Engelmann
   (2) Cornelius van Niel
   (3) Julius von Sachs
   (4) Jan Ingenhousz

4. Plants restore to the air whatever breathing animals and burning candles remove, it was hypothesised by: [NCERT Pg. 207]
   (1) Cornelius van Niel
   (2) Joseph Priestley
   (3) Julius von Sachs
   (4) T.W. Engelmann

5. The experiment where a part of a leaf is enclosed in a test-tube containing some KOH soaked cotton, while the other half is exposed to air, and the set up is then placed in light for some time, showed that: [NCERT Pg. 207]
   (1) Light is essential for photosynthesis
   (2) Chlorophyll is needed for photosynthesis
   (3) $CO_2$ is required for photosynthesis
   (4) Photosynthesis is temperature controlled.

6. T.W. Engelmann described the first action spectrum of photosynthesis, by working on the green alga: [NCERT Pg. 208]
   (1) *Cladophora* (2) *Eurodina*
   (3) *Chlorella* (4) *Ulothrix*

7. Which is the most abundant plant pigment in the world? [NCERT Pg. 210]
   (1) Carotenoids (2) Xanthophyll
   (3) Chlorophyll-b (4) Chlorophyll-a

8. Which of the following photosynthetic pigments, show yellow to yellow-orange colour in the chromatogram? [NCERT Pg. 210]
   (1) Chlorophyll-a (2) Chlorophyll-b
   (3) Carotenoids (4) Xanthophyll

9. The reaction centre chlorophyll-a molecule in PS-I has an absorption peak at: [NCERT Pg. 211]
   (1) 700 nm (2) 680 nm
   (3) 750 nm (4) 400 nm

10. The electrons needed to replace those removed from photosystem-I during the electron transport are provided by: [NCERT Pg. 212]
   (1) Water directly (2) $H_2S$ directly
   (3) Photosystem-II (4) $CF_0$-$CF_1$

11. PS-II and NADP reductase enzyme are: [NCERT Pg. 213]
   (1) Required for cyclic photophosphorylation
   (2) Absent on stroma lamellae membranes
   (3) Absent on lamellae of the grana
   (4) Not needed for non-cyclic photophosphorylation

12. $CF_0$ is embedded in the thylakoid membrane and forms a transmembrane channel that carries out: [NCERT Pg. 215]
   (1) Facilitated diffusion of protons across the membrane
   (2) Electron transport by diffusion
   (3) ATP synthesis in the channel
   (4) Active transport of protons and electrons

13. The first $CO_2$ fixation product in algal photosynthesis, discovered by radioactive $^{14}C$, was found to be: [NCERT Pg. 215]
   (1) a 4-carbon organic acid
   (2) 3-phosphoglyceric acid
   (3) 5-carbon ketose sugar
   (4) Ribulose bisphosphate

14. The basic pathway that results in the formation of sugars, which is common to the $C_3$ and $C_4$ plant is: [NCERT Pg. 220]
(1) Hatch and slack pathway
(2) The $C_4$-pathway
(3) Calvin cycle
(4) Photorespiration

15. The most crucial step of Calvin cycle, where $CO_2$ is utilized by RuBP is [NCERT Pg. 216]
(1) Carboxylation (2) Regeneration
(3) Reduction (4) Oxygenation

16. In the $C_4$-plants, mesophyll cells: [NCERT Pg. 219]
(1) Lack PEPcase enzyme
(2) Is the site of Calvin cycle
(3) Lack RuBisCO enzyme
(4) Are impervious to gaseous exchange

17. Select the incorrect statement w.r.t. photorespiration? [NCERT Pg. 220]
(1) In $C_4$-plants photorespiration does not occur
(2) The biological function of photo-respiration is not known yet
(3) RuBP binds with $O_2$ to form 2 molecules of 3-PGA
(4) There is no synthesis of ATP or NADPH

18. If $C_3$-plants like tomatoes and bell pepper are allowed to grow in $CO_2$ enriched atmosphere, it leads to- [NCERT Pg. 223]
(1) Lower yields
(2) Higher yields
(3) No change in productivity
(4) Very low photosynthesis

19. Select the odd one out w.r.t. external factors affecting photosynthesis? [NCERT 222]
(1) Orientation of leaves
(2) Availability of sunlight
(3) Temperature
(4) $CO_2$ concentration & water

20. How many turns of Calvin cycle pathway are required for the formation of one molecule of glucose? [NCERT Pg. 217]
(1) One complete turn
(2) Two complete turns
(3) Six turns of cycle
(4) Three complete turns

## Thinking in Context

1. Water stress makes leaves wilt, thus, reducing the _______ of the leaves and their metabolic activity as well. [NCERT Pg. 223]
2. Water stress causes the stomata to close hence reducing the _______. [NCERT Pg. 223]
3. Tropical plants have a _______ temperature optimum than the plants adapted to temperate climates. [NCERT Pg. 223]
4. At _______, neither $C_3$ nor $C_4$ group of plants respond to high $CO_2$ conditions. [NCERT Pg. 223]
5. Increase in incident light beyond a point causes the breakdown of chlorophyll and a _______ in photosynthesis. [NCERT Pg. 223]
6. The plant or internal factors are dependent on the _______ and the growth of the plant. [NCERT Pg. 222]
7. $C_4$-plants lack _______, so productivity and yields are better than $C_3$ plants. [NCERT Pg. 220]
8. The bundle sheath cells are rich in an enzyme __A__ but lack __B__. [NCERT Pg. 220]
9. For every _______ entering the Calvin cycle, 3 molecules of ATP and 2 of NADPH are required. [NCERT Pg. 218]
10. The regeneration step of Calvin cycle require _______ for the phosphorylation to form RuBP. [NCERT Pg. 217]
11. The carboxylation step of Calvin cycle, is catalysed by the enzyme _______. [NCERT Pg. 216]
12. Cyclic photophosphorylation occurs when only light of wavelengths _______ are available for excitation. [NCERT Pg. 213]

13. Water splitting complex is associated with _______. [NCERT Pg. 212]

14. _______ is the chief pigment associated with photosynthesis [NCERT Pg. 210]

15. When $H_2S$ is the hydrogen donor for purple and green sulphur bacteria, the oxidation product is _______. [NCERT Pg. 208]

16. Photosynthesis is a _______ process by which the plants use light energy to drive the synthesis of organic compounds. [NCERT Pg. 206]

17. During chromatographic separation of the leaf pigments yellow-green colour in the chromatogram in shown by _______. [NCERT Pg. 210]

18. _______ protect chlorophyll-a from photo-oxidation. [NCERT Pg. 211]

19. _______ is the synthesis of ATP from ADP and inorganic phosphate in the presence of light. [NCERT Pg. 213]

20. In photosynthesis, ATP synthesis is linked to the development of a _______ across a membrane. [NCERT Pg. 213]

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