13. Photosynthesis in Higher Plants

POINTS TO REMEMBER :

- Photosynthesis: Photosynthesis is an enzyme regulated anabolic process of manufacture of organic compounds inside the chlorophyll containing cells from carbon dioxide and water with the help of sunlight as a source of energy.

Historical Perspective :

- **Joseph Priestley (1770) :** Showed that plants have the ability to take up CO_2 from atmosphere and release O_2.
- **Jan Ingenhousz (1779) :** Release of O_2 by plants was possible only in sunlight and only by the green parts of plants.
- **Theodore de Saussure (1804) :** Water is an essential requirement for photosynthesis to occur.
- **Julius Von Sachs (1854) :** Green parts in plant produce glucose which is stored as starch.
- **T. W. Engelmann (1888) :** The effect of different wavelength of light on photosynthesis and plotted the first action spectrum of photosynthesis.
- **C. B. Van Niel (1931) :** Photosynthesis is essentially a light dependent reaction in which hydrogen from an oxidisable compound reduces CO_2 to form sugar. He gave a simplified chemical equation of photosynthesis.
- **Hill (1937) :** Evolution of oxygen occurs in light reaction.
- **Calvin (1954-55) :** Traced the pathway of carbon fixation.
- **Hatch and Slack (1965) :** Discovered C4 pathway of CO_2 fixation.

Site for photosynthesis :

- Photosynthesis takes place only in green parts of the plant, mostly in leaves.
- Within a leaf, photosynthesis occurs in mesophyll cells which contain the chloroplasts.
- Chloroplasts are the actual sites for photosynthesis.
- The thylakoids in chloroplast contain most of pigments required for capturing solar energy to initiate photosynthesis.
- The membrane system (grana) is responsible for trapping the light energy and for the synthesis of ATP and NADPH. Biosynthetic phase (dark reaction) is carried in stroma.

Pigments involved in photosynthesis:

- **Chlorophyll a :** (Bright or blue green in chromatograph). Major pigment, act as reaction centre, involved in trapping and converting light into chemical energy.
- **Chlorophyll b :** (Yellow green)
- **Xanthophylls :** (Yellow)
- **Carotenoid :** (Yellow to yellow-orange)
- In the **blue** and **red** regions of spectrum shows higher rate of photosynthesis.

What is light reaction?

- Light reactions or the 'Photochemical 'phase includes light absorption, splitting of water, evolution of oxygen and formation of high energy compound like ATP and NADPH.
- **Light Harvesting Complexes (LHC) :** The light harvesting complexes are made up of hundreds of pigment molecules bound to protein within the photosystem I (PSI) and photosystem II (PSII).
- Each photosystem has all the pigments except one molecule of chlorophyll 'a' forming a light harvesting system (antennae).
- The reaction centre (chlorophyll a) is different in both the photosystems.

- **Photosystem I (PSI) :** Chlorophyll ‘a’ has an absorption peak at 700 nm (P700).
- **Photosystem II (PSII) :** Chlorophyll ‘a’ has absorption peak at 680 nm (P680).

Process of photosynthesis :

- It includes two phases - Photochemical phase and biosynthetic phase.
- **Photochemical phase (Light reaction) :** This phase includes - light absorption, splitting of water, oxygen release and formation of ATP and NADPH.
- **Biosynthetic phase (Dark reaction) :** It is light independent phase, synthesis of food material (sugars).

The electron transport :

- In photosystem centre chlorophyll a absorbs 680 nm wavelength of red light causing electrons to become excited and release two electrons from the atomic nucleus.
- These electrons are accepted by primary electron acceptor i.e. **ferredoxin.**
- The electron from the ferredoxin passed to **electron transport system** consisting **cytochromes.**
- The electron moved in down hill in terms of redox potential by oxidation-reduction reactions.
- Finally the electron reached photosystem-I.
- Simultaneously electron released from photosystem-I is accepted by electron acceptor.
- Electron hole created in PS-I is filled up by the electron from PS-II.
- Electron from PS-I passed down hill and reduce NADP into $NADPH^+ + H^+$.

Photolysis of water :

- PS-II loose electrons continuously, filled up by electrons released due to photolysis of water.
- Water is split into H^+, (O) and electrons in presence of light and Mn^{2+} and Cl^-.
- This also creates O_2 the bi-product of photosynthesis.
- Photolysis takes place in the vicinity of the PS-II.
- $2H_2O \rightarrow 4H^+ + O_2 + 4e^-$.

Photophosphorylation :

- The process of formation of high-energy chemicals (ATP and NADPH).

Non Cyclic photophosphorylation :

- Two photosystems work in series – First PSII and then PSI.
- These two photosystems are connected through an electron transport chain (Z. Scheme).
- **ATP** and **NADPH + H^+** are synthesized by this process. PSI and PSII are found in lamellae of grana, hence this process is carried here.

Cyclic photophosphorylation :

- Only **PS-I** works, the electron circulates within the photosystem.
- It happens in the stroma lamellae **(possible location)** because in this region **PS-II** and **NADP reductase** enzyme are absent.
- Hence only ATP molecules are synthesized.

Chemiosmotic Hypothesis :

- Chemiosmotic hypothesis explain the mechanism of ATP synthesis in chloroplast.

- In photosynthesis, ATP synthesis is linked to development of a proton gradient across a membrane.
- The protons that are produced by the splitting of water are accumulated inside of membrane of thylakoids (in lumen).
- As the electron moves through the photosystem, protons are transported across the membrane.
- NADP reductase enzyme is located on the stroma side of the membrane, along with electrons from the acceptor it removes H+ from the stroma during reduction of NADPH + H^+.
- This creates proton gradients across the thylakoid membrane as well as a measurable decrease in pH in the lumen.
- ATPase has a channel that allows diffusion of protons back to stroma across the membrane.
- This releases energy to activate ATPase enzyme that catalyses the formation of ATP.

Biosynthetic phase in C3 plants :

- ATP and NADH, the products of light reaction are used in synthesis of food. The first CO_2 fixation product in C3 plant is 3-phosphoglyceric acid or PGA.
- In some other plants the first stable product is an organic acid called oxaloacetic acid a 4-C compound hence is called C4 plants.

The Calvin cycle :

- The CO_2 acceptor molecule is RuBP (Ribulose bisphosphate).
- The cyclic path of sugar formation is called Calvin cycle on the name of Melvin Calvin, the discoverer of this pathway. Calvin cycle proceeds in three stages:

- **Carboxylation :**
  - Carboxylation is the fixation of CO_2 into a stable organic intermediate.
  - CO_2 combines with Ribulose 1, 5 bisphosphate to form 3 PGA in the presence of **RuBisCo enzyme**.

- **Reduction :**
  - These are a series of reactions that lead to the formation of glucose.
  - 2 molecules of ATP for phosphorylation and two of NADPH for reduction per CO_2 molecule fixed.
  - The fixation of six molecules of CO_2 and 6 turns of the cycle are required for the formation of one molecule of glucose.

- **Regeneration :**
  - Regeneration of the CO_2 acceptor molecule RuBP is crucial if the cycle is to continue uninterrupted.
  - Regeneration steps required one ATP for phosphorylation to form RuBP.

- Hence for every CO_2 molecule entering the Calvin cycle, 3 molecules of ATP and 2 molecules of NADPH are required.

The C_4 pathway :

- Plants that are adapted to dry tropical regions have the C_4 pathway.
- C_4 oxaloacetic acid is the first CO_2 fixation product.
- These plants have special type of leaf anatomy, they tolerate higher temperatures.
- The leaf has two types of cells: mesophyll cells and Bundle sheath cells (Kranz anatomy).

- Initially CO_2 is taken up by phosphoenol pyruvate (PEP) in mesophyll cells and changed to oxaloacetic acid (OAA) in the presence of **PEP carboxylase**.
- Oxaloacetate is reduced to malate/asparate that reaches into bundle sheath cells.
- In the bundle sheath cells these C_4 acids are broken down to release CO_2 and a 3-carbon molecule i.e. pyruvic acid.
- The CO_2 released in the bundle sheath cell enters the C3 cycle because these cells are rich in enzyme Ribulose bisphosphate carboxylase-oxygenase **(RuBisCO).**
- The pyruvate formed in the bundle sheath cell transported back to the mesophyll cell, get phosphorylated to form phosphoenol pyruvate.

Photorespiration:

- The light induced respiration (evolution of CO_2) in green plants is called photorespiration.
- Active site of RuBisCO has active site for both O_2 and CO_2.
- In C3 plants some O_2 binds with RuBisCo and hence CO_2 fixation is decreased.
- In this process RuBP instead of being converted to 2 molecules of PGA, binds with O_2 to form one molecule of PGA and phosphoglycolate.
- In the photorespiratory pathway there is neither synthesis of sugar, nor of ATP. Rather it results in the release of $CO_2$with utilization of ATP.
- In the photorespiratory pathway there is no synthesis of ATP or NADPH.
- Therefore photorespiration is a wasteful process.
- In C_4 plant photorespiration does not occur:
  - RuBisCO enzyme is present in the bundle sheath cells.
  - Primary carboxylation is takes place in the mesophyll cell by PEP carboxylase.
  - CO_2 supplied to bundle sheath cell by C_4 acid intermediate.
  - Hence C_4 plants are photosynthetically more efficient than C3 plant.

Law of Limiting Factors :

- 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 quantity is changed.