Chapter 6: Photosynthesis

Photosynthesis is the process whereby organisms such as plants, some protists and some bacteria use the energy from sunlight to convert (fix) atmospheric carbon dioxide into carbohydrates, that is, light energy is converted into chemical energy. The organisms which can convert light energy into chemical energy in this way are called **autotrophs** as they are capable of making their own food from inorganic compounds such as CO_2. hence the name photosynthesis, from the Greek φῶς, Photo = light ; synthesis = to make "putting together". In most cases, oxygen is also released as a waste product. It is convenient to think of photosynthesis in this way as it takes place in two stages :

• The light-dependent reactions

• The light-independent reactions

1. Site of Photosynthesis

Photosynthesis takes place mainly in the green leaves and to some extent in other green parts of the plant. It takes place in the cell organelles called chloroplasts.

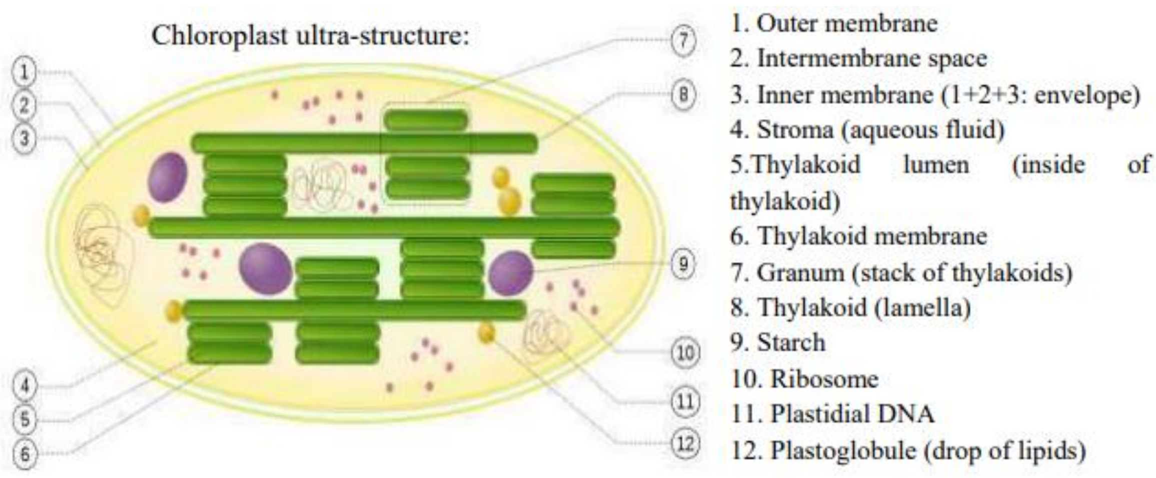

Fig 1 : Chloroplast ultra-structure

- The chloroplasts are found in large number in the mesophyll cells of leaves.
- The chloroplasts align themselves along the walls of the mesophyll cells, in such a way that they get maximum quantity of incident light; they will be aligned with their flat surfaces parallel to the wall under low or optimum light intensities and perpendicular to the walls when the intensity goes very high.

- There is a clear division of labour within the chloroplasts. The membrane system is responsible for the photo-chemical phase, where synthesis of ATP and NADPH occurs, whereas the stroma has enzymes for the reduction of carbon dioxide into carbohydrates and formation of sugars.
- The pigments are distributed in the membrane system.

2. Pigments Involved in Photosynthesis

- There are four pigments : chlorophyll a, chlorophyll b, carotene and xanthophyll (carotenoids).

○ **Chlorophyll a** ($C_{55}H_{72}O_5N_4Mg$) : **Bright green or bluish green.**

○ **Chlorophyll b** ($C_{55}H_{70}O_6N_4Mg$) : **Yellowish green.**

○ **Xanthophyll** (e.g., Lutein $C_{40}H_{56}O_2$) : **Yellow.**

○ **Carotene** ($C_{40}H_{56}$) : **Yellow-orange or reddish.**

- Chief or main pigment associated with photosynthesis : Chlorophyll a.

- Accessory pigments : Chlorophyll b, carotenoids (carotenes and xanthophylls).

- The accessory pigments help in two ways:

○ Thylakoid pigments like xanthophylls and carotenes also absorb light from the mid-part of visible light spectrum. Thus, widen the absorption of spectrum.

○ Chlorophyll b, xanthophylls and carotenes also protect chlorophyll a from photo-oxidation.

Note: Phycobillins is the group of photosynthetic pigments found in red algae and cyanobacteria (blue-green algae).

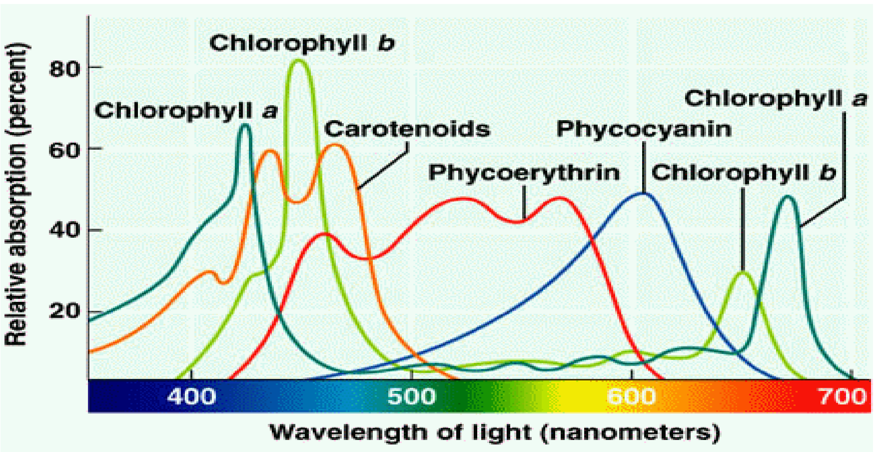

Fig 2 : Photosynthetic pigments absorb energy from sunlight, which is used during photosynthesis.

3. Photosystems

These are the functional and structural units of protein complexes involved in photosynthesis. Each photosystem has a reaction centre which contains a special chlorophyll-a molecule and is different in both the photosystems.

1. Photosystem-I (PS-I) is present in stroma thylakoids and non-appressed part of granal thylakoids. Its reaction centre has a peak absorption at 700 nm, called P700 .

● It can perform cyclic photophosphorylation independently.

● PS-I is active both in red and far-red light and it carries out reduction of NADP.

● PS-I is having pigments, chl-a 660, chl-a 670, chl-a 680, chl-a 690, chl-a 700 and carotenoids.

● It consists of photocentre, Light Harvesting Complex [LHC-I] and some electron carriers.

2. Photosystem-II (PS-II) is located in the appressed part of the grana thylakoids.

● The PS-II is inactive in far-red light (beyond 680 nm). Its reaction centre is P680 .

● It picks up electrons emitted during photolysis of water and performs non-cyclic photophosphorylation or the Z-scheme of light reaction.

● PS-II is having pigments chl-b 650, chl-a 660, chl-a 670, chl-a 678, chl-a 680 and phycobilins.

● It consists of photocentre, oxygen evolving complex, Light Harvesting Complex (LHC-II) and some electron carriers.

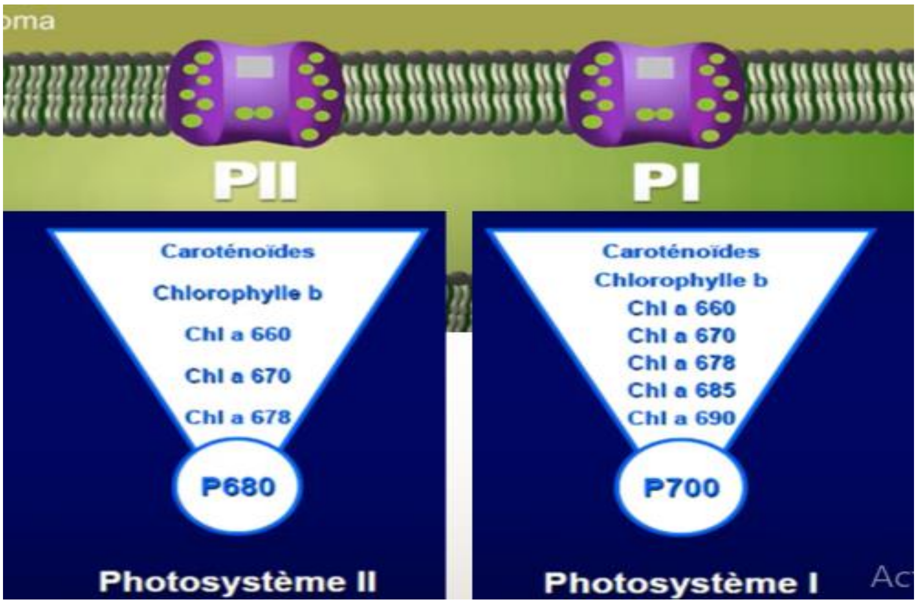

Fig 3 : photosystems I and II.

4. Mechanism of Photosynthesis

The two major steps of photosynthesis are as follows

- Light reaction or photochemical phase
- Dark reaction or biosynthetic phase

Light Reaction (Photochemical Phase	Dark Reaction (Biosynthetic Phase)
- It is directly dependent on sunlight (light).	- It is not directly dependent on sunlight (light) but is dependent on the products of light reaction.
- ATP and $NADPH_2$ are generated.	- ATP and $NADPH_2$ are consumed.
- Photolysis of water occurs and oxygen is liberated.	- Reduction of carbon dioxide occurs and carbohydrate is formed.
- It occurs in the grana of chloroplast.	- It occurs in the stroma of chloroplast

1. Light Reaction or Photochemical Phase

● It takes place only in the presence of light in the grana portion of the chloroplast.

● Light is trapped by photosynthetic pigments present in the grana thylakoids. The light reaction occurring in thylakoid completes in three stages described below

(i) Photoexcitation of Chlorophyll-a

● The process of light reaction starts when photosynthetic pigments of both PS absorb light energy.

● Then their antenna molecules transfer the absorbed energy to the reaction centre. This makes the reaction centre of both PS highly energised or photoexcited and as a result, it emits a pair of electrons.

● The electrons ejected by PS are accepted by primary electron acceptor Ferredoxin Reducing Substance (FRS). It passes them into an Electron Transport System (ETS). During non-cyclic photophosphorylation, it leads to reduction of NADP into $NADPH^+ H^+$, while during both cyclic and non-cyclic photophosphorylation, it results in the formation of ATP from ADP and inorganic phosphate. Thus, the flow of electrons through ETS is linked to photophosphorylation.

(ii) Photolysis of Water

● In this process, water splits into H^+ , [O] and electrons. The two electrons obtained from the photolysis of one water molecule is passed on to PS-II.

● An oxygen evolving complex is located on the inner side of thylakoid membrane. Photolysis of water also requires minerals such as Mn Cl $^{2+\,-}$, and Ca^{2+} .

● The protons and oxygen formed in this process are released within the lumen of thylakoids and O_2 is evolved as byproduct. Whole reaction is summerised as given below

$$2H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} 4H^+ + 4e^- + O_2\uparrow$$

● The photolysis of water or photochemical oxidation of water was first described by Van Niel in 1931. Later on it was demonstrated by R Hill 1937. Therefore, it is also known as Hill reaction.

(iii) Photophosphorylation

It is the light driven or light energised synthesis of ATP molecules. It was discovered by Arnon et al in 1954.

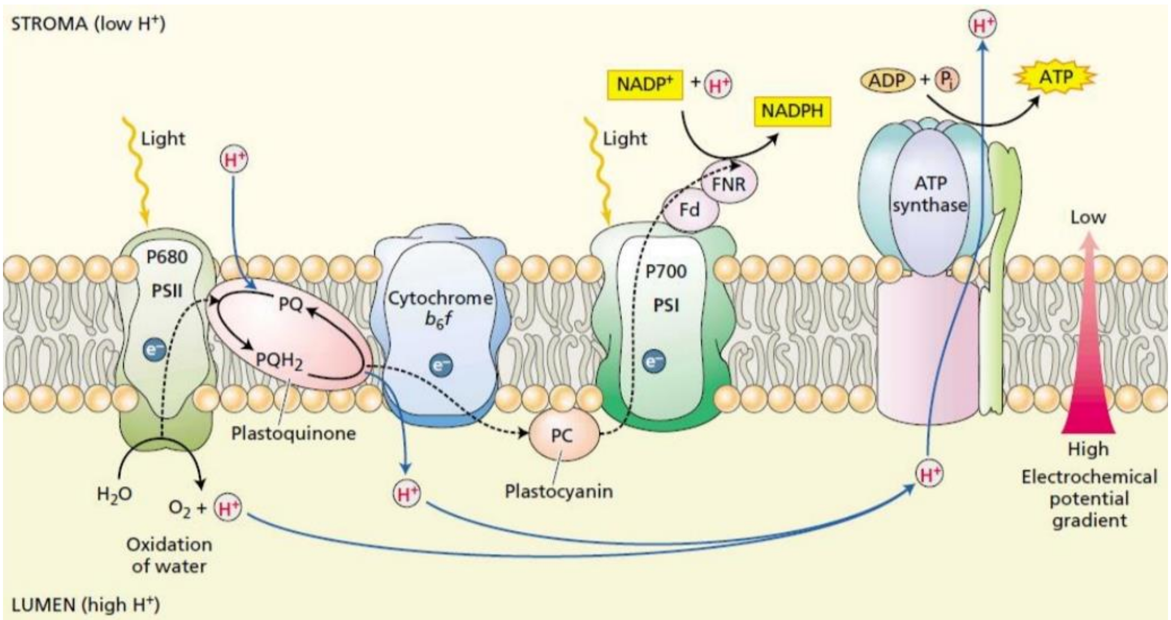

Fig 4 : Photophosphorylation

Photophosphorylation reactions are of two types

(a) Non-cyclic photophosphorylation

When ATP formation is coupled to a non-cyclic transfer of electrons, it is called as non-cyclic photophosphorylation.

● During this process, electrons are not cycled back to the P680 , i.e. PS-II. They are used in the reduction of NADP to $NADPH_2$. It also utilises water to release oxygen and hydrogen (photolysis).

● The electrons emitted by reaction centre P680 are first accepted by an electron acceptor PQ (plastoquinone).

● These electrons are then transferred through electron carriers like cytochrome-b6 , cytochrome-f and finally of plastocyanin. Cytochrome, plastoquinone and plastocyanin are the important electron carriers. They are described below

■ Cytochromes These are small proteins that contain a cofactor, haem, having an Fe-atom. Cytochromes are intrinsic membrane proteins of thylakoid membranes.

■ Plastoquinones (PQ) They transport electrons over short distance within a membrane. Their long hydrocarbon tail is hydrophobic, thus they dissolve easily into the lipid component of the chloroplast membrane.

■ Plastocyanin (PC) It is a small protein that carries electrons with the help of copper.

● From plastocyanin, electrons are finally transferred to the reaction centre of PS-I.

● PS-I also receives photons of light and becomes photoexcited. Now, it expels electrons that enters the ETS. Finally the $NADP^+$ present in stroma receive electrons through ETS. It also receives protons via photolysis of water. Thus, it gets reduced into

$$2NADP + 4e^- + 4H^+ \longrightarrow 2NADPH_2$$

● Due to the transfer of electrons, energy is released during non-cyclic transfer. This energy is utilised to form ATP from ADP and iP. ATP formation occurs by chemiosmosis.

● The process is also known as Z-scheme, due to the characteristic flow of electrons across the two photosystems.

(b) Cyclic-photophosphorylation

The process of formation of ATP from ADP $^+$ iP via a cyclic flow of electrons in photosystem-I is known as cyclic photophosphorylation. It is called, so because in this process, the donor and final acceptor is same, i.e. P700. This occurs in low light intensity, when CO_2 fixation is inhibited.

● The energy rich electrons from the PS-I, i.e. P700 are first accepted by primary electron acceptor, FRS and transferred to Fd (Ferredoxin). From Fd, the electrons are transferred to cytochrome-b6 (and not to NADP), cytochrome-f and then to PC.

● From PC, the electrons are finally returned back to the reaction centre of PS-I, i.e. P700. In this process, 2 molecules of ATP are synthesised, and no reduction of NADP to NADPH $^{+\,+}$ H takes place.

Chemiosmotic Hypothesis

● It explains the mechanism of how actually ATP molecule is synthesised in the chloroplast.

● In brief, chemiosmosis requires a membrane, a proton pump, proton gradient and ATPase. The photolysis of water (inside lumen of thylakoid) and movement of hydrogen ions ( )H+ from stroma to lumen of thylakoid during electron transport system as well as reduction of NADP+ to NADPH ^{2} , creates a gradient or a high concentration of protons within the thylakoid lumen.

● ATPase has a channel that allows diffusion of protons back across the membrane leading to the breakdown of the gradient.

● This releases enough energy to activate ATPase enzyme that catalyses the formation of ATP.

● This ATP is used immediately in biosynthetic reaction taking place in the stroma responsible for fixing CO_2 and synthesis of sugars.

● The products of light reactions are ATP, NADPH and O_2 . Of these, O_2 diffuses out of the chloroplast, while ATP and NADPH are used to derive the processes leading to the synthesis of food, i.e. sugar.

2. Dark Reaction or Biosynthetic Phase

● The Calvin cycle takes place in the stroma, it is similar to the citric acid cycle in that a starting material is regenerated after some molecules enter and others exit the cycle

● The citric acid cycle is catabolic, oxidizing acetyl CoA and using the energy to synthesize ATP, while the Calvin cycle is anabolic, building carbohydrates from smaller molecules and consuming energy

● Carbon enters the Calvin cycle in the form of CO_2 and leaves in the form of sugar, The cycle spends ATP as an energy source and consumes NADPH as reducing power for adding high-energy electrons to make the sugar

● Glyceraldehyde 3-Phosphate (G3P): a three-carbon carbohydrate that is the direct product of the Calvin cycle; it is also an intermediate in glycolysis

● For the net synthesis of one molecule of G3P, the cycle must take place three times, fixing three molecules of CO_2 –one per turn of the cycle.

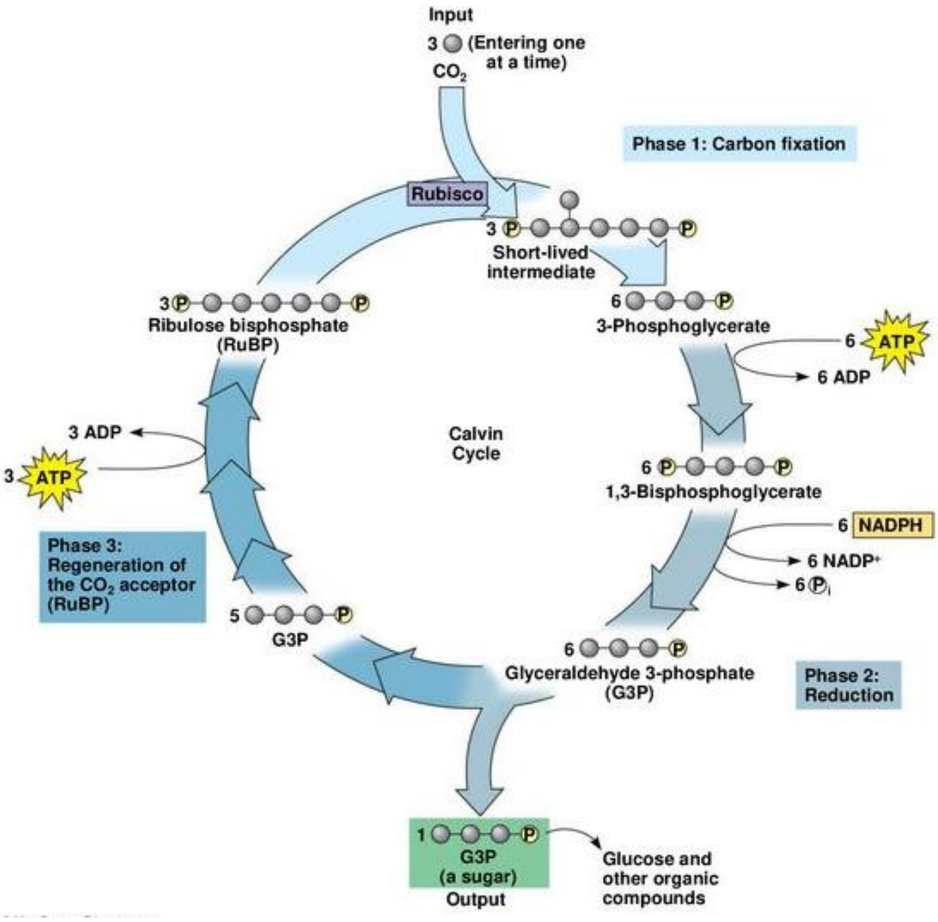

Fig 5 : Calvin cycle

The Calvin Cycle

● **Phase 1: Carbon Fixation**

○ The Calvin cycle incorporates each CO_2 molecule, one at a time, by attaching it to a five-carbon sugar called ribulose bisphosphate

○ Rubisco: the enzyme that normally catalyzes the first step of the Calvin cycle (the addition of CO_2 to RuBP). When excess O_2 is present or CO_2 levels are low, rubisco can bind oxygen, resulting in photorespiration

○ The product of the reaction is a six-carbon intermediate that is short-livedbecause it is so energetically unstable that it immediately splits in half, forming two molecules of 3-phosphoglycerate

● **Phase 2: Reduction**

○ Involved the reduction and phosphorylation of 3-phosphoglycerate to G3P.

○ Six ATP and six NADPH are required to produce six molecules of G3P, but only one exists the cycle for use by the cell.

● **Phase 3: Regeneration of the CO_2 ACCEPTOR (RUBP)**

○ The carbon skeletons of five molecules of G3P are rearranged by the laststeps of the calvin cycle into three molecules of RuBP.

○ To accomplish this, the cycle spends three more molecules of ATP.

○ The RuBP is nor prepared to receive CO_2 again, and the cycle continues.

● For the net synthesis of one G3P molecule, the Calvin cycle consumes a total of nine molecules of ATP and six molecules of NADPH