Unit 6

System physiology - Plant

Unit Map

6.A Photosynthesis

Photosynthesis is the process, which results in the production of organic compounds in the presence of chlorophyll by utilizing carbon dioxide, water and sunlight as source of energy.

$$6CO_2 + 6H_2O \xrightarrow[\text{Radiant energy}]{\text{Chlorophyll enzymes}} C_6H_{12}O_6 + 6O_2$$

In plants, photosynthesis occurs mainly within the leaves. Since photosynthesis requires carbon dioxide, water, and sunlight, all of these substances must be obtained by or transported to the leaves. Carbon dioxide is obtained through the tiny pores in plant leaves called ***stomata***. Oxygen is also released through the stomata. Water is obtained by the plant through the roots and delivered to the leaves through vascular plant tissue systems. Sunlight is absorbed by chlorophyll, a green pigment located in plant cell structures called ***chloroplasts***. Chloroplasts are the sites of photosynthesis.

Stages of Photosynthesis

Photosynthesis occurs in two stages. These stages are called the light reactions and the dark reactions. The light reactions take place in the presence of light. The dark reactions do not require direct light; however dark reactions in most plants occur during the day.

- **Light reactions** occur mostly in the grana thylakoid. The sunlight is converted to chemical energy in the form of ATP and NADPH. Chlorophyll absorbs light energy and starts a chain of steps that result in the production of ATP, NADPH, and oxygen. Oxygen is released through the stomata. Both ATP and NADPH are used in the dark reactions to produce sugar.
- **Dark reactions** occur in the stroma. Carbon dioxide is converted to sugar using ATP and NADPH. This process is known as ***carbon fixation*** or the ***Calvin cycle***. Carbon dioxide is combined with a 5-carbon sugar creating a 6-carbon sugar. The 6-carbon sugar is eventually broken-down into two molecules, glucose and fructose. These two molecules make sucrose or sugar.

Difference between the light and dark reactions

Light Reaction	Dark Reaction
Light dependent process	Light independent process
Photochemical reaction	Chemical reaction
Occurs in grana of chloroplast	Occurs in stroma of chloroplast
Formation of ATP and NADPH	Utilization of ATP and NADPH
Results in oxidation of H_2O	Results in reduction of CO_2

6.A.1 Light-harvesting complexes

The light-harvesting complex is a unique complex of the subunit proteins that may be a part of the larger super complex of the photosystem, which is the functional unit in *photosynthesis*. The plants use this light-harvesting system to collect more of the incoming light than it would have been captured by the photosynthetic reaction center alone. The light harvesting complexes are found in a wide variety amongst the different photosynthetic species of plants. These complexes comprise of proteins and photosynthetic pigments.

➢ **Photosynthetic pigments** In plants are mainly comprised of chlorophyll, carotenoids and phycobilin.

- **Chlorophyll** is the green photosynthetic pigment. There are five types of chlorophyll present in plants- a, b, c, d and e. Out of this chla andchl b occurs in higher plants. Chla is the universal photosynthetic pigment as it is found in all photosynthetic plants. It is the primary photosynthetic pigment as it performs primary reaction of photosynthesis that includes conversion of light energy into chemical and electrical energy.

  i. Chl a is bluish green in pure state and has empirical formula $C_{55}H_{72}O_5N_4Mg$

  ii. Chl b is olive green in pure state and empirical formula is $C_{55}H_{70}O_6N_4Mg$

  Both the Chlorophyll has a tadpole like structure with porphyrin head and phytol tail. Porphyrin head is made up of four pyrrole rings linked by methane bridges. Phytol is an insoluble long chain of carbon and hydrogen atoms with a formula $C_{20}H_{39}OH$. It anchors the chlorophyll molecule into the lipid part of thylakoid membrane.

- **Carotenoids** are present inside the chloroplast and are associated with chlorophyll. They are accessory pigments of yellow, brown to reddish pigments. There are two types of carotenoids namely ***carotenes*** and ***xantophylls***.
  - **i.** ***Carotenes*** are hydrocarbons and are responsible for red color of the tomato. β-Carotene is the most common carotene that is converted to vitamin A by animals and human beings.
  - **ii.** ***Xantophylls*** are oxygen-containing derivatives of carotene and are of yellow color. Both carotenes and xantophylls are soluble in organic solvents.
- **Phycobilins** are open tetrapyrole, which contains neither magnesium nor phytol. They are water-soluble. They are important accessory pigments of blue-green algal, red algal. They occur in association with proteins or billi proteins.

➢ **Spectra-absorption and action**

Emerson Effect Emersonfound that when a monochromatic beam of more than 680nm was used in photosynthesis a sharp reduction in the rate of photosynthesis was observed, even though chlorophyll absorbs well up to 700nm. Wavelengths beyond 700nm are apparently of insufficient energy to drive any part of photosynthesis. So a huge drop in efficiency has been noticed at 700nm. This phenomenon is called as ***Red Drop Effect*.** This decrease in quantum yield takes place in the red part of the spectrum. The number of oxygen molecules released per light quanta absorbed is called as ***quantum yield of photosynthesis***. Later on Emerson and his group observed that if chlorella plants are given the inefficient far red light and red light of shorter wavelengths in alternate fashion, the quantum yields were greater than could be expected from adding the rates found when either color was provided alone. This synergistic effect or enhancement is known as ***EEE*** or ***Emerson Enhancement Effect*.** This was the first good evidence that there are two photo systems; one absorbs far red light and other red light and both of them must operate to drive photosynthesis most effectively. Emerson found that this rate of photosynthesis could be enhanced if monochromatic beams of two different wavelengths were applied simultaneously. This photosynthetic enhancement phenomenon is called as ***Emerson effect***.

Absorption spectra this type of spectra shows the amount of light absorbed at different wavelengths by a pigment. The absorption of chla and b shows that they absorb maximum light in blue violet and red wavelengths.

Action spectra the first action spectra was studied by Engelmann in 1882 by using green algae which liberated oxygen according to the rate of photosynthesis in different wavelengths of light. This type of spectra shows the use of light energy of different wavelengths in photosynthesis. An action spectrum shows that chlorophyll a and b are the main photosynthetic pigments in photosynthesis.

➢ **Photosynthetic Unit (PSU)** is the smallest group of pigment molecule that takes part in photosynthesis. The photocentre or reaction center of PSU has about 200 harvesting pigment molecule. The harvesting molecules form light harvesting molecules. There are two types of light harvesting molecules; antenna molecules and core molecules. The antenna molecules absorb light of various wavelengths and get excited. In the excited state, an electron is pushed to other orbit where it stays for only 10^{-9} second. The excited molecule comes to the ground state by loosing energy to the core molecule by resonance.

- **Photosystems or Pigment system**
  - **i. PSI or P700** it is present in non-appressed parts of stroma and grana thylakoid. It consists of a photocentre; light harvesting complex and some electron carriers. It is first surrounding by chlorophyll a molecules, then by chlorophyll b and carotenoids, with Chlcontent more. It has a reducing agent, FeScenter or Ferrodoxin, plastoquinon cytochrome complex and plastocyanin. It is part in both cyclic and non-cyclic photophosphorylation but can carry cyclic photophosphorylation independently. The role of PSI is to drive an electron from PSII $NADP^+$.
  - **ii. PSII or P680** it is present in appressed parts of grana thylakoid. It has chl a, b and carotenoids, with equal contents of Chl a and b. The photo centre is P_{680}, which is a chl a molecule. The photo centre is surrounding by chl a molecules, chl b and carotenoids. PSII also contains quencher molecule Q, plastoquinone PQ cytochrome complex and plastocynin, Mn^{2+}, Cl^-. The electron that is released during water photolysis is taken by PSII, which is passed over to the cytochrome complex and sufficient energy is released to take part in the synthesis of ATP from ADP and inorganic phosphate. This photophosphorylation is non cyclic and can only operate in conjugation with PSI.

6.A.2 Mechanism of electron transport

Light reaction and Photophosphorylation

The light reaction, which is light dependent, occurs in the grana of the chloroplast that requires direct energy of light for NADPH and ATP synthesis. These NADPH and ATP are used in dark reaction by plants.**Photosphsphorylation** is the process of formation of ATP from ADP and inorganic phosphate by using the light energy. In 1954, Arnon et al discovered photophosphorylation. The light reaction in the photosynthetic plants starts the electron flow. The flow of electrons in the oxygenic photosynthetic organisms is of two type's namely cyclic and non-cyclic photophosphorylation.

- **Cyclic Photophosphorylation** is the process in which an electron after excitation and passing through a series of electron carriers returns to its original state. It is performed by PSI only. It occurs under low light intensity, wavelength greater than 680nm, inhibition of CO_2 fixation conditions. As NADPH is not oxidized to $NADP^+$, hence no electrons are required; therefore there is no need of CO_2 fixation. The photo centre P700 excites an electron by absorbing a photon of light that result in photo centre oxidation. The excited electron passes through a series of carriers that include a special Chl molecule (X), FeS, Ferredoxin, plastoquinone, cytochrome b-f complex and plastocyanine before returning to photo center. The electron loses energy to form ATP from ADP and inorganic phosphate when it passes between ferredoxin and plastoquinone and cytochrome complex.

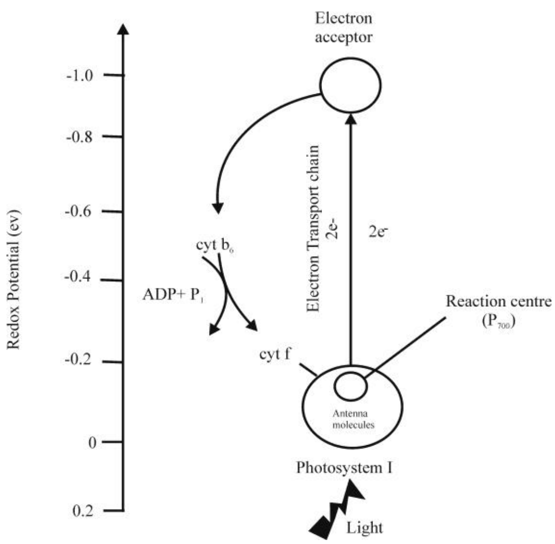

Figure 6.A.2-1
It results in the formation of ATP molecules. As electrons move downhill in the electron transport chain, they lose potential energy and ATP molecules are formed as in mitochondria during respiration. Electrons from photosystem-I are not passed to NADP from the electron acceptor. Instead the electrons are transferred back to P_{700}. This downhill movement of an electron from an electron acceptor to P_{700} results in the formation of ATP and this is formed as cyclic photo phosphorylation. Oxygen and NADPH are not formed during cyclic photophosphorylation.This pathway is known as cyclic photophosphorylation, and it produces neither O_2 nor NADPH. Unlike non-cyclic photophosphorylation, $NADP^+$ does not accept the electrons; they are instead sent back to photosystem II. In bacterial photosynthesis, a single photosystem is used, and therefore is involved in cyclic photophosphorylation. It is favoured in anaerobic conditions and conditions of high irradiance and CO2 compensation points.

- **Non Cyclic Photophosphorylation** is the process of photophophorylation in which the excited electron does not return to its original state. Both PSI and PSII take part in non-cyclic photophosphorylation; electron released during photolysis of water is taken by the photo centre of PSII. The electron also gets excited when the photo centre absorb light. It passes through a series of electron carriers, which are phaeophytin, PQ, cyt b-f complex and plastocyanin.

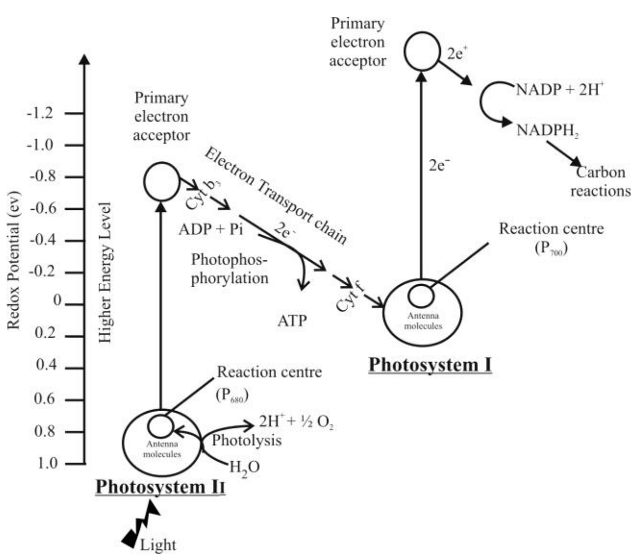

Figure 6.A.2-2
The electrons lost by P_{680} (PS II) are taken up by P_{700} (PS I) and do not get back at $P_{680,}$ unidirectional, hence called ***non-cyclic photophosphorylation.*** The electrons pass through the primary acceptor, plastoquinone (PQ), cytochrome complex, plastocyanin (PC) and finally to $P_{700.}$ The electrons give out by P_{700} are taken up by primary acceptor and are ultimately passed on to NADP. The electrons combine with H^+ and reduce NADP to $NADPH_2$. The net result is the formation of oxygen, NADPH and ATP molecules.

$$NADP^+ + 2H^+ + 2e^- \rightarrow NADPH + H^+ \text{ zap}$$

This consumes the H+ ions produced by the splitting of water, leading to a net production of $1/2O_2$, ATP, and $NADPH^+, H^+$ with the consumption of solar photons and water. The concentration of NADPH in the chloroplast may help regulate which pathway electrons take through the light reactions. When the chloroplast runs low on ATP for the Calvin cycle, NADPH will accumulate and the plant may shift from noncyclic to cyclic electron flow.

The energy is lost by the electron for synthesis of ATP when it passes over the cytochrome complex. After that the plastocyanin passes electron to P700. P700 excites the electron after absorbing light energy. The excited electron passes through X, FeS, ferredoxin and $NADP^-$reductase that combines the electron with $NADP^+$ for becoming reduced through H^+ released during photolysis to form NADPH. In this process the ATP is not directly synthesized. The energy that is released by the electron is used for H^+ ions pumping across thylakoid membrane that creates a proton gradient. This gradient triggers the coupling factors to synthesize ATP.

6.A.3 Photo protective mechanism

Protection and regulation of photosynthetic Machinery

Toxic photoproducts are formed in excess light conditions, including triplet state of Chl (^{3}Chl) and reactive oxygen species such as the superoxide anion (O_2^-), singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2), and hydroxyl radical ($^{\cdot}OH$). Singlet oxygen is the common name used for the two metastable states of molecular oxygen O_2 with higher energy than the ground state triplet oxygen. Singlet oxygen can damage many cellular components including lipids. The PSII reaction center is easily damaged by excess light, especially the D_1 core protein. Carotenoids, superoxide dismutase, and ascorbate serve as photoprotective agents, helping to prevent photoinhibition (a reduction in a plant's capacity for PS caused by exposure to strong light, which may be reversible or irreversible) and damaging effects of excess light. Carotenoids can quench the excess energy of singlet oxygen by converting it back to triplet oxygen releasing heat. Non-photochemical quenching of excess energy (conversion to heat without inducing photochemistry) can be done by xanthophylls. These are yellow pigments that are oxidized carotenoid derivatives (listed in order of least to greatest protectiveness: Violaxanthin<antheraxanthin<zeaxanthin) the least protective in the xanthophylls cycle; violaxanthin, converts to the most protective, zeaxanthin, when light is intense and protection is needed.Chloroplasts can reposition themselves along the sidewalls of cells, so that the more superficial ones provide shape to deeper chloroplasts along the same wall, in response to excessively intense light. Chloroplasts sometimes extend stromules, fine tubular interconnections with nearby chloroplasts and plastids that allow transfer of proteins but the ultimate purpose is unknown.

6.A.4 Carbon dioxide fixations

Carbon dioxide fixation is the process in plants and algae by which the atmospheric carbon dioxide is converted into organic carbon compounds, such as carbohydrates, usually by photosynthesis.

C3 Plants are those plants which survive solely on C3 fixation and tend to thrive in areas where the intensity of the sunlight is moderate, temperature is moderate, carbon dioxide concentrations are around 200 ppm or higher and plenty of ground water. The C3 plants that originated during the Mesozoic and Paleozoic eras; predate the C4 plants and still represent approximately 95% of Earth's plant biomass. The C3 plants lose 97% of the water taken up through their roots to transpiration. Examples of C3 plants include rice and barley. C3 plants cannot grow in hot areas because the enzyme **Ribulose-1, 5-bisphosphate carboxylaseoxygenase (RuBisCO)** incorporates more oxygen into the organic substance **Ribulose-1, 5-bisphosphate (RuBP)** as temperatures increase. This leads to photorespiration, which leads to a net loss of carbon and nitrogen from the plant, which potentially limits its growth. In dry areas, C3 plants shut their stomata to reduce the water loss, but this stops CO_2 from entering the leaves and, therefore, reduces the concentration of CO_2 in the leaves. This lowers the CO_2:O_2 ratio and therefore also increases photorespiration. C4 and CAM plants have adaptations that allow them to survive in hot and dry areas where they can out-compete C3 plants.

- **The Calvin cycle**

  Plants, which use only the Calvin cycle for fixing the carbon dioxide from the air, are known as ***C3 plants***. About 85% of plant species are C3 plants. They include the cereal grains: wheat, rice, barley, oats, peanuts, cotton, sugar beet, tobacco, spinach, soybeans and most trees are C3 plants. Most lawn grasses such, as rye and fescue are C3 plants.The cycle uses ATP as an energy source and consumes $NADPH_2$ as reducing power for adding high-energy electrons to make the sugar. There are three steps of the cycle.

  Step 1 Carboxylation

  CO_2 is incorporated into a five-carbon sugar named ribulosebisphosphate (RuBP). The enzyme, which catalyzes this first step, is RuBP carboxylase oxygenase (RuBisCO). It is the most abundant protein in chloroplasts.

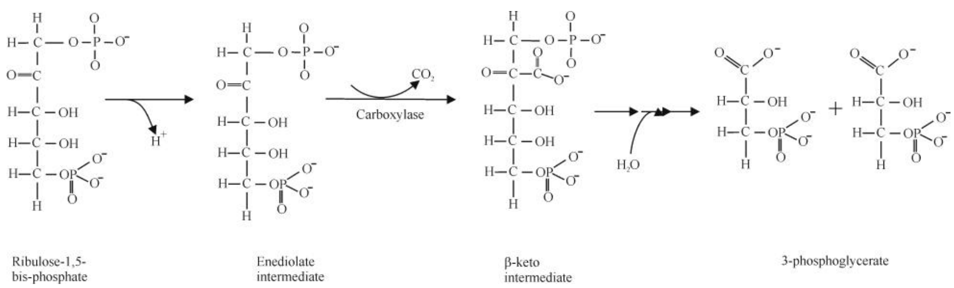

Figure 6.A.4-1
Carbon dioxide enters in this step and is added to ribulose 1,5-bisphosphate.An intermediate is formed which splits to form two 3-phosphoglycerate molecules. The product of carbon fixation is three carbon molecules.