Photosynthesis

Life on Earth is solar powered. The chloroplasts of plants use a process called photosynthesis to capture light energy from the sun and convert it to chemical energy stored in sugars and other organic molecules. Photosynthesis (Photo = light; synthesis = to join) is the single most important process on earth on which depends the existence of human and almost all other living organisms. It is a process by which green plants, algae and chlorophyll containing bacteria utilize the energy of sunlight to synthesize their own food (organic matters) from simple inorganic molecules. Photosynthesis nourishes almost all the living world directly or indirectly. Photosynthesis is the process by which green plants use sunlight to manufacture food from simple molecules like CO_2 and H_2O. Photosynthesis is sometimes called carbon assimilation and is represented by following equation;

$$6CO_2 + 6H_2O \text{ ------}\rightarrow C_6H_{12}O_6 + 6O_2$$

Significance of photosynthesis

1. Green plants possess the green pigment, chlorophyll that can capture, transform, translocate and store energy, which is readily available for all forms of life on this planet.

2. Photosynthesis is a process in which light energy is converted into chemical energy.

3. Except green plants no other organism can directly utilise solar energy, hence they are dependent on green pants for their survival.

4. Green plants can prepare organic food from simple inorganic elements (autotrophic) while all other organisms cannot prepare their own food and are called heterotrophic.

5. During photosynthesis, oxygen liberated into the atmosphere makes the environment livable for all other organisms.

6. Simple carbohydrates produced in photosynthesis are transformed into lipids, proteins, nucleic acids and other organic molecules.

7. Plants and plant products are the major food sources of almost all other organisms of the earth.

8. Fossil fuels like coal, gas, oil etc represent the photosynthetic products of the plants belonging to early geological periods.

Where does photosynthesis occur?

Photosynthesis occurs in green parts of the plant, mostly the leaves, sometimes the green stems and floral buds. The leaves contain specialized cells called mesophyll cells that contain the chloroplast the pigment containing organelle. These are the actual sites for photosynthesis.

Photosynthetic pigments

The thylakoids of the chloroplast contain the pigments that absorb light of different wavelength and carry out the photochemical reaction of photosynthesis. The role of the pigments is to absorb light energy, thereby converting it to chemical energy. These pigments are located on the thylakoid membranes and the chloroplasts are usually so arranged within the cells that the membranes are at right angles to the light source for maximum absorption. The photosynthetic pigments of higher plants fall into two classes: the chlorophyll and carotenoids. The photosynthetic pigment chlorophyll is the principle pigment involved in photosynthesis. It is a large molecule and absorbs light in the violet blue and in the red region of the visible spectrum and reflects green light and thus leaves appear green in colour. Carotenoids (carotene and xanthophyll) absorb light in the regions of the spectrum not absorbed by the chlorophyll.

Chlorophyll

Chlorophyll a (a special type of chlorophyll) is the main pigment that traps solar energy and converts it into electrical and chemical energy. Thus it is called the reaction centre. All other pigment such as chlorophyll b and carotenoids are called accessory pigments since they pass on the absorbed energy to chlorophyll a (Chl a) molecule. These pigments, that are the reaction centres (Chl a) and the accessory pigments (harvesting centre), are packed into functional clusters called photosystems. Photosystems are of two types PSI and PSII.

About 250-400 pigment molecules constitute a single photosystem. Two different photosystems contain different forms of chlorophyll a in their reaction centres. In photosystem I (PSI), chlorophyll a with maximum absorption at 700 nm (P700) and in photosystem II (PSII), chlorophyll a with peak absorption at 680 nm (P680), act as reaction centres. (P stands for pigment). The primary function of the two photosystems, which interact with each other, is to trap the solar energy and convert into the chemical energy (ATP).

Differences between Photosystem I and Photosystem II

PS I has a reaction centre of chlorophyll 'a' molecule with maximum light absorption at 700 nm wavelength. This reaction centre is also referred to as P700. Primary electron acceptor is an iron protein (Fe-S protein). A set of electron carriers the plastocyanin, ferredoxin and cytochrome.

PS II has a reaction centre of chlorophyll 'a' molecule with maximum light absorption at 680 nm. This reaction centre is also referred to to as P680. Primary electron acceptor is a colourless chlorophyll a that lacks magnesium (Mg) and is known as phaeophyll a. A set of electron carriers the phaeophytin, plastoquinone, cytochromes.

Light consists of small particles or packages of energy called "photons". A single photon is also called quantum. What does the chlorophyll do? It absorbs light energy. Chlorophyll molecules absorb light energy and get into an excited state and lose an electron to the outer orbit. No substance can remain in an excited state for long, so the energised and excited chlorophyll molecule comes down to a low energy state known as ground state and release the extra amount of energy. This energy can be lost as heat, or as light (flourescence) or can do some work. During photosynthesis, it works by splitting water moelcule to produce H+ and OH– ions.

Carotene is orange-yellow pigment present along with chlorophylls in the thylakoid membrane. A carotene molecule breaks down into the vitamin A molecules. It is this pigment that gives carrot its colour.

The process of photosynthesis consists of two phases.

1. Light dependent phase (Light reaction or Hill reaction)

2 Light independent phase (Dark reaction or Blackman reaction)

Light or Hill Reaction:

Photo-phosphorylation is the process in which the light energy is converted into chemical energy in the form of ATP.

Light reaction is the first step in photosynthesis occurring in grana of chloroplast and needs the utilization of light energy. It consists of following three phases:

(a) Photolysis of water:

The light energy trapped by chlorophyll molecule decomposes water into its constituent elements, called photolysis of water.

$H_2O \quad \rightarrow(\leftarrow) \quad 4H^+ + OH^-$

$4\ OH^- \quad \rightarrow \quad 2H_2 + 4e^- + 2O_2$

(b) Photo-phosphorylation:

The electrons produced during the photolysis of water pass via 2 photosystems (PS –I and II). Each photo system has its own trap center and a primary pigment molecule.

It is the process of synthesis of ATP from ADP using light energy.

ADP+ ip → (light) ATP

It is of further two types:

1) Non-cyclic photo-phosphorylation:

High-energy electrons released from P680 of PS-II are accepted by primary electron acceptor. The electrons pass via a series of electron acceptor i.e. PQ- cytochorome complex- PC and finally to P700 of PSI.

Again, the electrons given out by P700 of PS-I are taken up by primary pigment molecule and are ultimately passed to NADP through Fd. The electrons combine with ions and reduce NADP to NADP H_2.

The net result of non-cyclic photo phosphorylation is the formation of 1oxygen (as a waste), 2 NADP H_2 and 1 ATP molecule.

2) Cyclic photo-phosphorylation:

High-energy electrons expelled from P700 of PS-I are taken up by primary pigment molecule, when the pass through series of electron acceptors i.e. Fd-PQ-Cytochorome complex-PC and finally to the same pigment molecule from which they have been originated.

There is formation of 2ATP molecules at the end.

(c) Photo reduction:

Chloroplast contains naturally occurring electron acceptor NADP. With addition of H^+ from photolysis, it is reduced to NADP H_2

Dark reaction or Blackman's reaction:

This is the second step in the mechanism of photosynthesis. The chemical processes of photosynthesis occurring independent of light is called dark reaction. It takes place in the stroma of chloroplast. The dark reaction is purely enzymatic and it is slower than the light reaction. The dark reactions occur also in the presence of light. In dark reaction, the sugars are synthesized from CO2. The energy poor CO2 is fixed to energy rich carbohydrates using the energy rich compound, ATP and the assimilatory power, NADPH2 of light reaction. The process is called carbon fixation or carbon assimilation. Since Blackman demonstrated the existence of dark reaction, the reaction is also called as Blackman's reaction. In dark reaction two types of cyclic reactions occur

1. Calvin cycle or C_3 cycle

2. Hatch and Slack pathway or C_4 cycle

Calvin cycle or C_3 cycle:

It is a cyclic reaction occurring in the dark phase of photosynthesis. In this reaction, CO_2 is converted into sugars and hence it is a process of carbon fixation. Melvin Calvin first observed the Calvin cycle in chlorella, unicellular green algae. Calvin was awarded Nobel Prize for this work in 1961. Since the first stable compound in Calvin cycle is a 3 carbon compound (3 phosphoglyceric acid), the cycle is also called C_3 cycle. The reactions of Calvin's cycle occur in three phases.

1. Carboxylative phase

2. Reductive phase

3. Regenerative phase

1. Carboxylative phase:

Three molecules of CO2 are accepted by 3 molecules of 5C compound , ribulose diphosphate to form three molecules of an unstable intermediate 6C compound. This reaction is catalyzed by the enzyme, carboxy dismutase

3 CO_2 + 3 Ribulose diphosphate → 3 unstable intermediate 6 carbon compound

Carboxy

dismutase

The three molecules of the unstable 6 carbon compound are converted by the addition of 3 molecules of water into six molecules of 3 phosphoglyceric acid.This reaction is also catalyzed by the enzyme carboxy mutase.

3 unstable intermediate 6 C compound + 3 H_2O → Carboxy dismutase3 phosphoglyceric acid

Carboxy

Dismutase

3 phosphoglyceric acid (PGA) is the first stable product of dark reaction of photosynthesis and since it is a 3 carbon compound, this cycle is known as C3 cycle.

2. Reductive phase

Six molecules of 3PGA are phosphorylated by 6 molecules of ATP (produced in the light reaction) to yield 6 molecules of 1-3 diphospho glyceric acid and 6 molecules of ADP. This reaction is catalyzed by the enzyme, Kinase

3 Phospho

glyceric acid + ATP → 1,3 diphosphoglyceric acid + ADP

Kinase

Six molecules of 1, 3 diphosphoglyceric acid are reduced with the use of 6 molecules of NADPH2 (produced in light reaction) to form 6 molecules of 3 phospho glyceraldehyde. This reaction is catalysed by the enzyme, triose phosphate dehydrogenase.

1,3 diphosphoglyceric acid + $NADPH_2$ → 3 phosphoglyceraldehyde + NADP + H_3PO_4

Triose phosphate Dehydrogenase

3. Regenerative phase

In the regenerative phase, the ribose diphosphate is regenerated. The regenerative phase is called as pentose phosphate pathway or hexose monophophate shunt.

C4 cycle or Hatch and Slack pathway:

It is the alternate pathway of C3 cycle to fix CO2. In this cycle, the first formed stable compound is a 4 carbon compound, oxaloacetic acid. Hence it is called C4 cycle. The pathway is also called as Hatch and Slack as they worked out the pathway in 1966 and it is also called as C4 dicarboxylic acid pathway. This pathway is commonly seen in many grasses, sugar cane, maize, sorghum and amaranthus.

The C4 plants show a different type of leaf anatomy. The chloroplasts are dimorphic in nature. In the leaves of these plants, the vascular bundles are surrounded by bundle sheath of larger parenchymatous cells. These bundle sheath cells have chloroplasts. These chloroplasts of bundle sheath are larger, lack grana and contain starch grains. The chloroplasts in mesophyll cells are smaller and always contain grana. This peculiar anatomy of leaves of C4 plants is called Kranz anatomy. The bundle sheath cells are bigger and look like a ring or wreath. Kranz in German means wreath and hence it is called Kranz anatomy. The C4 cycle involves two carboxylation reactions, one taking place in chloroplasts of mesophyll cells and another in chloroplasts of bundle sheath cells. There are four steps in

Hatch and Slack cycle:

1. Carboxylation

2. Breakdown

3. Splitting

4. Phosphorylation

1. Carboxylation

It takes place in the chloroplasts of mesophyll cells. Phosphoenolpyruvate, a 3 carbon compound picks up CO2 and changes into 4 carbon oxaloacetate in the presence of water. This reaction is catalysed by the enzyme, phosphoenol pyruvate carboxylase.

2. Breakdown

Oxaloacetate breaks down readily into 4 carbon malate and aspartate in the presence of the enzyme, transaminase and malate dehydrogenase. These compounds diffuse from the mesophyll cells into sheath cells.

3. Splitting

In the sheath cells, malate and aspartate split enzymatically to yield free CO2 and 3 carbon pyruvate. The CO2 is used in Calvin's cycle in the sheath cell. The second Carboxylation occurs in the chloroplast of bundle sheath cells. The CO2 is accepted by 5 carbon compound ribulose diphosphate in the presence of the enzyme, carboxy ismutase and ultimately yields 3 phosphoglyceric acid. Some of the 3 phosphoglyceric acid is utilized in the formation of sugars and the rest regenerate ribulose diphosphate.

4. Phosphorylation

The pyruvate molecule is transferred to chloroplasts of mesophyll cells where, it is phosphorylated to regenerate phosphoenol pyruvate in the presence of ATP. This reaction is catalysed by pyruvate phosphokinase and the phophoenol pyruvate is regenerated. In Hatch and Slack pathway, the C3 and C4 cycles of carboxylation are linked and this is due to the Kranz anatomy of the leaves. The C4 plants are more efficient in photosynthesis than the C3 plants. The enzyme, phosphoenol pyruvate carboxylase of the C4 cycle is found to have more affinity for CO2 than the ribulose diphosphate carboxylase of the C3 cycle in fixing the molecular CO2 in organic compound during Carboxylation