Chapter - 10
Photosynthesis

Photosynthesis is the most important biochemical reaction on the Earth by which energy is stored in the living organisms. All living organisms on earth is possible by the direct or indirect utilization of this energy. Generally, plants directly convert solar energy into chemical energy however, animals directly or indirectly depend on plants for energy related requirement. Photosynthesis is an oxidation reduction reaction in which oxidation of water takes place and carbondioxide reduced. Photosynthesis can be defined as follows.

Definition : Conversion of CO_2 obtained from the atmosphere and water absorbed from the soil by the green plants, is the presence of sun light into chemical energy in the form of sugar is known as photosynthesis.

This can be represented by the following chemical equation

$$6CO_2 + 12H_2O \xrightarrow[\text{chlorophyll}]{\text{Sunlight}} C_6H_{12}O_6 + 6H_2O + 6O_2$$

In this reaction, the water is oxidized by the radiant energy of the Sun and the CO_2 is reduced into sugar by the energy obtained from the oxidation and oxygen is released as a byproduct. According to Rabinowitch (1956) "Sensitized photo chemical oxidation and reduction reactions between water (hydrogen donor) and CO_2 at biological temperature are called as photosynthesis".

It is a matter of surprise that though photosynthesis is the most important process for living organisms, it could not attract the attention of scientists till 18[th] Century. In fact, the real history of photosynthesis starts from the 18[th] century. The history of photosynthesis can be clearly divided into two parts : Pre-isotopic age (1800-1925) and Post isotopic age (1925 to present time)

History of Photosynthesis

$$CO_2 + H_2O \xrightarrow[\text{Light (Ingenhouz, 1779)}]{\text{Chlorophyll (Dutrochet, 1837)}} \text{Organic Substances} + O_2$$

CO_2 ↑ (Senebier) 1782; H_2O ↑ (de Sausssure) 1804; Organic Substances ↑ (Ingenhousz) 1779; O_2 ↑ Pristeley (1771)

A brief detail of ancient history of photosynthesis is as follows.

S. No.	Scientist	Contribution of Scientist
1.	Stephen Hales, 1727	Plants synthesize their food in the presence of air and sunlight. Stephan Hales is called as father of plant physiology.
2.	Joseph Pristeley,1772	Plants purify the atmosphere they release oxygen during Photosynthesis.
3.	Jan Ingenhousz,1779	Discovered that sunlight is necessary for photosynthesis and gave confirmation of synthesis of organic substance by this process

4.	Jean Senebier,1782 & D.Sesor,1804	They stated that CO_2 is necessary for photosynthesis
5.	J.R.Mayer,1845	Green plants convert light energy into chemical energy
6.	F.F. Blackman,1905	In photosynthesis two types of reactions i.e., photochemical and biochemical reactions take place, which are known as light reactions and dark reactions respectively. He also postulated the 'Law of limiting factors'.
7.	C.B.Von Neil,1930	While studying the bacterial photosynthesis, he disclosed that during photosynthesis in higher class plants, O_2 is released from water molecules and not from CO_2 molecules.
8.	Robert Hill,1937	He demonstrated Hill Reaction and proved that the source of O_2 evolved during photosynthesis is water and not CO_2.
9.	S. Ruben and M.Coman,1941	Used radioactive oxygen $18O_2$ (H_2O^{18}) and proved that O_2 evolved was part of water.
10.	Calvin and Benson, 1954	Discovered C_3 or Calvin Cycle in photosynthesis. They used C^{14} radio isotope and Calvin was awarded Nobel Prize in 1961 for this discovery.
11.	Daniel Arnon, 1954	He discovered photo phoshorylation and gave the signification of two pigment systems or photosystems.
12.	Hatch and Slack, 1966	Discovered C_4 pathway
13.	P. Mitchell, 1978	Proposed the principle of chemiosmotic theory of phosphorylation.

Site of photosynthesis

Chloroplast is the organelle where photo synthetic reactions take place. It is present in all the green parts and leaves of the plants. In higher plants these are present in mesophyll cells. Each mesophyll cell has 20-40 chloroplast. Each chloroplast is covered with two-unit membranes made up of lipoprotein and inter membrane space is available between both the membranes. Outer membrane is permeable for protons however inner membrane is impermeable. Internal part of chloroplast is divided in two parts grana and stroma. Stroma is the matrix part of the chloroplast which is filled with protein rich heterogeneous liquid substance. 70S ribosomes, small, circular, double stranded DNA, osmophilic drops, dissolved salts and enzymes are present in it.

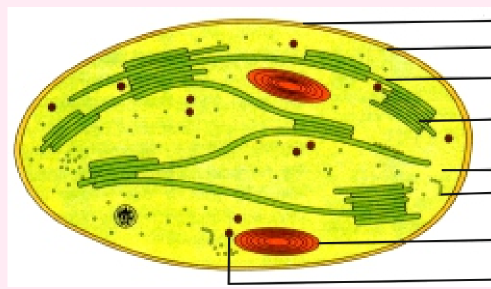

Fig. 10.1 : Diagram showing site of photosynthesis online diagrame of Chloroplast

Matrix of chloroplast contains unit membranous tube system which are called sacs or thylakoids. Thylakoids are arranged one above the other in the form of stacks of coins and prepare a typical structure called Granum (plural of granum). Few grana are attached with stroma plates of frets tubules at different places. Photosynthetic pigment chlorophyll and carotenoids are present in thylakoids membrane. Grana are the site of light reaction for photosynthesis. Photosynthetic pigments absorb violet, blue and red colors from visible spectrum which is 400 nm to 700 nm part of the visible spectrum. Hence this part of the spectrum is called photo synthetically active radiation (PAR). According to Park and Pon (1963) inner membrane of thylakoid contains small circular globule like structures called quantosome. These are the units of photosynthesis. Each quantosome has 230 chlorophyll molecules. (160 Chl-a 70 Chl-b). 48 carotenoids, 46 quinones, 116 phospholipids and other molecules and enzymes.

Photosynthetic Pigments

In plants light energy is absorbed by pigments so these are called photosynthetic pigments. Mainly in plants Chlorophylls, Carotenoids and phycobilin pigments are present. chlorophyll is the principal pigment and rest pigments are called accessory pigments.

1. Chlorophyll : Chlorophyll is the main green color pigment which is useful in photosynthesis. In plant kingdom there are seven types of chlorophyll pigments. These are Chl a, Chl b, Chl c, Chl d, Chl e, bacteriovirdin and bacteriochlorophyll. Out of these Chl a is the universal pigment which is present in all the phototrophs except bacterium. Chl b functions as accessory pigment which is present in all the photosynthetic plants and green algae. Chlorophyll pigments are soluble in organic solvents. The solubility of Chl b is maximum.

Structure of Chlorophyll Molecule : Chemical structure of chlorophyll was studied by Willstatter, Stall, Fischer in 1912 for the first time.. Chlorophyll is a polar molecule which has well developed head made of porphyrin ring and a tail is made of phytol chain. Head of the chlorophyll molecule made up of four pyrol ring configuration which is combined with methyl bonds and make cyclic tetrapyrol ring. Atom of ionic Magnesium is present in the center of tetrapyrol ring. Fourth pyrol ring is attached with long alcoholic chain which is called phytol tail molecular formula of Chl a is $C_{55}H_{72}O_5N_4Mg$ and Chl b is $C_{55}H_{70}O_6N_4$ Mg. In Chl-a, the carbon of porphyrin end has methyl group (-CH_3) however, in Chlorophyll - b, CHO group is present at this place. Chlorophyll - a is blue colored and Chlorophyll b is yellow colored pigment.

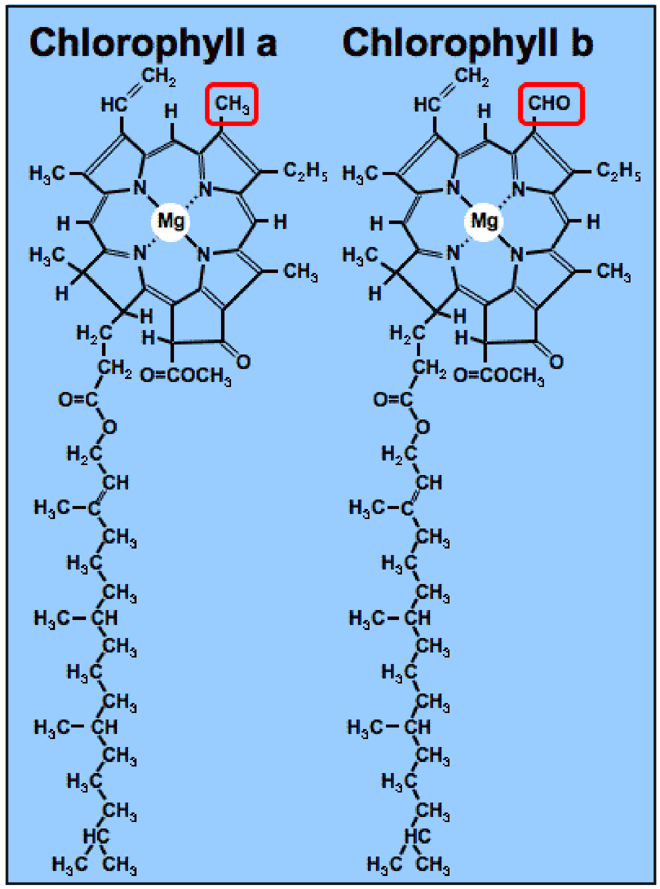

Fig. 10.2 : Molecules of Chlorophyll - a an and Chlorophyll - b

2. Carotenoids : These are the pigments found in plants with chlorophyll. These absorb energy from radiation and carry it to chlorophyll which cannot be absorb by chlorophyll hence, they are called accessory pigments. Carotenoids were first discovered by Wackenroder in carrot in 1831. There are two types of carotenoids present in plants carotene and xanthophyll's.

(i) Carotenes : These molecules are combined with carbon and hydrogen. Mostly these are red in colour and its empirical formula is $C_{40}H_{56}$e.g, Lycopene, α Carotene. β Carotene.

(ii) Xanthophyll's or Carotenoles : These are combination of carbon, Hydrogen and Oxygen. Its Empirical Formula is $C_{40}H_{56}O_2$. These are yellow or Brown in color. e.g. Lutein, Xiaxenthin, Cryptoxenthin. Neoxanthin etc.

β carotene among carotenes and lutin among xanthophyll's are found in all the green plants.

3. Phycobilins : These pigments are found in red and blue green algae and are two types:

(i) Phycoerythrin : This is red colored pigment found in red algae (Rhodophyceae).

(ii) Phycocyanin : This is blue colored pigment found in blue green algae (Cynophyceae)

Nature of Light

Sunlight moves in the form of electro magnetic waves; The distance between two successive crests or troughs of a wave is called wave length (λ). Energy of wave is inversely proportional to wavelength. Hence, rays of small wavelength (Under Cosmic Rays) have high Energy however, rays of long wave length (Under Radio Waves) have low energy. Visible part of electromagnetic radiation is called light or visible spectrum which has wavelength between 390 to 760 nm. This visible spectrum can be divided into Seven different colors. Each color has its own wavelength Red color has the longest wavelength (660 to 780 nm) while violet has the least (390 to 430 nm) wave length in visible spectrum. Region of wave length greater than red color wavelength called Infra-Red (IR) region and the area of wavelength smaller than violet color wavelength is called Ultra Violet (UV) region. Light has high energy particles known as photon. A photon has energy called quantum. During photosynthesis for reduction of a CO_2 molecule 8 photons are required- which is called quantum need of photosynthesis. The amount of O_2 atom released from each quantum or photon that is reabsorbed or consumed is called quantum yield. Plants shows foremost photosynthesis in blue and red color light. The rate of Photosynthesis is zero in green light rays. Why?

Mechanism of Photosynthesis

On the basis of research till now following facts are seen is the process of Photosynthesis.

1. Light energy absorbed by chlorophyll and accessory pigments is used in photolysis of water by which O_2, H^+ and electron (e^-) are released.

2. These electrons flow in different receptors of photo systems in which ultimately the energy is stored in the form of the ATP and NADPH + H^+ ion.

3. These highly energetic molecules (ATP, $NADPH^+$, H^+) are used for reduction of CO_2hence photosynthesis is an oxidation reduction reaction in which oxidation of water and reduction of CO_2 take place.

Photosynthesis reaction completed in two stages. Both the stages are different from each other however both are corelated from one another.

I. Light Reactions : First step is photo chemical reactions which takes place in the presence of Light. It creates the power of assimilation. This process takes place in the grana part of chloroplast.

II. Dark or Blackman Reaction : Second step is dark reaction which does not required the presence of light. In dark reaction assimilation power is used to reduce CO_2 into carbohydrates. This reaction takes place in stroma of the chloroplast. It has been proved by temperature coefficient and other experiments that one process of photosynthesis affected by light is called light reaction however, other process affected by temperature which is called dark reaction. Temperature coefficient of light reaction is approximately (Q_{10}=1) whereas in dark reaction, temperature coefficient is (Q_{10}=2 or 3)

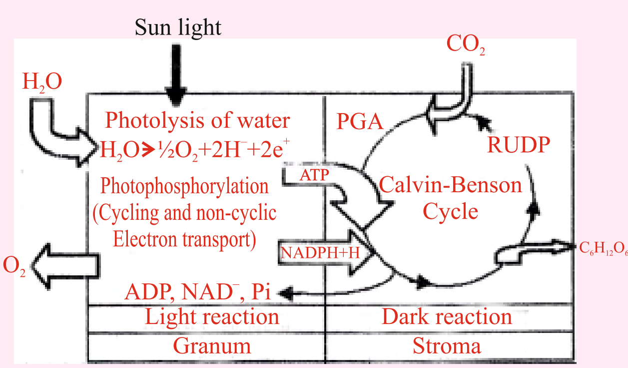

Fig. 10.3 : Diagram showing of Light and Dark reactions of Photosynthesis

Light Reactions

These are called photo chemical reactions or Hill reaction. This is a complex process which has different reactions.

1. Absorption of Light and Excitation of chlorophyll molecule : Chlorophyll molecule gets excited for some time after absorption of energy packets or quantum from electromagnetic waves Hence electrons released from chlorophyll molecule.

Chlorophyll (Normal) + Photon (Quantum) = Chlorophyll (Excited stage)

2. Photolysis of water and removal of Oxygen: Energy consumed by chlorophyll used in photolysis of water. Due to decomposition of water O_2 gets released some part of it used in respiration and rest is removed in environment. In this reaction (Mn) and (Cl) ions play an important role.

$$2H_2O \xrightarrow[Cl]{Mn^{++}} 4H^+ + 4e^- + O_2$$

3. Formation of NADPH+ H^+: Formation of this molecule takes place on thylakoids membrane towards stroma surface. Energy release from reduction of water convert NADP in to NADPH and H^+ ion. $4H^+$ ions released by photolysis of two water molecules form 2NADP + H^+ion which is required to reduce a CO_2 molecule. In this reaction $4e^-$ are required which are received from PS-I.

4. Photo Phosphorylation : Free electrons released from chlorophyll go through the different receptors. ATP synthesize from free energy due to this electron transfer is called photo phosphorylation.

5. Red Drop, Emerson Effect and two Pigment Systems : Emerson and coworkers 1957 measure rate of photosynthesis at different wave lengths and get the following observations.

(a) Rate of photosynthesis decreased when high wave length's (680 nm) monochromatic light is used in photosynthesis. As this decrease in rate of photosynthesis is related to the red region of photo spectrum hence it is called red drop.

(b) In different Experiments Emerson and coworkers found that rate of photosynthesis is more if they have used high and low wavelength light radiation differently. Enhancement in rate of photosynthesis is called Emerson enhancement effect. After above mentioned experiment Emerson concluded that plants contain minimum two pigments groups for photosynthesis, one which absorb long or high wavelength and second which absorb smaller low wavelength. These pigment groups are called photo system I (Ps I) and photo system II (PS II). Each photo system contains 300 to 400 pigment molecules. Each photo system contains a reaction centre and all around the reaction centre accessory pigments are found. These accessory pigments absorb light energy and give to reaction centre. These molecules are called antenna molecule.

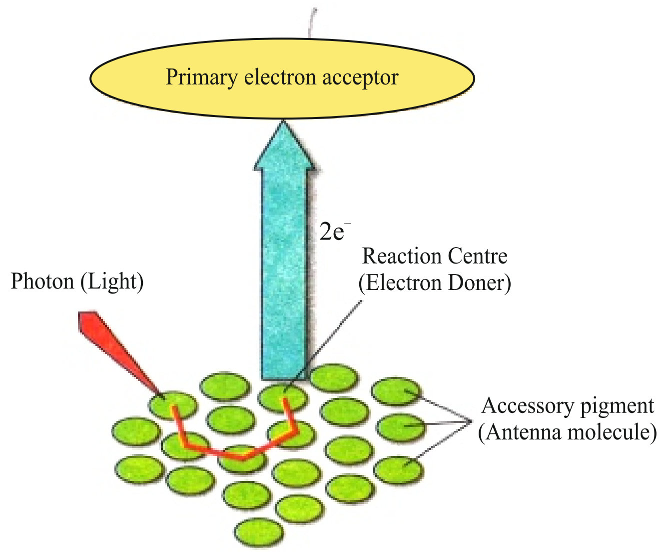

Fig. 10.4 : Mechanism of Photo System

Photo System-1 (PSI) : In photo system I different molecules of chlorophyll (Chl_{660}, Chl_{670}, Chl_{680}, Chl_{690}, Chl_{700}) and carotenoids are present which absorb different wavelength and at the end transfer it to the Chl a_{700} (P_{700}) they act as reaction centre. Due to the photo chemical reaction in the reaction centre, high energy electrons are released from chlorophyll. This Photo system takes part in cyclic and noncyclic Phosphorylation. This is present in the thylakoids of grana and stroma.

Mechanism of photo System-I (PS-I) : In this photo system solar light particles (Photon) clashes with Chlorophyll a (P_{700}). This energy absorbed by reaction centre of photo system-I and released its electrons. By which chlorophy-ll molecule (P_{700}) comes in oxidized stage. Electron released from PSI passes through other electron receptors like iron, Sulphur protein, [A(FeS)], ferredoxin (Fd) etc. and in the end it is accept by NADP and converted into NADPH + H^+ ion. It is strong reducing agent in reduction of CO_2 in dark Reaction.

Photo System II : In this photo system different molecules of chlorophyll like (Chl_{650}, Chl_{660}, Chl_{670}, Chl_{680}) Chlorophy-ll b, carotenoids, plastoquinon, cytochrome b_6 , cytochrome f are found. In this photosystem also Antenna molecule absorb photon energy and transfer to reaction centre P_{680} In this photo system wavelength absorbed are less than 680 nm. PS II found in grana lamellae. It is only used in non-cyclic phosphorylation.

Mechanism of Photo System ll : By this photo system photolysis of water takes place, Pigments of this photo system absorb the wavelength less than 680 nm by which chlorophyll gets excited and release electrons. These free electrons are received by electron receptor pheophytin. Now chlorophyll molecule acts as strong oxidizer so water molecule is oxidized and this reaction is called photo reduction of water. Manganese, chloride and calcium ions play a important role in this reaction. Free Electron released from photolysis of water accept by P_{680} by which it again reached to its original stage. Electron Transferred from P_{680} to pheophytin plastoquinon (PQ) to cytochrome b_6 and cytochrome and accepted by plastocyanin (PC) so it is reduced by it. Electron from reduced plasto cyanin used to fill gap merge in photo system I. Hence, in electron receptor series plastocyanin acts as connective link between both the photo systems.

$$H_2O \xrightarrow[\text{Chlorophyll, } Mn^{++}, Cl^-]{\text{photon}} \tfrac{1}{2}O_2 + 2H^+ + 2e^-$$

Electron Transport Chain, ETC

During photosynthesis the electron released from chlorophyll by light accept by the different electron receptors step wise and they release energy at each transfer.

Equal to the energy difference between two receptors. When energy is enough, then ATP are synthesized otherwise energy is lost in the form of heat.

Photo phosphorylation : The synthesis of ATP from ADP by using the light energy in chloroplast is called photophosphorylation. It discovered by Arnon et.al in 1954. Photophosphorylation is of two type :

(1) Cyclic Photophosphorylation

(2) Non Cyclic Photophosphorylation

1. **Cyclic Photophosphorylation :** In this reaction only PS I takes part. Electron released from P_{700} by Light energy in PS I passes through different electron acceptors like A (FeS), Fd →Cyt b_6→ Cyt f- through plastocyanin reaches back to P_{700} . Energy release between Cyt b_6,Cyt-f used in the synthesis of ATP from ADP. In this way ATP are formed in this reaction free electrons form P_{700} return back to P_{700} after synthesis of ATP. That is why it is known as cyclic phosphorylation.

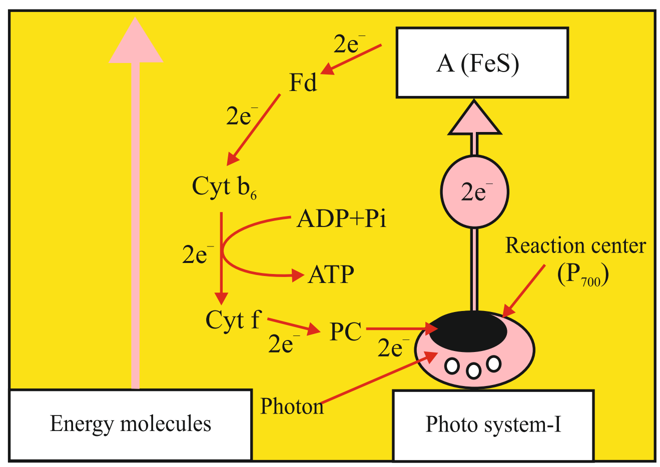

Fig. 10.5 : Cyclic phosphorylation completed in light reaction

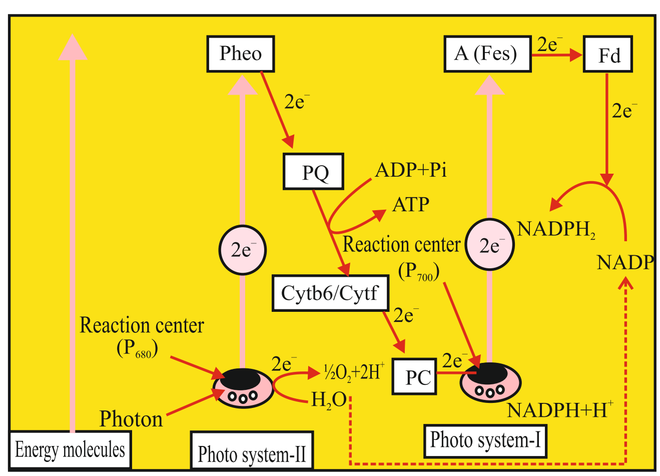

Fig. 10.6 : Non cyclic phosphorylation completed in light reaction

2. Non Cyclic Photophosphorylation : This phosphorylation is completed by both the photo system PS I and PS II. In this reaction free electron by P_{680}, instead of coming back to P_{680} reaches to electron receptor Phaeo→ Plastoquinon→ Cytochrome b_6→ Cytochrome f →Plastocynin through linear path and reaches to P_{700}.From P_{700} electrons associate with NADP through Feredoxin (Fd). NDAP accept $2H^+$ ions obtained from the hydrolysis of water and converts into $NADPH+H^+$. In this reaction released electron from P_{680} does not come back to P_{680} and produced ATP from ADP at between a site of PQ^-cyt b_6. This process is called non-cyclic phosphorylation. In this cycle ATP and NADPH, are termed by the transfer of electrons and O_2 is released. Non cyclic phosphorylation is called Z-schemes. A comparative study of cyclic and noncyclic phosphorylation is given in table below:

S.No.	Cyclic Photophosphorylation	Non Cyclic Photophosphorylation
1.	Only PSI participates in it	Both PS I and PS II participate in
2.	Photolysis of water does not occur	Photolysis of water occur
3.	Oxygen is not evolved	Oxygen is evolved
4.	Synthesis of $NADPH_2$ does not occur	Synthesis of $NADPH_2$ occur

In this way due to photolysis of water by the photo systems take part in light chemical reaction O_2 is released and ATP and $NADPH+H^+$ are formed. ATP and $NAPH+H^+$ are known as assimilatory power and reducing power respectively which are used in dark reaction to produce carbohydrates from CO_2.

Dark Reaction

Dark reaction was discovered by Blackman (1905) but study of its all biochemical reactions done by Calvin and his coworkers. This reaction of photosynthesis takes place in stroma of the chloroplast and happens in the absence of light. In this reaction CO_2 absorbed from atmosphere reduced or fixed to carbohydrate. That is why dark reactions are called carbon fixation. In this reaction energy required for reduction of $CO_2$is obtained from the ATP and NADPH + H^+ which is formed during light reaction. In green plants carbon fixation takes place by three different ways:

a. Calvin Benson Cycle (C_3 Cycle)

b. Hatch-Slack Cycle, C_4 Cycle

c. Crassulacean acid Metabolism, CAM Cycle

a. Calvin Benson Cycle (C_3 Cycle) : Calvin Benson and et.al during 1946-1953 discovered the path of conversion of carbon dioxide into carbohydrates in the process of photosynthesis by Radioactive tracer technique. In this work they used $C^{14}O_2$ containing C^{14} carbon isotope on unicellular green algae *Chlorella* and *Scenedesmus*. By this study they told that in this reaction first stable product formed is 3-phosphoglyeric acid (3PGA) containing three carbon atoms. For this work Calvin and Benson were awarded noble prize in 1961. The important reactions of this cycle are given below:

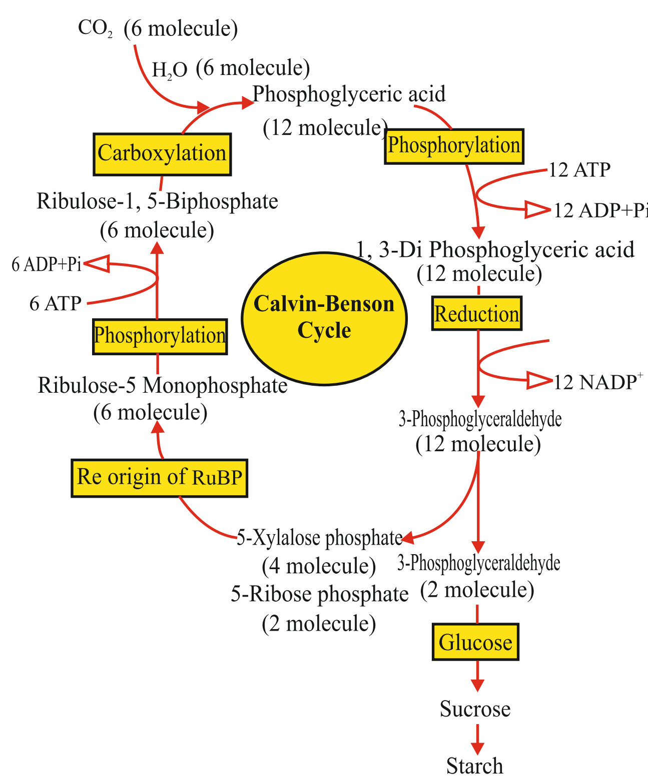

Fig. 10.7 : Diagram showing Calvin-Benson cycle or C_3 cycle

(1) Phosphorylation of Ribulose Mono Phosphate : In dark reaction acceptor of carbon di oxide is a 5-carbon containing sugar ribulose 1-5 bisphosphate (RuBP). It is formed by phosphorylation of ribulose mono phosphate in the presence of phosphopento kinese enzyme and ATP. To accept 6 molecules of CO_2 for the formation of a molecule of glucose 6 molecules of ribulose-1, 5 bi phosphates are required.

6 Ribulose-5-phosphate $\xrightarrow{\text{Phosphopentokines}}$ 6-Ribulose 1, 5-Bi phosphate

6ATP → 6ADP

(2) Carboxylation of Ribulose 1-5 bisphosphate (Carboxylation Stage) : Ribulose 1-5 bi phosphate acts as carbon di oxide acceptor which is formed in first phosphorylation. In the presence of carboxylase enzyme 6 molecules of ribulose 1-5, bi phosphate react with 6 molecules of H_2O and 6 molecules of CO_2 to form 12 molecules of 3-phosphoglyeric acid (PGA) containing three carbon atoms which is the first stable compound of dark reaction

Ribulose-1,5 Biphosphate $+6CO_2+6H_2O$ $\xrightarrow[\text{(RuBISCO)}]{\text{RuBP Carboxylase}}$
(6 molecule)

3- phosphoglyceric acid (3C)
(12 molecule)

(3) Phosphorylation of Phosphoglyceric acid : 12 molecules of phosphoglyceric acid formed by the carboxylation reaction gives 12 molecules of 1-3 di phosphoglyceric acid in the presence of phosphoglyceric kinase enzyme and 12 molecules of ATP which were formed during light reaction.

3 phosphoglycric acid $\xrightarrow{\text{Phosphoglycric kines}}$
(12 molecules)

12ATP → 12ADP

1, 3- Diphoglyceric acid
(12 molecules)

(4) Reduction of 1-3 diphosphoglyceric acid (Reduction stage) : In the reduction phase, reduction of 12 molecules of 1, 3-diphospho-glyceric acid produced by the carboxylation and phosphorylation takes place by the 12 molecules of reducing power NADPH+H^+ produced during light reaction by which 12 molecules of 3-phospho-glyceraldehyde (3 PGAL) are formed. This reaction is catalyzed by triose phoshate dehydrogenase.

1,3-Diphosphoglycric acid $\xrightarrow{\text{Triose phophate dehydrogenase}}$
(12 molecules)

NADPH+H^+ → $NADP^+$

3-Phosphoglyuceraldehyde + 12 H_3PO_4
(12 molecules)

Out of above mentioned 12 molecules of 3-Phosphoglyuceraldehyde only 2 molecules for sugar (glucose) produced which later covert into sucrose or starch. Remaining 10 molecules form 6 molecules of ribulose mono phosphate which again take part in reaction and provide continuity to Calvin cycle.

(5) Formation of hexose sugar (Synthesis stage) : Out of 12 molecules of 3-Phosphoglyceraldehyde formed in reduction reaction only 2 molecule form one glucose molecule by following biochemical reaction:

(i) 3-Phosphoglyceraldehyde $\xrightarrow{\text{Phospho triose isomerase}}$
(3PGAL)

3-Dihydroxy aceton phosphate
(3-DHAP)

(ii) 3-Phosphoglyceraldehyde + 3dihydroxy aceton phosphate
(one molecule)

$\xrightarrow{\text{Aldolase}}$ Fructose 1-6 diphosphate
(one molecule)

(iii) Fructose 1-6 diphosphate $\xrightarrow{\text{Phosphatose}}$
Fructose 6 phosphate + H_3PO_4

(iv) Fructose -6 phosphate $\xrightarrow{\text{Isomerase}}$ Glucose 6-phosphate

(v) Glucose 6-phosphate + H_2O ⟶ Glucose + H_3PO_4

Above mentioned all the reactions are in the opposite series of glycolysis reaction of respiration so it is also known as glycolytic reversion.

(6) Reorigin of Ribulose-5 Phosphate (Recombination stage) : In the beginning of Calvin Benson cycle 6 molecules of ribose bi phosphate accept 6 molecules of CO_2 and form 12 molecules of phosphoglyceric acid. 5-Ribulose bi Phosphate is formed by the phosphorylation of ribulose 5-phosphate hence, for the continuity of cycle in the end of each cycle formation of 5 ribulose mono phosphate is necessary. Hence, 10 molecules of 3-PGAL through different biochemical reactions formation of 6 molecules of RuMP is called reformation or rearrangement phase.

(i) Formation of Dihydroxyaceton phosphate : 4 molecules of 3PGAL form 4 Molecules of DHAP in the presence of triose phosphate isomerase

$$\underset{\text{(4 Molecules)}}{\text{3-PGAL}} \xrightarrow{\text{Triose phosphate isomerase}} \underset{\text{(4 Molecules)}}{\text{DHAP}}$$

(ii) Formation of Fructose1-6 Di Phosphate : Two molecules of 3-PGAL and 2 molecules of DHAP in the presence of aldolase form 2molecues of fructose 1-6 di phosphate

$$\underset{\text{(2 Molecule)}}{\text{3-PGAL + DHAP}} \xrightarrow{\text{Aldolase}} \underset{\text{(2 Molecule)}}{\text{Fructose 1-6 di phosphate}}$$

(iii) Formation of Fructose-6 phosphate: Fructose 1, 6-di phosphate by hydration in the presence of phosphatase enzyme form fructose 6-phosphate

$$\underset{\text{(2 Molecule)}}{\text{Fructose 1, 6-di phosphate} + 2H_2O} \xrightarrow{\text{Phosphatase}} \underset{\text{(2 Molecule)}}{\text{fructose 6-phosphate} + 2H_3PO_4}$$

(iv) Formation of xylulose and erythrose Phosphate : Two molecules of fructose 6 phosphate and 2 molecules of 3-PGAL in the presence of transaketolase enzyme form 2 molecules of xylulose 5 phosphate and 2 molecules of erythrose 4 phosphate.

$$\underset{\text{(2molecues)}}{\text{Fructose 6-phosphate}} + \underset{\text{(2molecues)}}{\text{3 PGAL}} \xrightarrow{\text{Transaketolase}}$$

$$\text{2-Xylulose -5- phosphate+ 2-erythrose-4-phosphate}$$

(v) Formation of Pseudoheptulose 1-7 Di phosphate : 2 Molecules of erythrose 4-phosphate react with 2molecules of DHAP and form 2 molecules of pseudoheptulose 1, 7-di phosphate. This reaction is catalyzed by trans aldolase enzyme.

$$\underset{\text{(2 molecue)}}{\text{Erythrose -4-phosphate}} + \underset{\text{(2 molecue)}}{\text{DHAP}} \xrightarrow{\text{Transketolase}} \underset{\text{(2 molecue)}}{\text{Pseudoheptulose 1, 7-di phosphate}}$$

Pseudoheptulose L-7 diphosphate formed in this reaction forms 2 molecules of phosphoric acid and 2 molecule of pseudoheptulose-7-phosphate by hydration in the presence of phospatese enzyme.

$$\text{Pseudoheptulose 1-7 Di phosphate} \xrightarrow[2H_2O \;\rightarrow\; 2H_3PO_4]{\text{phosphotase}} \text{Pseudoheptulose 7-phosphate}$$

(vi) Formation of Ribose 5-phosphate and xylulose 5-phosphate : 2 molecules of Pseudoheptulose 7 phosphate and 3PGAL in the presence of transketolase form 2 molecules of Ribose 5 Phosphate and 2 molecules of xylulose 5-Phosphate.

$$\underset{\text{(2 molecue)}}{\text{Pseudoheptulose 7-phosphate}} + \underset{\text{(2 molecue)}}{\text{3-PGAL}} \xrightarrow{\text{Transketolase}} \text{Ribose -5- Phosphate + 2 xyloses -5-Phosphate}$$

(vii) Four molecules of xylulose 5 phosphate and 2 molecules of ribose 5 phosphate form 6 molecules of xylulose 5 phosphate, (RuMP)

$$\text{(i)}\quad \underset{\text{(2 molecue)}}{\text{Ribose 5 phosphate}} \xrightarrow{\text{Phospho pento isomerase}} \underset{\text{(2 molecue)}}{\text{Ribulose 5 phosphate}}$$

$$\text{(ii)}\quad \underset{\text{(4 molecue)}}{\text{Xylose 5 phosphate}} \xrightarrow{\text{Phospho pento isomerase}} \underset{\text{(4 molecue)}}{\text{Ribulose 5 phosphate}}$$

In this way by rearrangement phase 6 molecules of ribulose 5-phosphate are formed which are phosphorelized from 6 molecules of ATP and form 6 molecules of ribulose 1-5 di phosphate. Which are again used in Calvin cyclic reactions.

(B) Hatch Slack Cycle or C_4 Cycle

Kaprilav studied on Maize Leaf and C. E. Korts Chak and his coworkers studied on sugarcane leaf and they found that after accepting CO_2 first stable compound according to C_3 cycle instead of

3PGA a four carbon compound oxalo acetic acid is formed (OAA). After some time Hatch and Slack (1966) proved above results and discovered the whole path of the cycle. That is why it is known as Hatch and Slack cycle. This is called C_4, cycle because first stable carbon compound has four carbons, this cycle is found in monocotyledons (maize, sorghum, sugarcane) and in few dicotyledons plants like *Amaranths, Euphorbia* etc.:

Special structure of C_4, Plants : There are two types of photo synthetic cells are found in C_4 plants which are known as mesophyll cells and bundle sheath cells. The bundle sheath cells are found around the vascular bundles arranged in one or two layer monali form. In German language wreath is called kranz so this anatomy of leaves is–called Kranz anatomy. In C_4, Plants two types of Chloroplast are found, so chloroplast present in mesophyll cells are small and has well developed grana however, chloroplast found in Bundle sheath cells are big and without grana. Thylakoids are found in the form of stroma lamelae. Hence in C_4, Plants light reaction takes place in mesophyll Cells and dark reaction (assimilation of CO_2) takes place in bundle sheath Cells.

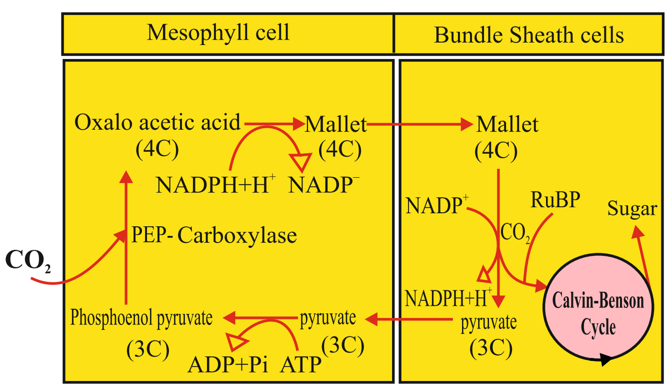

Fig. 10.8 : Diagram showing Hatch and Slack cycle or C_4 cycle

Mechanism of C_4, Cycle : In C_4, cycle CO_2 from environment reaches to mesophyll cells of the leaf through stomata. This CO_2 absorbed by phosphoenol pyruvic acid (PEP) and in the presence of carboxylase enzyme convert it into oxalo acetic acid. Then oxalo acetic acid reduced in malic acid. In this stage oxidation of $NADPH+H^+$ takes place and $NADP^+$ is formed. Malic Acid enters in to bundle sheath cells through mesophyll cells. Carbon di oxide is released by decarboxylation and it is converted in to pyruvic Acid. Pyruvic acid again enters into mesophyll cells and combines with ATP Molecule to form phosphoenol pyruvic acid which provides the continuity to this cycle. CO_2 released from bundle sheet cells enters in to C_3 cycle and form sugar. In this way$CO_2$is stored in C_4 cycle in mesophyll cells and in C_3 cycle, carbon fixation occur in bundle sheet cells.

Characteristics of C_4 Cycle and C_4 Plants

(I) C_4 plants are able to perform photosynthesis even at extreme less CO_2 so important from biological point of view.

(ii) Due to the absence of photo respiration these are more productive in comparison to C_3 plants.

(iii) Main Enzyme (PEP carboxylase) of C_4 cycle remain active even at low concentration of CO_2. C_4 plants can easily grow in low water and high temperature (30-45°C) area.

Above Features explained that C_4 plants are most successful plants of tropical area.

Major Difference Between C_3 AND C_4 cycle

S.No.	Characteristics	C_3 cycle	C_4 cycle
1.	Optimum temperature	10 to 25°C	30 to 40°C
2.	Kranz Anatomy	Absent	Present
3.	First stable product	Phosphoglyceric acid (3C)	Oxalo acetic acid (4C)
4.	Site of CO_2 fixation	Only mesophyll cells	Mesophyll and bundle sheath cells
5.	First receptor of CO_2	RuBP (5 carbon compound)	PEP (3 carbon compound)
6.	For carboxylation	RUBISCO	PEP carboxylase and RUBISCO
7.	Photo respiration	Present	Absent
8.	Productivity	Due to defective photorespiration, less	Due to absence of defective photorespiration more

(C) Crassulacean Acid Metabolic Cycle

Crassulacean acidic metabolic cycle mostly found in fleshy and dry environmental plants. Leaves of these plants are thick fleshy and pulpy. Stomata of these leaves are open in the night and closed in the day time, these types of stomata are called scotoactive stomata. In these plants during night leaves absorb carbon di oxide. Their

Mesophyll cells in the presence of PEP accept CO_2 and form 4 carbon compound oxalo acetic acid which convert into malic acid. In this way CO_2 fixation takes place in the night in the form of malic acid.

In the day time CO_2released from decarboxylation of malic acid which diffused in chloroplast and reduced into carbohydrate through Calvin cycle. Important feature of this cycle is that CO_2fixation takes place in the night time and reduction of CO_2 and formation of sugar takes place in the day time in same cell. This cycle is a physiological adaptation found in succulents and xerophytic in which plants produce organic substances without loss of water. This metabolic reaction first studied on plants of crassulaceae family so it called as crassulacean acidic metabolism. Few important CAM Plants are-*Ageva, Yakka, Crasula, Pineapples, Snake dragon, Echinocactus* etc.

Photo respiration

In photo synthetic parts of the plants in the presence of sunlight instead of normal respiration the respiration takes place in which oxygen oxidized carbon compounds and does not produce energy and release CO_2 called photo respiration, in this reaction food material decomposed like respiration process but does not release energy. It is also known as destructive reaction. Photo respiration word was first used by Krotkov in 1963. This reaction only takes place in C_3Plants. Ottowarberg (1920) started that presence of oxygen retard the rate of photo synthesis. This Effect of oxygen is known as Warberg effect. Oregen and Bow explained Warberg effect and gave that there is a competition between O_2 and CO_2 for RUBISCO. In the excess of CO_2 RUBISCO acts as carboxylase however, in the excess of oxygen it acts as oxygenase enzyme instead of carboxylase by which RUBISCO formed oxygenated phospho glycolic acid (2 carbon containing compound) hence, this cycle is also known as glycolate cycle due to which formation of PGA gets blocked and rate of carbon di oxide assimilation being increased. This cycle was studied by Decker and Tio (1959). Pohtorespiration takes place in chloroplast, peroxysome and mitochondria. All the three cell organelles act as a unit in photo respiration.

Factors Affecting Photosynthesis

As various biochemical processes, photo synthesisis also affected by environmental and hereditary factors. These factors are internal and external type. External factors or environmental factors are light, availability of CO_2, temperature, soil, water etc. which affect process of photosynthesis directly or indirectly. Before detailed study of these factors it is required to study Sach's cardinal point hypothesis and Blackman's Theory of limiting Factors.

Sach's cardinal point hypothesis: According to cardinal point hypothesis proposed by Sach (1860) there are three main values of a factor to affect photosynthesis or any other physiological reaction.

(i) Minimum Value or Point : Amount of factor at which process of photosynthesis initiated.

(ii) Maximum or optimum value point : This shows the amount of factor where rate of photosynthesis is maximum.

(iii) Highest value or Point : Amount of factor at which photosynthesis process stopped.

All these three phases are called cardinal points.

Blackman's Theory of Limiting Factors : Blackman (1905) proposed Principal of Limiting Factors. This Principal is actually the conversion of earlier published Lebeig's Law of minimum. According to theory Blackman's limiting factor, if any process affected by many factors than rate of reaction depends on a particular factor or limited by that factor which is present in minimum amount. Increase in limiting factor increase the rate of photosynthesis, like light is present for photosynthesis however CO_2 is not present. In this phase rate of photosynthesis depends on availability of CO_2. If CO_2 and light both are limited than rate of photosynthesis depends on that limiting factor which is in excess.

External Factor or Environmental Factor :

External factors that affect photosynthesis are light, temperature, carbon dioxide, water, oxygen etc.

(i) Light : Photo synthetic reaction takes place in the visible part the spectrum of light which has value between 400 nm to 700 nm and it is called photo synthetically active radiations (PAR). Photosynthesis affected by intensity of light and type of light. Highest rate of photosynthesis found in red area of visible spectrum and little in blue area. Photosynthesis does not take place in green colour because leaves do not absorb it. Due to the increase in intensity of light rate of photosynthesis increases in the beginning but at high intensity of light rate of photosynthesis decreases because either the factors affecting rate of photosynthesis gets limited or chloroplast or other cellular material are destroyed by oxidation of light which is called solarization.

(ii) Temperature : Photo synthetic reactions takes place in the wide range of temperature. In some conifers like *Uniparous* photosynthesis can go on normally at the temperature of 35°C. Few xerophytes can perform photosynthesis at 55°C and few algae found in hot water can perform photosynthesis at 75°C. In most of the plants rate of photosynthesis increases at the temp. between 10-35°C but after some time it decreases because at high temperature photo synthetic enzymes start denature and the main enzyme of C_3 cycle RUBISCO affinity the bonding with CO_2 decreases.

(iii) Carbon Di Oxide : Percentage of CO_2 in the environment is .03% (300ppm). As the amount of CO_2 in the atmosphere increases, the rate of photosynthesis increases evenly for some time and this increase continue till the limitation of other factors. Generally, rate of photosynthesis increase till 1% concentration of CO_2 but excess of CO_2 concentration creates poisonous effect on plants by which stomata get closed and exchange of gases reduced. In C_3 plants with increase of the concentration of CO_2upto 0.05% rate of photosynthesis increases while in C_4, plants rate of photosynthesis increases up to 0.03% concentration of CO_2.

(iv) Water : Water is the main reactant of photosynthesis because it acts as a hydrogen donor. Only 1% part of the total absorbed water is used in plants for photosynthesis hence it is not the limiting factor in the process of photosynthesis it is effective indirectly. When there is a shortage of soil water it become a limiting factor and affect the rate of photosynthesis indirectly, Stomata close due to deficiency of water in which exchange of gas stops and water utilization by leaves is reduced.

(v) Oxygen : lncrease in oxygen concentration affect the reactions of photosynthesis It acts as competitive inhibitor for RUBISCO. In C_3 plants due to the increase of concentration of oxygen RUBISCO acts as oxygenase enzyme instead of carboxylase enzyme which initiates photo respiration.

Internal Factors

Rate of photosynthesis affected by different types of internal factors. Below are some important factors:

(1) Chlorophyll : Chlorophyll is the main pigment of photo synthetic reactions which convert light energy into chemical energy. Normally rate of photosynthesis increases with the increase in amount of chlorophyll

(2) Amount of Stored Food : End product of photosynthesis stored in plant cells. Continuous storage decreases the rate of photosynthesis but transfer of these products in different parts of the plant, the rate of photosynthesis increase again.

(3) Internal Structure of Leaf : Rate of photosynthesis depends on the number of stomata, their distribution and structure. More number of stomata open for long time influence the more absorption of CO_2 which increase the rate of photosynthesis.

Important Points

1. Photosynthesis is an important biochemical reaction in which green plants in the presence of sunlight by CO_2 and water form organic compounds.
2. In the process of photosynthesis oxidation of

water and reduction of CO_2 occur.

3. Photosynthesis occurs in chloroplast because it contains pigments like chlorophyll, carotenoids etc.
4. Light reaction takes place in the grana part of the chloroplast and dark reaction takes place in the stroma part of the chloroplast.
5. Chlorophyll-a is the universal pigment which act as reaction center in light reaction. Energy absorbed by accessory pigments transferred to reaction center in the end.
6. Two types of photo systems are necessary in photo synthetic reaction (PS I and PS II) .Wave length more than 680nm absorbed in PS I and wavelength less than 680nm is absorbed in PS II.
7. Quantosome are the unit of photosynthesis which are found on thylakoids membrane in the form of granular structure. This accept light energy.
8. The lowering in rate of photosynthesis when a plant is illuminated with light of wavelength more than 680 nm, then this lowering is called red drop.
9. In photo chemical reaction photolysis of water occurs which release O_2 . PSII participate in this reaction. Electrons release in this reaction takes part in electron transport series and from ATP and $NADPH_2$ which is used in reduction of CO_2.
10. Reduction of CO_2 takes place in stroma. RUBISCO enzyme catalyzes initial reactions which form 3 carbon compound 3PGA. Hence it is called C_3 cycle on the basis of inventors name it is called Calvin Benson cycle.
11. In few tropical plants first product of carbon fixation is 4 carbon compound oxaloacetate. These plants are called C_4 plants and this cycle is known as C_4 Cycle.
12. In the photosynthesis for reduction of one molecule of CO_2 , 4 electrons will transfer and 8 photons are required by which 2ATP and $2NADPH_2$ are formed.
13. Rate of Photosynthesis depends on many environmental factors like concentration of CO_2 availability of water, intensity of light, temperature etc.
14. The end product of photo synthesis is sucrose and it is distributed by phloem through leaves and stored in the form of starch.

Practice Questions

Multiple Choice Questions

1. Which metal found in the center of chlorophyll molecule?

   (a) Fe (b) Mg

   (c) Ni (d) Cu

2. Pigment system Il Related to

   (a) Photolysis of water

   (b) Reduction of CO_2

   © Flowering

   (d) All mentioned above

3. Reaction centers in Photo system I and Photo system II are

   (a) P_{700} and P_{680} (b) P_{680} and p_{700}

   (c) P_{580} and P_{700} (d) P_{700} and P_{580}

4. Origin of oxygen related to

   (a) PS I (b) PS II

   (c) Phytochrome

   (d) All mentioned above

5. What is the main reaction which differentiate C_3 and C_4 plants

   (a) Glycolysis (b) Photo respiration

   (c) transpiration (d) Photosynthesis

6. Unit of photosynthesis is

   (a) Quantosome (b) Microsome

   (c) Peroxysomes (d) Spherosomes

7. Which is essential for photolysis of water

   (a) Mn (b) Mg

   (c) Zn (d) Fe

8. During photosynthesis process

   (a) Oxidation of CO_2 and water occur

   (b) Reduction of CO_2 and water occur

(c) Reduction of water and oxidation of CO_2 occur

(d) Oxidation of water and reduction of CO_2 occur

9. Source of free oxygen in photosynthesis is

(a) Water (b) CO_2

(c) Both (d) None of the above

10. Dark reaction of photosynthesis takes place in

(a) Grana (b) Stroma

(c) Mitochondria (d) All the above

11. Kranz anatomy found in

(a) C_3 plants (b) C_4 plants

(c)Succulent plants (d) All the above

12. First stable product of C_4 cycle is

(a) Pyruvic acid (b) Oxalo acetic acid

(c) Malic Acid (d) None of the above

13. For Reduction of 6 Molecules of CO_2 non cyclic phosphorylation has

(a) 24 H^+ (b) 36 H^+

(c) 32 H^+ (d) 12 H^+

14. Wave Length found in photosynthesis active radiation

(a) 340-450 nm (b) 400-700 nm

(c) 500-600 nm (d) 450-950 nm

Very Short Answer Questions

1. Define photosynthesis.
2. What is the first stable product of photosynthesis?
3. What is the difference between chlorophyll-a and chlorophyll-b ?
4. Give the full name of NADP
5. Give name of the cell organelles that take part in photo respiration.
6. Who is known as the father of plant physiology?
7. Name the sites of dark and light reactions during photosynthesis.
8. What is the rule of limiting factors?
9. Which is the most commonly found protein in the biosphere?
10. Red drop phenomenon takes place in which part of visible spectrum?
11. Which are the accessory pigments in photosynthesis?
12. Photo respiration is a destructive reaction. Why?

Short Answer Questions

1. Which are the pigments that take part in photosynthesis?
2. Give a brief description of structure of chloroplast.
3. What is the contribution of Blackman in plant physiology?
4. Give a brief description of chemical structure of chloroplast.
5. What is the difference between C_3 and C_4Cycles? Explain
6. Fixation of CO_2 by crassulacean acid metabolism is the physiological adaptation in xerophytis and succulent plants. Explain?
7. What do you understand by photo phosphorylation?

Essay Type Questions

1. Describe the light reaction of photosynthesis.
2. Explain the fixation of CO_2 by Calvin Benson cycle
3. What do you understand by photophosphorylation? Explain this reaction in detailed.
4. Describe Hatch Slack Cycle and give its importance.
5. Write a note on:

   i. Photosynthetic pigments

   ii. Photo system I and Photo system II

   iii. Photolysis of water

   iv. Importance of C_4 Cycle

   v. Photo respiration and photosynthesis
6. Give detailed explanation of factors affecting photosynthesis.

Answers Key-

1.(b) 2. (a) 3. (a) 4. (b) 5. (b) 6. (a) 7. (a)

8. (d) 9. (a) 10. (b) 11. (b) 12. (b) 13. (a) 14. (b)