4 Bioenergetics

At the end of this chapter students will be able to:

- Explain the role of light in photosynthesis.
- Identify the two general kinds of photosynthetic pigments (carotenoids and chlorophylls).
- Describe the roles of photosynthetic pigments in the absorption and conversion of light energy.
- Differentiate between the absorption spectra of chlorophyll 'a' and 'b'.
- Describe the arrangement of photosynthetic pigments in the form of photosystem-I and II.
- State the role of CO_2 as one of the raw materials of photosynthesis.
- Explain, narrating the experimental work done, the role of water in photosynthesis.
- Describe the events of non-cyclic photophosphorylation and outline the cyclic photophosphorylation.
- Explain the Calvin cycle (the regeneration of RuBP should be understood in outline only).
- Explain the process of anaerobic respiration in terms of glycolysis and conversion of pyruvate into lactic acid or ethanol.
- Outline (naming the reactants and products of each step of) the events of glycolysis.
- Illustrate the conversion of pyruvate to acetyl-CoA.
- Outline (naming the reactants and products of each step of) the steps of Krebs cycle.
- Explain the passage of electron through electron transport chain.
- Describe chemiosmosis and relate it with electron transport chain.
- Explain the substrate-level phosphorylation during which exergonic reactions are coupled with the synthesis of ATP.
- Justify the importance of PGAL in photosynthesis and respiration.
- Outline the cellular respiration of proteins and fats and correlate these with that of glucose.
- Define photorespiration and outline the events occurring through it.
- Rationalize how the disadvantageous process of photorespiration evolved.
- Explain the effect of temperature on the oxidative activity of RuBP carboxylase.
- Outline the process of C4 photosynthesis as an adaptation evolved in some plants to deal with the problem of photorespiration.

Introduction

This chapter deals with the most fundamental metabolic processes i.e. photosynthesis and respiration. Bioenergetics is the study of energy transformation in biological systems. Metabolic processes are going on all the times inside the bodies of living organisms. These processes involve chemical reactions that are concerned with making or breaking of bonds in the molecules. When chemical bonds are broken, energy is released and when bonds are formed, energy is stored. All living cells use energy for performing functions. Sunlight is the main source of energy maintaining all life forms on the earth. But no organism can make use direct energy of sunlight as source of energy for metabolism. All organisms use chemical energy stored in food molecules such as carbohydrates, fats etc. Photosynthesis is carried out by green plants which capture solar energy, transform it into chemical energy and is stored in organic compounds.

4.1. Photosynthesis

Photosynthesis is the process in which green plants synthesize organic food from carbon dioxide and water using energy of sunlight. CO_2 and water are used as raw materials in the process for synthesis of organic food molecules. Chlorophylls and other photosynthetic pigments capture energy of sunlight and convert it into chemical energy.

Photosynthesis acts as energy capturing and storing process. Energy of sunlight is used in the fixation of carbon dioxide to a carbohydrate. This serves as food not only for plants but for the entire life on the planet earth. Therefore all living organisms, directly or indirectly depends on photosynthesis. Autotrophic organisms which are the green plants are able to carry out photosynthesis. Heterotrophic organisms cannot carry out photosynthesis and are unable to use direct energy of sunlight. They, therefore, are dependent for their energy requirement on green plants.

Point To Ponder

Imagine if the process of photosynthesis stops what would be the state of life condition on earth?

Overall reaction of photosynthesis is:

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

Photosynthetic Reactants and Products:

The water and carbon dioxide are the reactants in photosynthesis while glucose, oxygen and water are the products.

4.1.1. The Role of Sunlight in Photosynthesis

Sun is the main source of energy for all living organisms. Light is a kind of energy tqchat travels in the form of electromagnetic waves of different wavelengths. It also acts as beam of particles of different frequencies called photons. There is a wide range of waves for synthesis of organic food molecules (wavelengths occurring between gamma rays and radio rays). Energy content of photons is inversely proportional to the wavelengths. Short wavelengths are more energetic i.e. have high energy content than long wave lengths. A portion of the solar radiation is called visible spectrum.

Our eyes are sensitive to only a small portion of this solar radiation i.e. visible light that ranges from about 390 nm to 760 nm in wavelength. Photosynthetic pigments absorb and utilize a portion of the visible spectrum. Wavelengths shorter than the visible light i.e. ultraviolet radiation are more energetic and are dangerous to the cells because they can break organic molecules. Wavelengths longer than visible light i.e. infrared have low energy content that cannot affect photosynthetic process. Wavelengths of the visible spectrum have the right amount of energy absorbed by photosynthetic pigments for photosynthesis.

About forty percent of the total of sunlight that enters our atmosphere reaches the earth surface. Most of this radiation is within the visible light range. Dangerous higher energy wavelengths are screened out by the ozone layer and upper layers of the atmosphere. Lower energy wavelengths are mostly absorbed or reflected by water vapours and other gases and are scattered in the atmosphere.

Of the total sunlight that strikes the green plants only about a fractionis used in the photosynthesis. This small portion of sunlight sustains all forms of life on earth. There are two types of photosynthetic pigments i.e. chlorophylls and carotenoids. Chlorophylls absorb mostly violet-blue wavelengths (390-460nm) and red wavelengths (630-700nm).

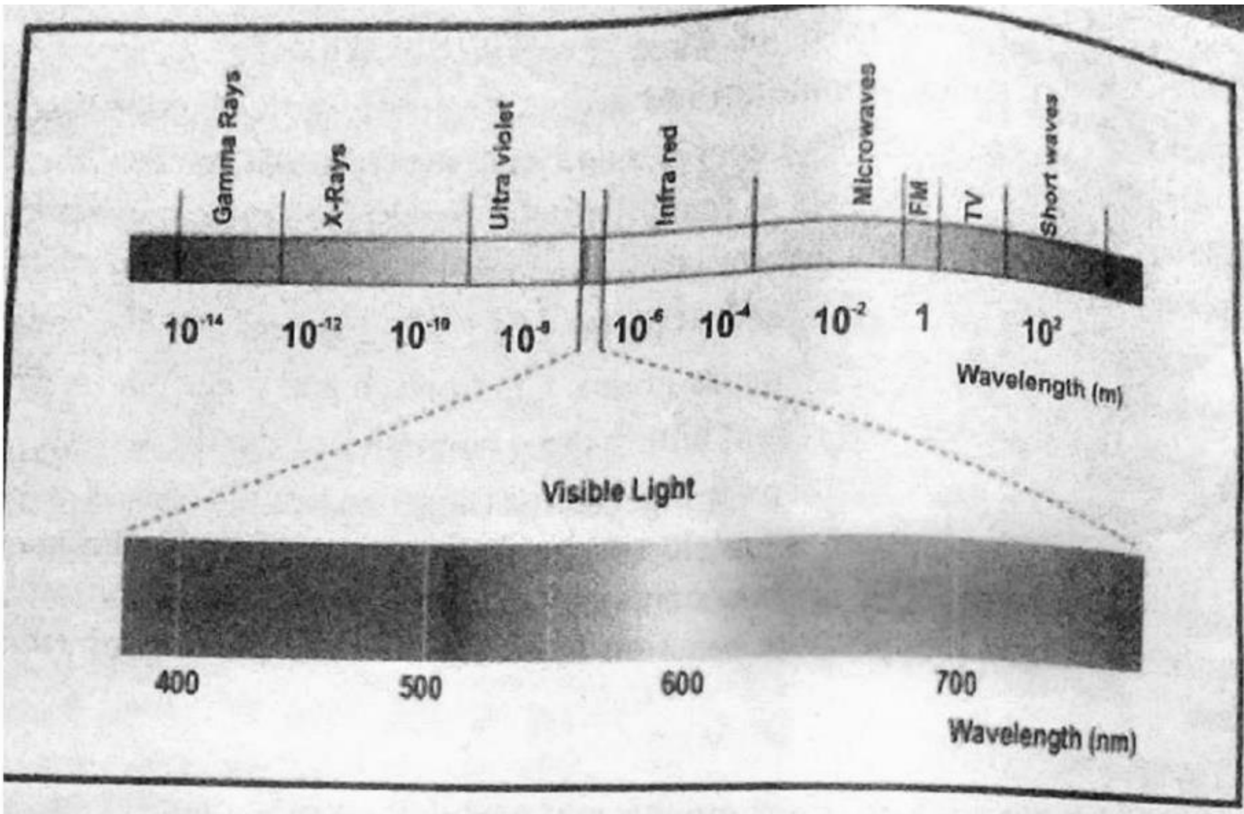


Fig: 4.1 Electromagnetic radiation that has a wavelength between 380nm and 780nm is visible to the human eye and is commonly referred to as light.

For Your Information

Quran says "And made the moon a light in their midst, and made the sun as a (Glorious) Lamp?

Sura Noor Aayah:16

"And placed (therein) a blazing lamp (sun).

Sura An naba. Aayah: 13

"Blessed is He Who made constellations in the skies, and placed therein a Lamp and a Moon giving light;

Sura Al-fur'qan Aayah: 61

wavelengths are mostly reflected therefore chlorophyll appears green. The oids which are called accessory pigments absorb light in the visible spectrum between 500nm and 600 nm in wavelengths.

otosynthetic Pigments

Photosynthetic pigments absorb different wavelengths of solar n. There are two types of photosynthetic pigments involved in nthesis. These are chlorophylls and carotenoids. In eukaryotes thetic pigments are located in the chloroplasts.

A chloroplast consists of three components; An outer most covering (envelop), **grana** (singular granum) and stroma. The outer most covering (envelop) of the chloroplast is formed by a double membrane structure that encloses the grana and stroma. A granum consists of many flattened fluid-filled membranous sacs or discs called thylakoids which form stacks and resemble a pile of coins. There are many grana which are interconnected by lamellae called intergrana. The grana are visible under the light microscope as grains. Chlorophyll and other photosynthetic pigments (carotenoids) are present within the membranes of the thylakoids. These membranes are the sites of light trapping reaction (light reaction) of photosynthesis.

The double membranes envelop of the chloroplast surrounds a large central space called **stroma.** The stroma contains enzyme rich gel-like solution called matrix where light independent reaction (dark reaction) of photosynthesis takes place.

a. Chlorophylls

Chlorophyll is a complex organic compound. It absorbs mainly blue and red portion of sunlight. The green portion is mainly reflected therefore chlorophyll appears green. There are many types of chlorophyll i.e. Chlorophyll a, b, c, d, e and bacteriochlorophyll

Do You Know?

Photosynthetic prokaryotes lack chloroplasts but they do have unstacked photosynthetic membrances, which work like thylakoid membrane. Chlorophyll is attached to the thylakoid membrane

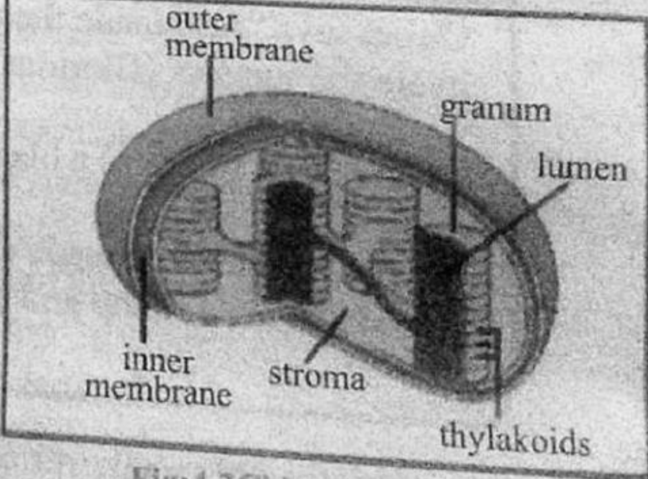


Fig:4.2Chloroplast

Chlorophyll "a" is the most abundant and most important photosynthetic pigment. It is found in all green plants except bacteria. It exists in several forms depending on its arrangement in the membrane. Chlorophyll "b" is found in all higher plants and green algae. Chlorophyll "c", d and "e" are found in various groups of algae. Bacterio-chlorophyll is found in bacteria.

Chlorophyll molecule is composed of two parts, i.e. head and tail. The head contains a central magnesium atom to which are attached four N-rings called Pyrrole rings. The four rings (tetra Pyrrole ring) are collectively called porphyrin. The head is hydrophilic and lies on the surface of the thylakoid membrane. Long hydrocarbon chain called phytol side chain (tail) is attached to one of the Pyrrole rings. It is hydrophobic. It lies embedded in the thylakoid membrane.

Chlorophyll "a" and "b" differ from each other in only one of the functional groups bonded to the **porphyrin**. Chlorophyll "a" has methyl group ($-CH_3$) while Chlorophyll "b" has carbonyl group (-CHO). The empirical formulae of chlorophyll "a" and "b" are

Chlorophyll "a" ($C_{55}H_{72}O_5N_4Mg$)

Chlorophyll "b" ($C_{55}H_{70}O_6N_4Mg$)

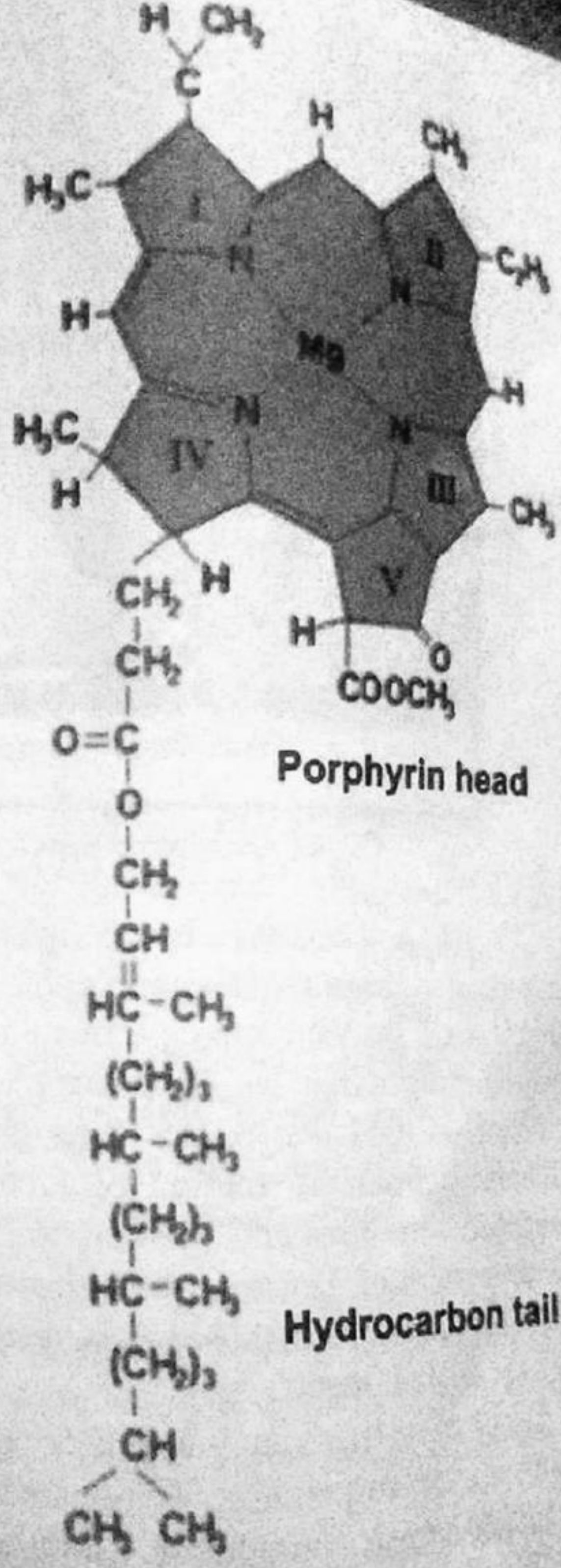


Fig: 4.3 Chemical structure of Chlorophyll

b. Carotenoids

They include carotenes and xanthophylls. They are yellow, orange, red or brown pigments. Carotenoids play two important roles in plants. They absorb light and transfer light energy to chlorophyll "a". Therefore, they are called accessory pigments. Carotenoids protect chlorophyll from intense light and from oxidation by oxygen produced in photosynthesis.

4.1.3. Absorption Spectra of Chlorophylls and Carotenoids

Absorption spectrum is the amount of light absorbed at different wavelengths from the visible spectrum of light. Photosynthetic pigments absorb light only in the visible part of light spectrum. The most important pigments in photosynthesis are chlorophyll "a" and chlorophyll "b". They chiefly absorb light in violet blue (390 nm -460 nm) and red parts (630nm -700 nm) of the spectrum.

The absorption spectra of both of these chlorophylls are somewhat different from each other. This is clear from the different peaks as shown inthe following fig 4.4.

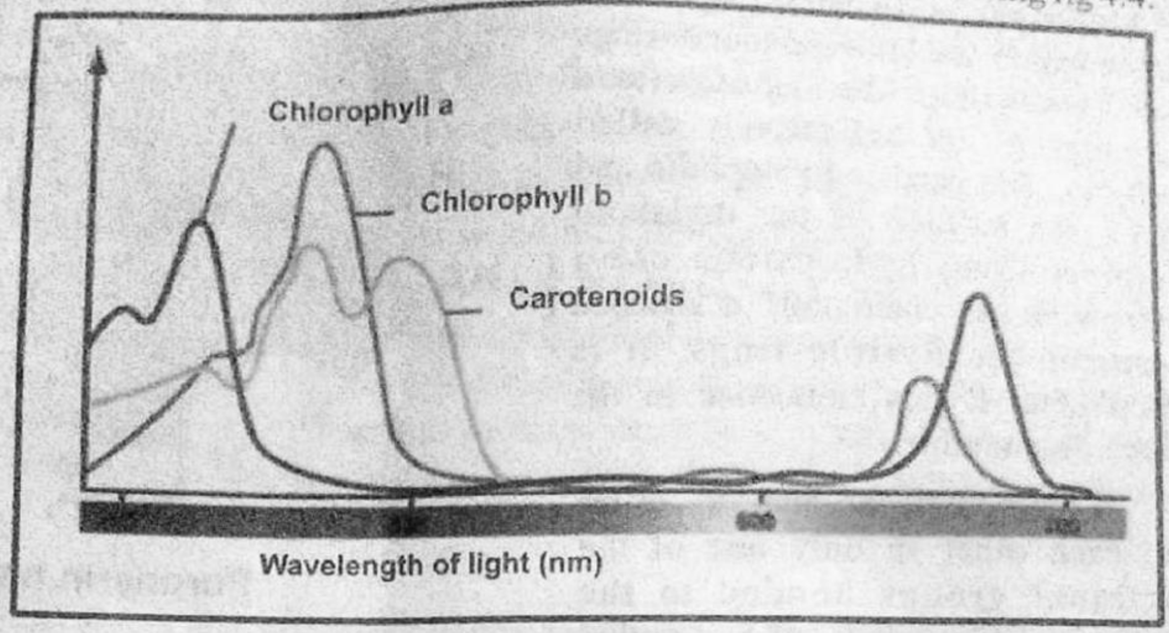


Fig: 4.4 Absorption Spectra of Chlorophylls and Carotenoids

The carotenoids absorb light between 430-470 nm of light spectrum and transfer it to chlorophyll 'a' molecule. To measure the absorption of a pigment, a pure solution of the extracted pigment is obtained. It is then exposed to different wavelengths of light inside spectrophotometer. It is an instrument that measures the amount of light that passes through the solution. The amount of light can be calculated from the amount projected on the solution and the amount of light received at the other end after passing through the spectrophotometer. This gives the measurement of the absorption spectrum of a particular pigment. Chlorophyll "a" and "b" show different absorption spectra as shown above.

4.1.4 Action Spectrum

Action spectrum is a measure of effectiveness of light of various wavelengths in driving photosynthesis. Whole amount of energy absorbed by the pigments is not stored in organic compounds. Some of it is released as heat and the rest is stored in organic compounds as chemical energy.

Action spectrum of a particular pigment can be calculated by measuring the rate of photosynthesis at each type of wavelength of light. As photosynthesis produces oxygen; the rate of production of oxygen can be used as a measure of the rate of photosynthesis. This gives an action spectrum of photosynthetic pigments for different wavelengths. Red and blue turn out to be the most effective wavelengths in photosynthesis. The action spectrum is somewhat different from absorption spectrum of chlorophyll.

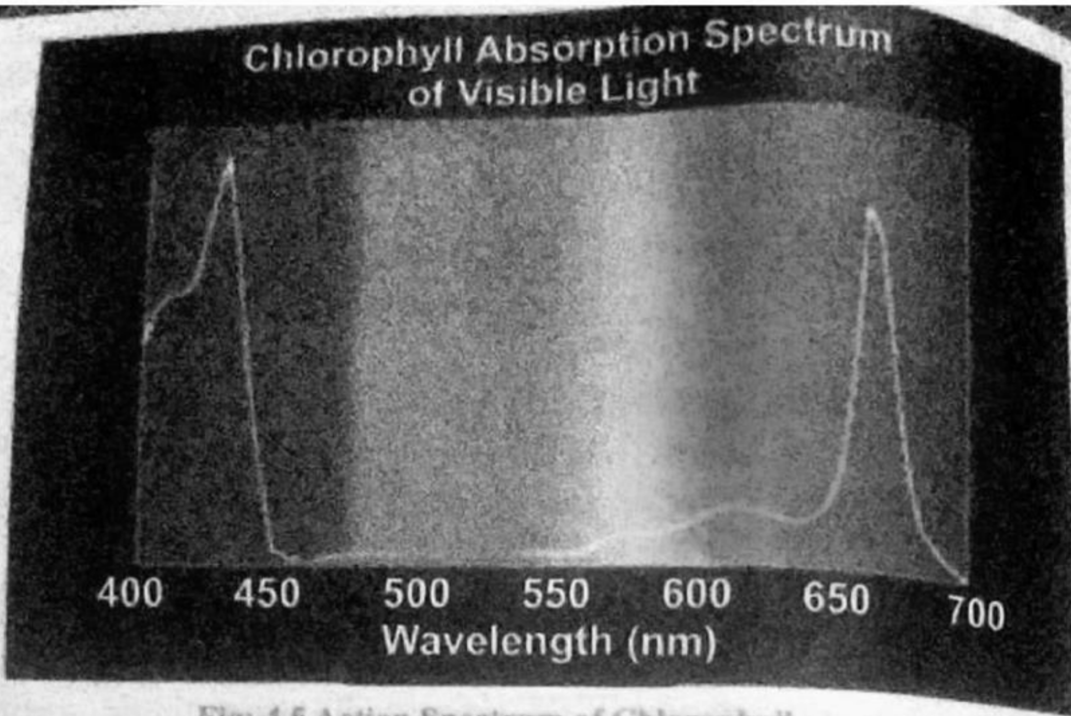


Fig: 4.5 Action Spectrum of Chlorophyll

4.1.5 Role of CO_2 as one of the raw materials of photosynthesis

The carbon of CO_2 is fixed in organic compounds in photosynthesis. Carbon is most important component of organic compounds. Carbon-carbon chain forms the back bone of the long hydro-carbon molecule and makes a stable and symmetric compound. Carbon makes bonds with oxygen linking the monosaccharide of carbohydrates. It makes bonds with nitrogen linking amino acids of protein molecules. Carbon dioxide is used as one of the raw material for photosynthesis. In the absence of carbon dioxide the process of photosynthesis does not occur.

4.1.6 Role of water in photosynthesis

Water is one of the raw materials used in photosynthesis. Water molecule is broken down into hydrogen and oxygen. Hydrogen combines with carbon dioxide forming organic food molecule. Oxygen is released into the air and is the source of atmospheric oxygen.

Earlier it was thought that the oxygen released in the process of photosynthesis comes from CO_2. In 1930, **Van Neil** hypothesized that plants split water to release oxygen as a by-product. The idea of Neil was supported by Hill. In 1937 he observed that when isolated chloroplasts were given light in complete absence of CO_2 and some hydrogen acceptor was present oxygen is released. Other scientists later confirmed **Neil's** hypothesis when first use of an isotopic tracer (O^{18}) in biological research was made. Water and carbon dioxide containing heavy-oxygen isotope O^{18} were prepared in the laboratory.

Experimental green plants in one group were supplied with H_2O containing O^{18} and with CO_2 containing only common oxygen O^{16}. Plants in the second group were supplied with water containing common oxygen O^{16} but with CO_2 containing O^{18}. It was found that plants of first group produced O^{18} but the plants of second group did not.

Group I $CO_2^{16} + 2H_2O^{18} \longrightarrow CH_2O^{16} + H_2O + O_2^{18}$

Group II $CO_2^{18} + 2H_2O^{16} \longrightarrow CH_2O^{18} + H_2O + O_2^{16}$

4.2 Mechanism of Photosynthesis

The Mechanism of photosynthesis consists of two distinct steps; one that requires light is called **light reaction** and the other that does not require light called **dark reaction**.

4.2.1 Light Reaction (Light dependent reaction)

Light reaction takes place in the granum of chloroplast. It is initiated when photosynthetic pigments capture light energy. Photosynthetic pigments are organized into clusters called photosystems. There are two photosystems i.e. photosystem I (PS I) and photosystem II (PS II). Each photosystem consists of several hundred pigment molecules including chlorophyll a, chlorophyll b, carotenoids and electron acceptors. There are two parts of each photosystems i.e. antenna complex and reaction center. The antenna complex has many molecules of chlorophyll b and carotenoids, all absorb energy and transfer it to the reaction center. Reaction center has one or more molecules of chlorophyll a molecules along with primary electron acceptor and electron carriers.

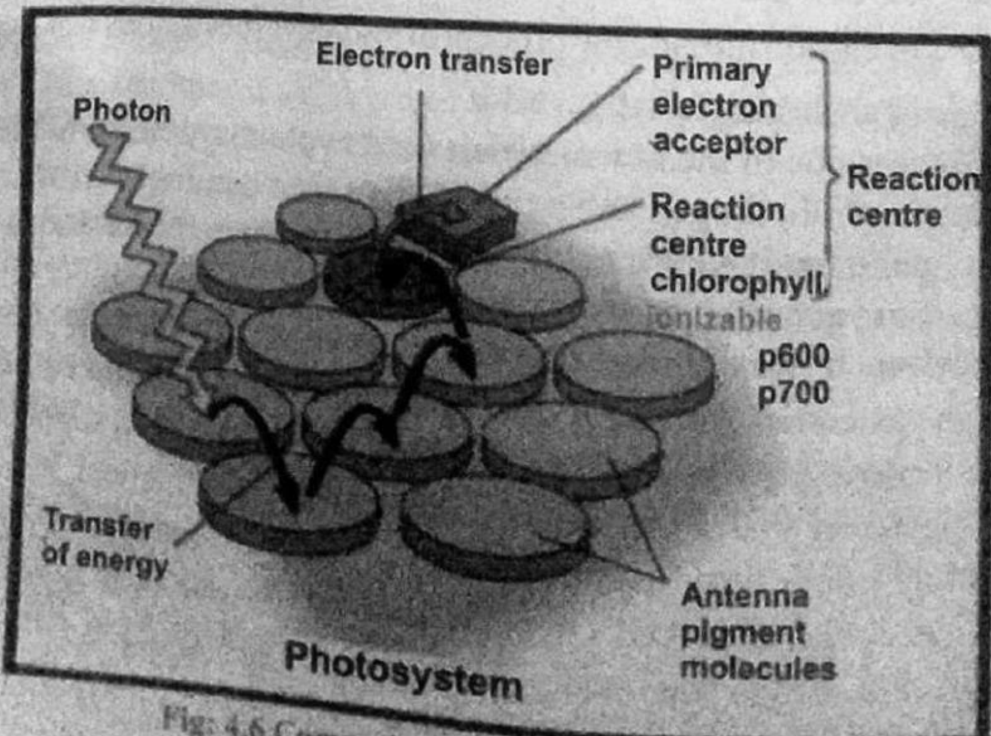


Fig: 4.6 Composition of a Photosystem

Photosystem I absorbs light of 700 nm and is called P700 whereas photosystem II absorbs light of 680 nm and is called P680. The primary electron accepter traps the electrons from the reaction center and then passes them on to the series of electron carriers. There are two possible pathways of the electrons in the light reaction of photosynthesis. They are called non-cyclic electron transport and cyclic electron transport

a. Non Cyclic Electron Transport of Light Reaction

- This reaction starts when sunlight strikes the photosystem II (P 680). Energy is absorbed by the chlorophyll molecules which loses its two electrons and becomes positively charged with a deficit of two electrons.
- The lost high energy electrons are captured by an electron acceptor called Plastoquinone (PQ).
- From plastoquinone the electrons pass along a series of electron transport chain which includes cytochrome 'b', cytochrome 'f' and plastocyanin molecules.
- Each molecule in the electron transport chain is alternately reduced when it gains electron and is oxidized when it losses electrons.
- When electrons are passed through electron transport chain, they lose energy. This energy is used in making ATP from ADP and inorganic phosphate using energy from sunlight in a process called as **photophosphorylation**.
- The electrons from plastocyanin are received by another photosystem called photosystem I (P700).
- At the same time light falls on photosystem I and activates its two electrons which are received by Ferredoxin reducing substance (FRS); electron accepter of PS I. From FRS electrons are passed to oxidized NADP (Nicotinamide adenine dinucleotide phosphate). The reduced NADP receives hydrogen from water and is converted into $NADPH_2$
- When photosystem II absorbs light, water molecule splits (photolysis) into OH^- and H^+. The OH^- ions react to form some water again and release oxygen and electrons.

$$4H_2O \longrightarrow 4H^+ + 4(OH^-)$$
$$4(OH^-) \longrightarrow 2H_2O + O_2$$

- Electrons from water molecules are accepted by positively charged chlorophyll molecule of Photosystem II, filling the gap produced by the two energized electrons. The electron deficiency of photosystem I has been filled by electrons coming from photosystem II.

This transport of electrons is called **Non cyclic electron transport** because electrons don not move in a cycle. The ATP synthesis during this non-cyclic electron flow is called **Non-cyclic Photophosphorylation**.

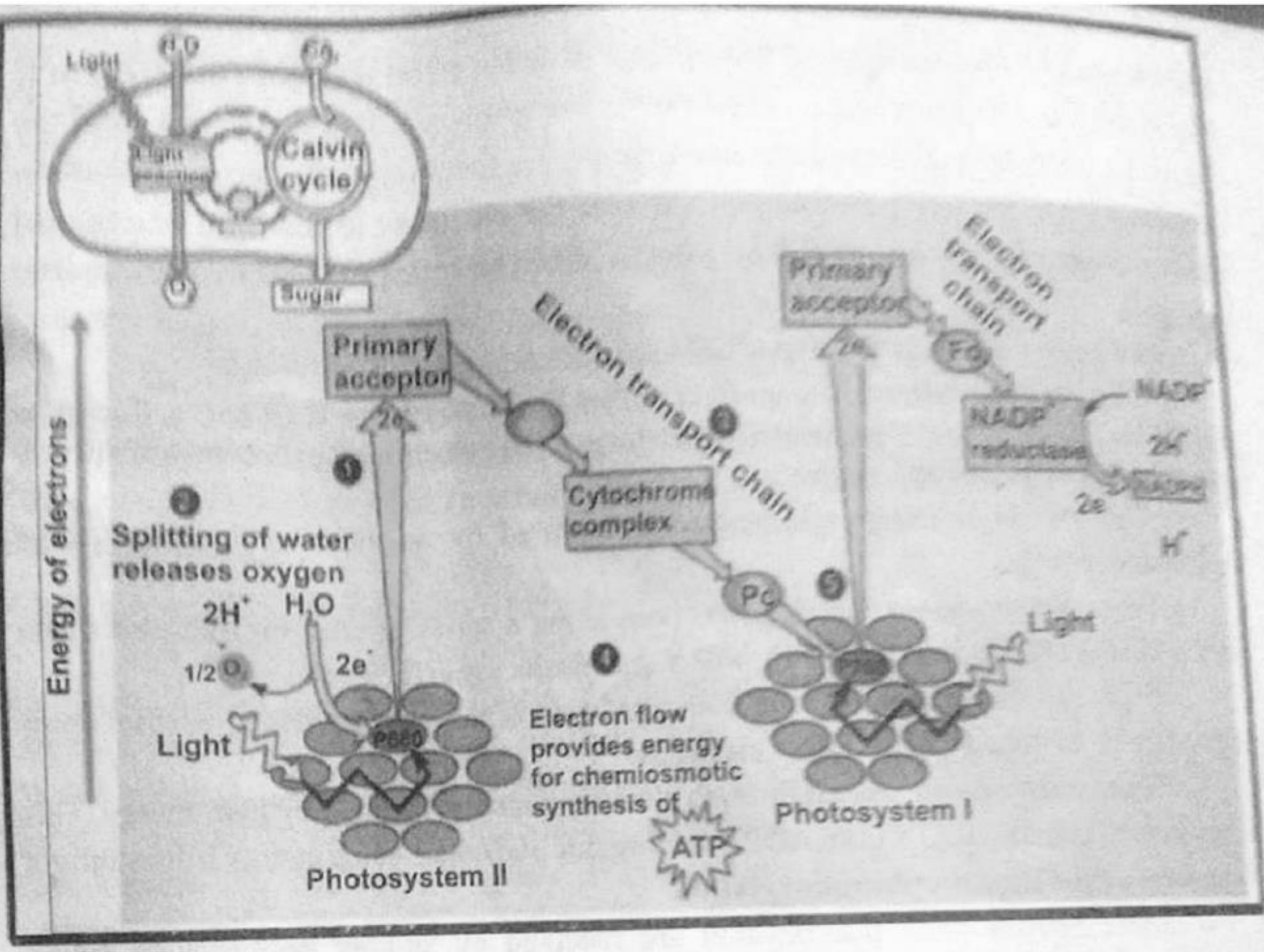


Fig: 4.7 Non Cyclic Electron Transport of Light Reaction

b. Cyclic electron transport

- Cyclic electron transport involves only photosystem I. It occurs in rare conditions if the activity of photosystem II is blocked.
- When P 700 form of chlorophyll molecule in photosystem I absorbs light, it is activated and it loses electrons, which are captured by ferrodoxin reducing substance (FRS).
- From FRS the electrons fall back to P 700 chlorophyll molecule through a series of electron carriers.
- ATP molecules are produced during cyclic electron flow.
- The electrons which are ejected from P 700 molecules are cycled back in the above electron transport therefore the process is called cyclic electron transport.
- ATP synthesis during this cyclic electron flow is called cyclic **photophosphorylation.**

Water and energy of sunlight are used in light reaction. The products of light reactions are ATP and NADPH. Both of these are transported from grana to stroma for use in dark reaction.

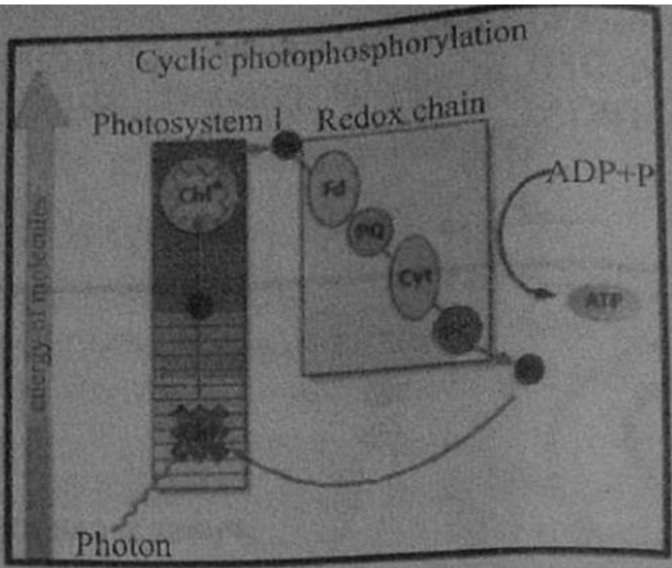


Fig: 4.8 Cyclic electron transport

4.2.2 Dark Reactions (Calvin Cycle) (Light-independent reactions)

Light independent reactions do not require direct energy of sunlight it may occur during day time but are called dark reactions so as to differentiate them from the light reactions. The sequence of dark reactions in photosynthesis was investigated by Melvin Calvin and his colleagues in 1950. They occur in a series of reactions in the stroma of chloroplast and taking the course of a cycle known as Calvin-Benson cycle.

The Calvin cycle is completed in three stages.

i. Carbon fixation

The cycle starts when ribulose bisphosphate, a 5-carbon sugar, already present in stroma reacts with CO_2 of air to form a 6-Carbon compound. This compound is unstable and soon splits up into two molecules of 3-carbon compound called Phosphoglycerate (PGA). This process is accelerated by an enzyme known as Rubisco (Ribolose biphosphate carboxylase). This is regarded as the most common protein in nature. The carbon that was part of CO_2 molecule is now a part of an organic molecule. This is called carbon fixation. PGA is regarded as the first product of photosynthesis to be identified.

RuBP + CO_2 ⟶ short lived 6- Carbon compound

6-C compound ⟶ 2PGA

ii. Reduction

PGA formed in the previous step is reduced into phosphoglyceraldehyde (PGAL) in this stage. The products of light reaction i.e. NADPH and ATP are used in the process. Each molecule of phosphoglyceric acid (PGA) receives energy from ATP and hydrogen from NADPH of light reaction, forming phosphoglyceraldehyde (PGAL) and water.

ADP and NADP return back to light reaction where ADP is converted into ATP and NADP is reduced into NADPH. In reduction process fixed carbon is reduced to a 3-carbon sugar molecule of PGAL.

$$PGA + ATP + NADPH \xrightarrow{H_2O} PGAL + ADP + P_i + NADP$$

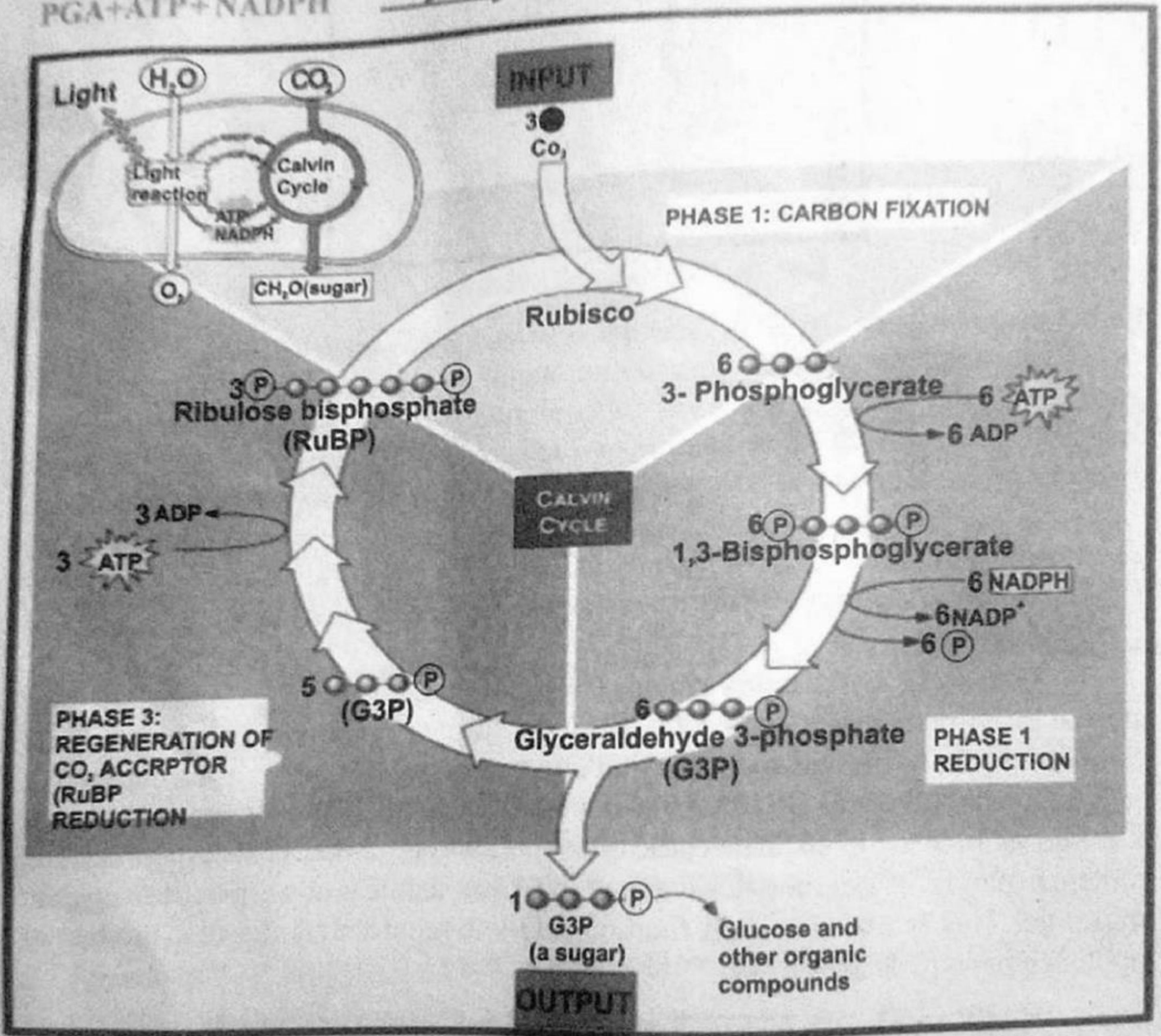


Fig : 4.9 Dark Reaction (Calvin Cycle) Occurs in stroma of chloroplast

iii. Regeneration of RuBP

In this stage RuBP molecules are regenerated so as to continue the cycle. The PGAL molecules formed in the reduction stage have many alternatives. Out of every six molecules of PGAL formed, only one molecule leaves the cycle to be used by the plant for making glucose and other organic compounds. The other five PGAL molecules are recycled to regenerate 3 molecules of five carbons RuBP by means of several intermediates including 3-C, 4-C, 6-C, 7-C etc. This process also uses some ATP produced in light reaction. Ribulose bisphosphate (RuBP) is then available to accept CO_2 and restarts the cycle. With the regeneration of RuBP the Calvin cycle or dark reactions complete.

4.3 Respiration

Respiration is defined as oxidation-reduction processes which occur inside the living cells during which organic food is broken down and energy is released. Respiration is of two types i.e. aerobic and anaerobic

4.3.1 Aerobic respiration (Cellular Respiration)

Aerobic respiration needs free O_2. In aerobic respiration organic food is completely broken down into CO_2 and H_2O and the stored energy is released. The overall equation of aerobic respiration for glucose breakdown can be written as follows:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 36\,ATP$$

Glucose and oxygen are used and carbon dioxide and water are produced. Energy is released which is used in the synthesis of ATP molecules. This is just the opposite of photosynthesis where glucose and oxygen are produced and carbon dioxide and water are used as raw materials.

Do You Know?

The overall equation of aerobic respiration gives a perception that oxygen combines with glucose molecule which is broken down into water and carbon dioxide and stored energy is released. But in fact this does not happen. Complete breakdown of glucose molecule, in aerobic respiration, occurs in three different steps i.e. glycolysis, Kreb's cycle and electron transport chain. Glycolysis occurs in cytosol (cytoplasm) while the latter two stages occur in mitochondria.

Organic food molecules are used by the living organisms as building materials and source of energy. Among the food molecules carbohydrates are the primary source of energy broken down by the living cells for the synthesis of ATP molecules. ATP are energy rich molecules also called energy currency of the cells.

The purpose of respiration is to release energy stored in organic food molecules and ATP molecules are produced. Why living cells do not acquire direct energy from the breakdown of food molecules? Why do they synthesize ATP? This is because if whole amount of energy of glucose is released it will be too great for individual reactions. This will result in heating up of the cells and also a large amount of energy will be wasted. ATP contains the right amount of energy available to the cell for its functions when it is broken down into ADP and inorganic phosphate. All living cells therefore use ATP molecules for energy requirement.

a. Glycolysis

Glycolysis is the breakdown of glucose, a 6-C molecule, in two molecules of pyruvate (3-C molecule) and a net gain of two ATP molecules. It takes place in cytosol (cytoplasm) and is common in both aerobic and anaerobic respirations. Glycolysis does not need free oxygen.

Glycolysis completes in two phases i.e. preparatory phase and oxidative phase.

1. Preparatory phase

Preparatory phase is phosphorylation of glucose by two ATP molecules.

- Glycolysis starts when glucose reacts with ATP molecule.
- ATP transfers energy and phosphate to glucose forming glucose 6-Phosphate and itself converts to ADP.
- Glucose –6 Phosphate is isomerised into Fructose-6 Phosphate.
- Fructose-6 Phsophate reacts with another ATP molecule forming fructose-1-6 bisphosphate.

Glucose + ATP ⟶ Glucose-6-Phsophate+ADP

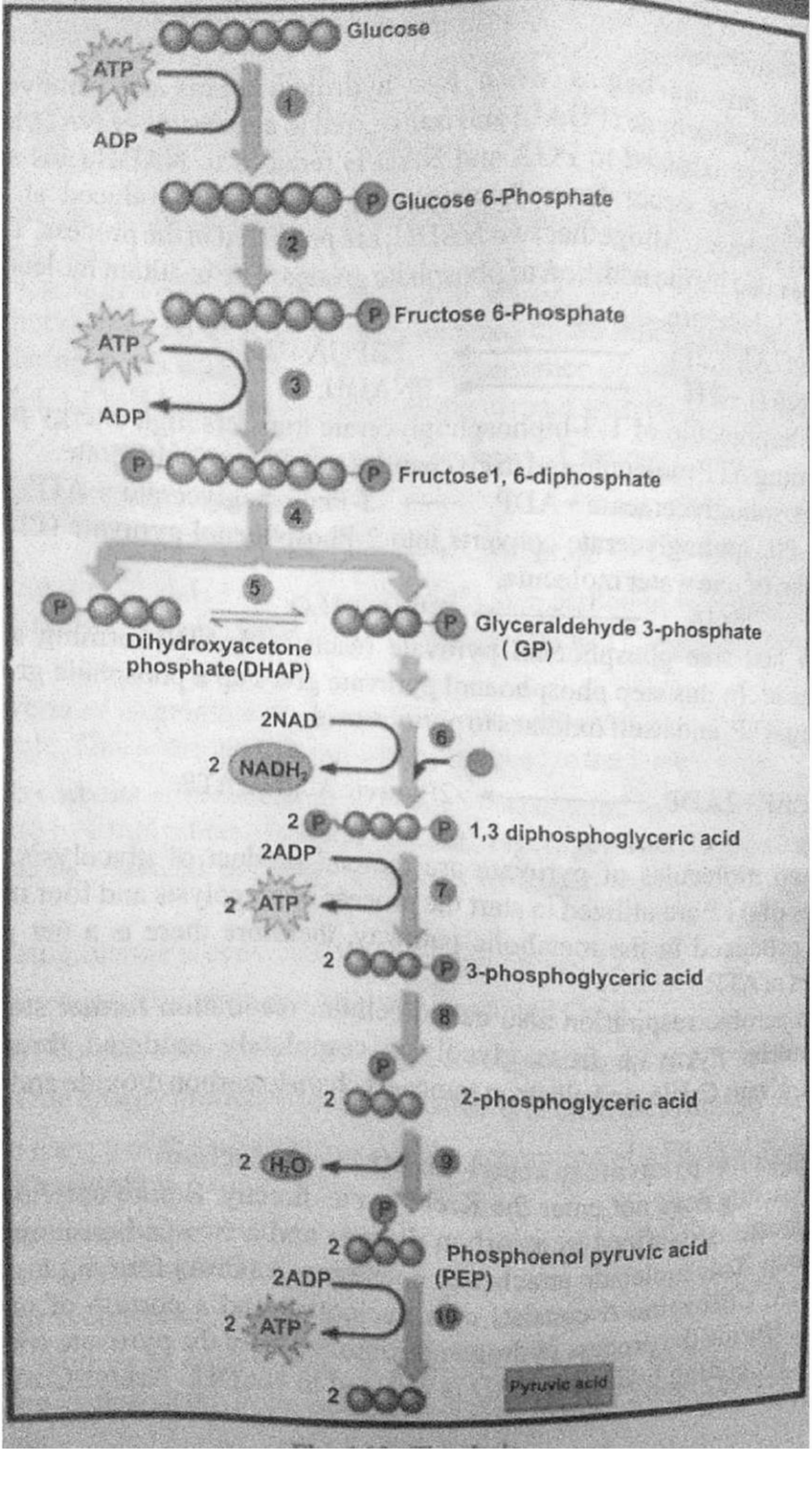
Glucose-6 Phosphate ⟶ Fructose-6 Phosphate.

Fructose-6 Phosphate+ ATP ⟶ Fructose-1-6 bishosphate+ ADP.

- Fructose-1-6-bishosphate splits into 3-carbon Phosphoglyceraldehyde (PGAL) and dihydroxy acetone phosphate (DAP).

- Dihydroxy acetone phosphate changes to phosphoglyceryldehyde.

Preparatory phase completes with the splitting of fructose biphosphate into PGAL and dihydroxyacetone phosphate.



Glucose
ATP
1
ADP
P Glucose 6-Phosphate
2
P Fructose 6-Phosphate
ATP
3
ADP
P
P Fructose1, 6-diphosphate
4
5
P
Dihydroxyacetone
phosphate(DHAP)
P Glyceraldehyde 3-phosphate
(GP)
2NAD
2 NADH2
6
2 P
P 1,3 diphosphoglyceric acid
2ADP
2 ATP
7
2
P 3-phosphoglyceric acid
8
P
2
2-phosphoglyceric acid
2 H2O
9
P
2
Phosphoenol pyruvic acid
(PEP)
2ADP
2 ATP
10
2
Pyruvic acid

ii. Oxidative Phase

- The process begins when two hydrogen atoms are removed from 3-Phosphoglyceraldehyde (PGAL) and transferred to a molecule of NAD, a coenzyme. Thus PGAL is oxidized to PGA and NAD is reduced to $NADH_2$(this step and the subsequent steps occur twice because two PGAL are produced at the end of preparatory phase). Altogether two $NADH_2$ are produced in the process. This reaction is accompanied by the addition of phosphate groups. The resultant molecules are 1-3-bisphosphoglycerate.

$$2PGAL + 2Pi \longrightarrow 2BPGA + 2H_2$$
$$2NAD + 2H_2 \longrightarrow 2NADH_2$$

- Each molecule of 1-3-biphosphoglycerate transfers high energy phosphate to ADP forming ATP molecule and itself changes to 3-Phosphoglycerate.

1-3 bisphosphoglyceracate + ADP $\longrightarrow$ 3-Phosphoglycerate + ATP

- 3-Phosphhoglycerate converts into 2-Phosphoenol pyruvate (PEP) with the elimination of one water molecule.

$$2PGA \longrightarrow 2PEP + 2H_2O$$

- In last step phosphoenol pyruvate reacts with ADP forming an ATP and Pyruvic acid .In this step phosphoenol pyruvate gives up a phosphate group to ADP generating ATP and itself oxidizes to pyruvic acid.

$$2PEP + 2ADP \longrightarrow 2\text{Pyruvic Acid} + 2\,ATP.$$

- Two molecules of pyruvate are the end product of glycolysis. Since two molecules of ATP are utilized to start the process of glycolysis and four molecules of ATP are produced in the metabolic pathway, therefore there is a net gain of two molecules of ATP.

In aerobic respiration also called cellular respiration further steps occur in mitochondria. Pyruvate from glycolysis completely oxidized through linked reactions, Krebs Cycle, and electron transport chain to carbon dioxide and water.

b Conversion of pyruvate to acetyl-CoA (Linked reaction)

Pyruvate does not enter the Krebs cycle directly. Before entering the Krebs cycle pyruvate is oxidized to a carbon dioxide and a two carbon molecule called acetyl group. This molecule attaches to coenzyme A (CoA) forming a group called acetyl CoA. Coenzyme A consists of a nucleotide and a portion of one of the B vitamins. During the process hydrogen is removed from the pyruvate which is taken by NAD. By getting hydrogen NAD is reduced to $NADH_2$. Acetyl-CoA enters the Krebs cycle.

This process is called linked reaction because it links Glycolysis to the Krebs cycle.

Pyruvic Acid $\longrightarrow$ Acetyl group + CO_2 + 2H

Acetyl group + CoA $\longrightarrow$ Acetyl CoA

NAD + 2H $\longrightarrow$ $NADH_2$

Further oxidation of acetyl - CoA takes place in a cyclic manner. This cycle is called Krebs cycle.

c. **Kreb's Cycle or Tricarboxylic Acid Cycle (TCA)**

- In first step of cycle, Acetyl CoA produced in the linked reaction combines with pre existing oxalo acetic acid (4-C) in the presence of water molecule to form citric acid (6-C). Co-A becomes free and is ready to react with another acetyl group.

Acetyl Co.A + oxaloacetate $\longrightarrow$ Citrate + Co.A.

- Citrate is converted to isocitrate

Citrate $\longrightarrow$ Isocitrate

- Iso-citrate is oxidized to -ketoglutarate (5-C). one carbon of isocitrate is oxidized to carbon dioxide and hydrogen is removed which is picked up by NAD reducing into $NADH_2$.
- One carbon of -Ketoglutarate is oxidized into carbon dioxide which is released from the cycle. This is second CO_2 molecule produced in the Krebs cycle.
- The two carbons of the acetyl group which was entered into the Krebs cycle are oxidized into two molecules of carbon dioxide. Hydrogen atoms are released which are accepted by oxidized NAD. By accepting hydrogen atoms NAD is reduced to $NADH_2$.
- The - Ketoglutarate is converted into succinyl group (4-C).
- Co-A reacts with succinyl group forming succinyl Co-A.
- Succinyl Co-A is converted to succinate Acid (4-C) and Co-A is released.
- Some of the energy produced in the oxidation is used in the synthesis of ATP.

The energy of the substrate used in the generation of ATP is called **substrate-level phosphorylation.**

- Succinate is oxidized to fumarate (4-C). Co-enzyme FAD (flavin adenine di-nucleotide) is reduced in the reaction.
- Fumarate is converted to malate (4-C).
- Malate oxidizes to oxaloacetate. A molecule of NADH is produced during this step. The oxaloacetate is now able to react with another acetyl Co-A and continue the cycle.

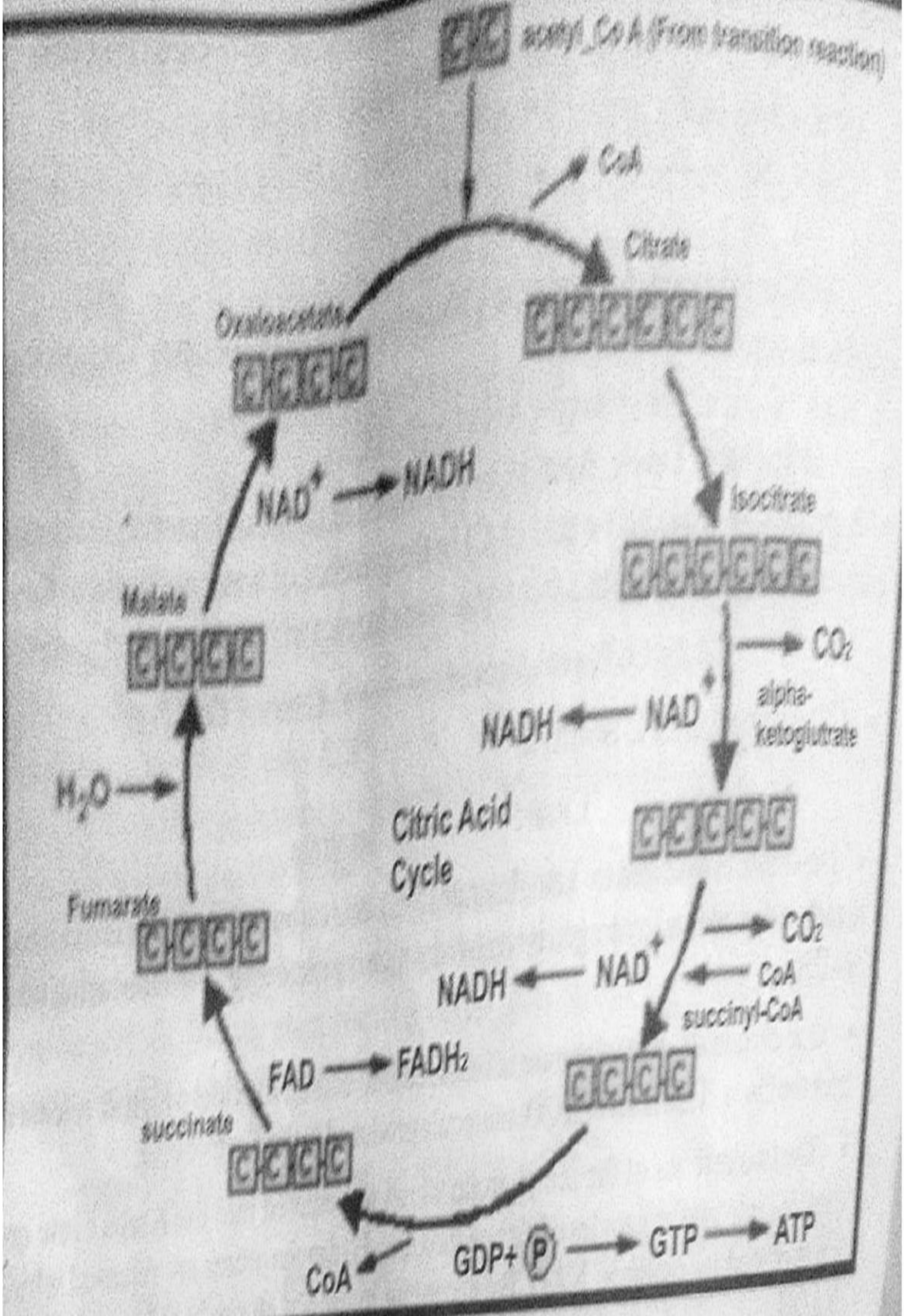


Fig: 4.11 Kreb's cycle.

Respiratory Electron transport Chain

The last step in aerobic respiration is the oxidation of reduced coenzymes DH, and FADH, produced in glycolysis and Krebs cycle by molecular oxygen. pairs of hydrogen atoms released from glucose during glycolysis and Krebs le of aerobic respiration are not received directly by oxygen but pass along a es of electron carriers called coenzymes and cytochromes. This series of electron iers constitute respiratory electron transport chain. The final electron acceptor at end of the electron transport chain is oxygen forming water. Various molecules olved in the electron transport are $NADH_2$, $FADH_2$ coenzyme Q, cytochrome b t.b), cytochrome c (Cyt.c), cytochrome a (Cyt.a) and Cytochrome a_3 (Cyt.a_3). coenzyme Q and cytochromes are alternately reduced and oxidized. ctrons are passed along a series of carriers as they lose energy at each transfer. ne of this energy is used in the formation of ATP from ADP and inorganic sphate. In the electron transport chain each next molecule is at lower energy level the previous one. At the end oxygen accepts electrons and hydrogen to form er.

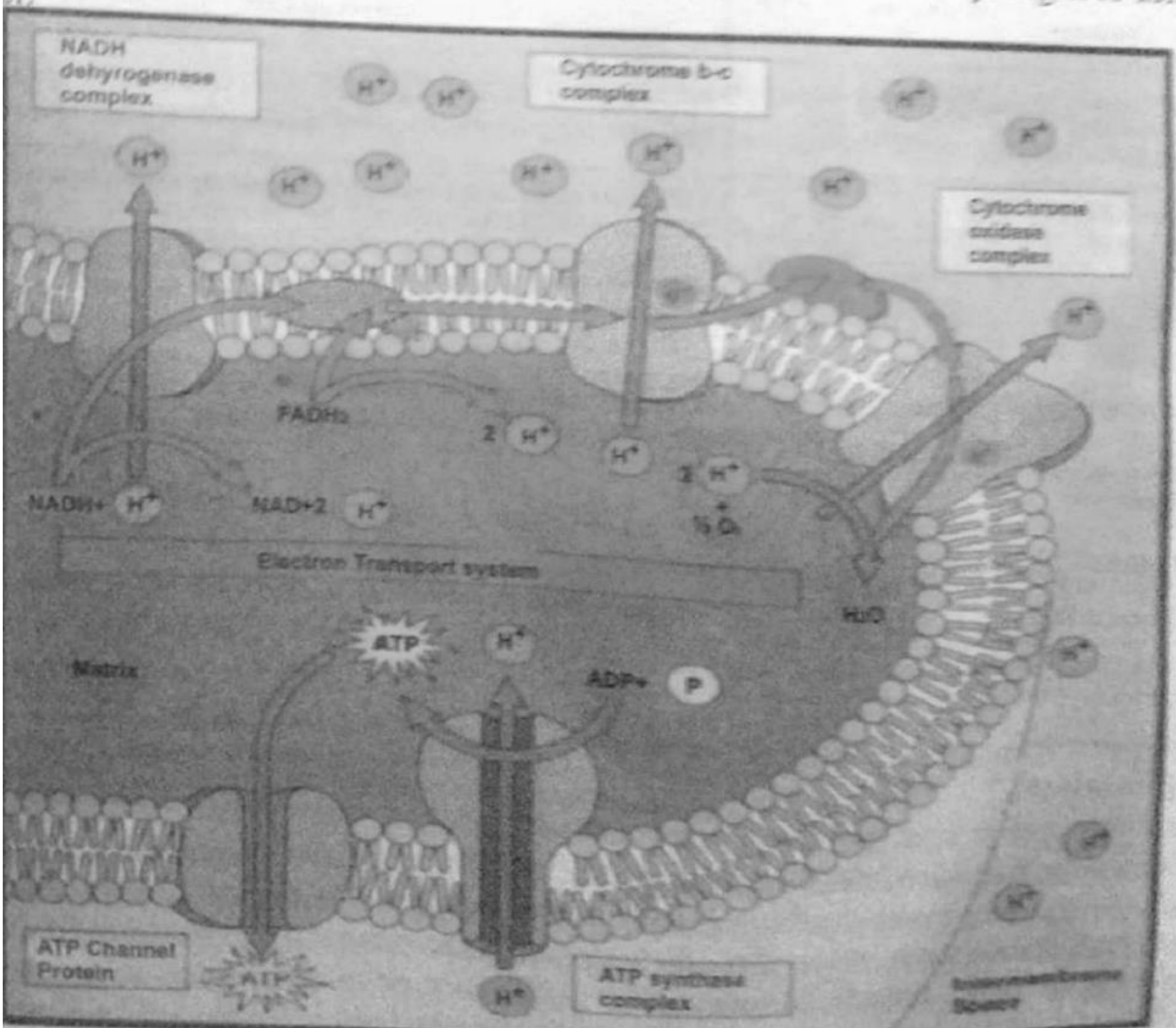


Fig: 4.12 Electron transport Chain

Chemiosmotic ATP Synthesis

The synthesis of ATP from ADP and inorganic phosphate in the electron transport system through the joint event of chemical and osmotic processes is called chemiosmotic ATP synthesis. Chemiosmotic theory of ATP synthesis suggests how ATP formation is coupled with the energy release in the electron transport system. Mitochondria are surrounded by double membrane. The outer membrane is smooth while the inner membrane forms enfolding which are shelf-like projections or protuberances called cristae. The cristae are present in the inner chamber or mitochondrial matrix that is filled with a gel-like substance. The carriers of electron transport system are present on the cristae. A space is present between the outer and inner membrane called intermembrane space.

Table No: 4.1Production of ATPs in respiratory chemical pathways.

Pathway	Coenzyme yield	ATP yield	Source of ATP
Glycolysis preparatory phase		-2	To begin glycolysis requires the input of two ATP from the cytoplasm. This is the activation energy needed to start this reaction.
Glycolysis pay-off phase		4	ATPs made by glycolysis. Note the Net Yield for glycolysis would be 2ATPs (4 ATP-2ATP).
	2 NADH (Ext)	4 (6)	These molecules are created by glycolysis, but they can only be converted into ATP in the mitochondrial electron transport chain. This requires them to enter the mitochondria. A step that is free in some organisms, and costs 2ATP in others. This is what causes the differences in the Net yield of aerobic respiration
Pyruvate Oxidation	2 NADH (Int)	6	ETC (Electron Transport chain)
Krebs cycle		2	Substrate-level phosphorylation
	6 NADH	18	ETC
	2 $FADH_2$	4	ETC
Total yield		36 (38) ATP	From the complete breakdown of one glucose molecule to carbon dioxide and oxidation of all the high energy molecules.

During the passage of electrons through the electron transport system certain carriers of the system pump hydrogen ions from the mitochondrial matrix into the intermembrane space. As result hydrogen ions accumulate on the outside of the inner membrane in the intermembrane space. Difference of hydrogen ion concentration increases across the membrane which develops a gradient of hydrogen ions between the matrix and the intermembrane space i.e. across the inner membrane.

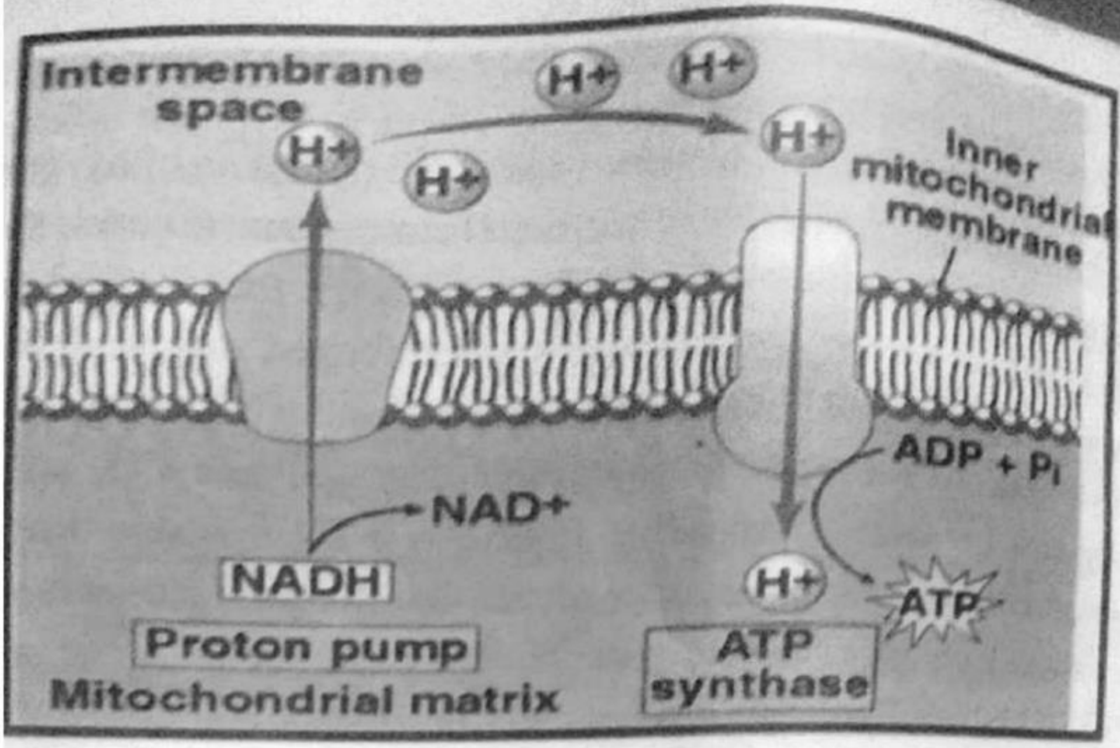


Fig : 4.13 Chemiosmotic ATP synthesis

ions diffuse down the inner membrane through electrochemical gradient ermembrane space into the matrix. The passage of hydrogen ions through ane is coupled to ATP synthesis from ADP and inorganic phosphate TP synthase complex. This process of ATP synthesis is called sis because electrochemical and osmotic events are involved.

spiration of Proteins and Fats

s degrade mostly glucose to release energy. However cells can oxidize other food molecules such as proteins and fats to release energy.

n and Glucose Metabolism

eins are broken down to amino acids. Amino group is removed from forming ammonia and the remaining molecule enters the Krebs cycle. o the Krebs cycle depends on the number of carbon atoms of the entering

n fat is used as energy source it is hydrolyzed into glycerol and three Glycerol (a 3-C compound) is converted to PGAL which enters the spiration into the glycolytic pathway. Each fatty acid is degraded into fragments acetyl groups which enter into Krebs cycle. For example d is a fatty acid with 16 carbon atoms. It breaks down into eight acetyl estimated that these eight acetyl groups would generate net 129 ATP ecause of very large number of production of ATP molecules fats are ery efficient form of stored energy.

4.3.2 Anaerobic Respiration

The incomplete breakdown of glucose without the utilization of oxygen is called anaerobic respiration. Anaerobic respiration (Fermentation) occurs in the absence of oxygen. It involves incomplete breakdown of organic food molecule and only a small amount of energy is released. Pyruvate formed in glycolysis has two pathways. In human cells it depends on the availability of oxygen. If oxygen is available then pyruvic acids is completely degraded into CO_2 and water in mitochondria i.e. aerobic respiration. If oxygen is not available then anaerobic respiration continues and fermentation occurs. The process of fermentation consists of two steps i.e. glycolysis and the reduction of pyruvate into alcohol or to lactate. Anaerobic respiration is of two types.

a. Lactic Acid Fermentation

This form of fermentation occurs in muscle cells of human and in many microorganisms. It completes in two steps. In the first step glucose is broken down into pyruvic acid which is basically glycolysis. In the next step pyruvic acid is reduced by $NADH_2$ into lactic acid. Compared to aerobic respiration which yields 36 ATP molecules from the breakdown of one glucose, anaerobic respiration yields only 2 ATP molecules. Despite its low yield of ATP, anaerobic respiration has its importance because of rapid production of ATP (energy) when demanded.

A) $\text{Glucose} + 2\text{ATP} \longrightarrow \text{Pyruvic acid} + 4\text{ATP}$

B) $$\underset{\text{Pyruvic Acid}}{2(C_3H_4O_3)} \xrightarrow{\text{2NADH} \;\; \text{2NAD}} \underset{\text{Lactic Acid}}{2(C_3H_6O_3)}$$

b. Alcoholic Fermentation

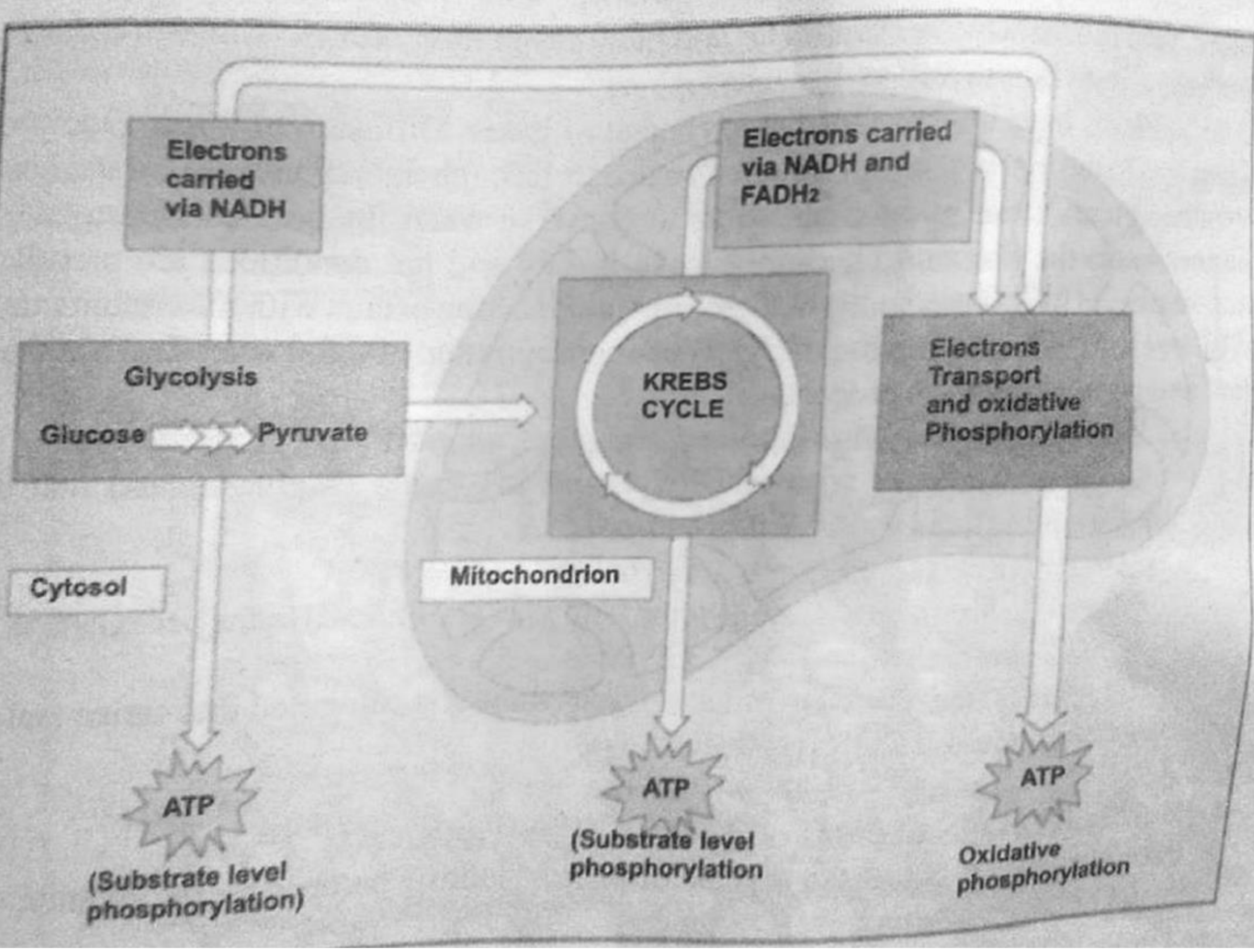
Alcoholic Fermentation is brought about by microorganisms.

This type of anaerobic respiration also completes in two steps.

First step is the same glycolysis during which glucose molecule is broken down into two molecules of pyruvic acid and NAD is reduced to $NADH_2$.

In the next step $NADH_2$ gives hydrogen to pyruvic acid, which is converted into ethyl alcohol and CO_2. In alcoholic fermentation also 2 ATP molecules are produced from one glucose molecule. This is called alcoholic fermentation because alcohol is produced at the end.

$$\underset{\text{Pyruvic Acid}}{(C_3H_4O_3)} \xrightarrow{2CO_2} \underset{\text{Acetaldehyde}}{2(C_2H_4O)} \xrightarrow[2NADH \;\rightarrow\; 2NAD]{} \underset{\text{Ethyl Alcohol}}{2\,(C_2H_5OH) + ATP}$$



Photosynthesis needs optimum concentration of the requirements for normal functioning. If however one of the requirement is present in less concentration than the optimum, the process of photosynthesis is affected and slows down.

In the Dark reaction of photosynthesis, normally CO_2 combines with RuBP (carboxylation) forming PGA molecules. The process occurs in the presence of an enzyme called ribulose biphosphate carboxylase (rubisco). This enzyme can act both as carboxylase and oxygenase. The reaction depends on the concentration of CO_2 and O_2. If the concentration of CO_2 is more, then rubisco combines with CO_2 and photosynthesis proceeds normally. On the other hand if the concentration of O_2 is more, then rubisco combines with O_2 and photorespiration occurs. (Rubisco can act both as carboxylase as well as oxygenase).

Plants have stomata for the exchange of gases. Diffusion of water vapours from leaf to the external environment also occurs through the stomata. In dry and hot weather plants close up stomata so as to conserve water. In such condition CO_2 cannot enter the leaf and O_2 cannot leave it. Dry and hot conditions are usually accompanied by intense sunlight therefore light reaction occurs with maximum rate which results in maximum use of CO_2 Since concentration of CO_2 lowers down in the leaf and photorespiration proceeds.

The following steps are involved in photorespiration:

1. Oxygen combines with RuBP (present in stroma of chloroplast) and a compound called Glycolate is produced.

$$\text{RuBP} + O_2 \longrightarrow \text{Glycolate}$$

2. Glycolate is converted into glycine (simplest amino acid) in the peroxisome.

$$\text{Glycolate} \longrightarrow \text{Glysine}$$

3. Glycine is transported to mitochondria where it is converted into serine and a molecule of CO_2 is produced.

$$\text{Glysine} \longrightarrow \text{Serine} + Co_2$$

4.4.1 Disadvantages of Photorespiration (Consequences)

1. Photorespiration is just the reverse of photosynthesis hampering the fixation of CO_2photosynthesis.
2. The process wastes energy and does nothing to serve the needs of the plant.

4.5 C_4Photosynthesis

In normal process of photosynthesis a 3C carbon compound called PGA is formed as the first detected product of photosynthesis (carbon dioxide fixation) and therefore these plants are called C_3 plants. There are some plants growing in dry and hot conditions produce a 4C carbon compound called oxaloacetate as the first product of carbon dioxide fixation in dark reactions of photosynthesis.

These plants are called C_4 plants and this type of photosynthesis is called C_4 photosynthesis. C_3 plants use rubisco to react CO_2 with RuBP. On the other hand C_4 plants use another enzyme called pepco (phosphoenolpyruvate carboxylase) to fix CO_2 to a compound called phosphoenolpyruvate (PEP) and oxaloacetic acid (OAA). This OAA is reduced to another molecule called malate. The malate carries CO_2 to the special type of cells called bundle sheath cells where Calvin cycle proceeds.

In C_3 plants chloroplasts are present only in mesophyll cells of leaf. However in a C_4 plant chloroplasts are present both in mesophyll cells and in bundle sheath cell. In a C_3 plant all the mesophyll cells carry out Calvin cycle by fixing CO_2 and producing glucose. In a C_4 plant the mesophyll cells only fix CO_2 by using pepco while the bundle sheath cells carry out Calvin cycle producing glucose.

This is a special condition evolved by C_4 plants so as to prevent photorespiration even in dry and hot environment as pepco does not bind to O_2 irrespective of the concentration of CO_2. Examples of C_4 plants are sugar cane, maize etc.

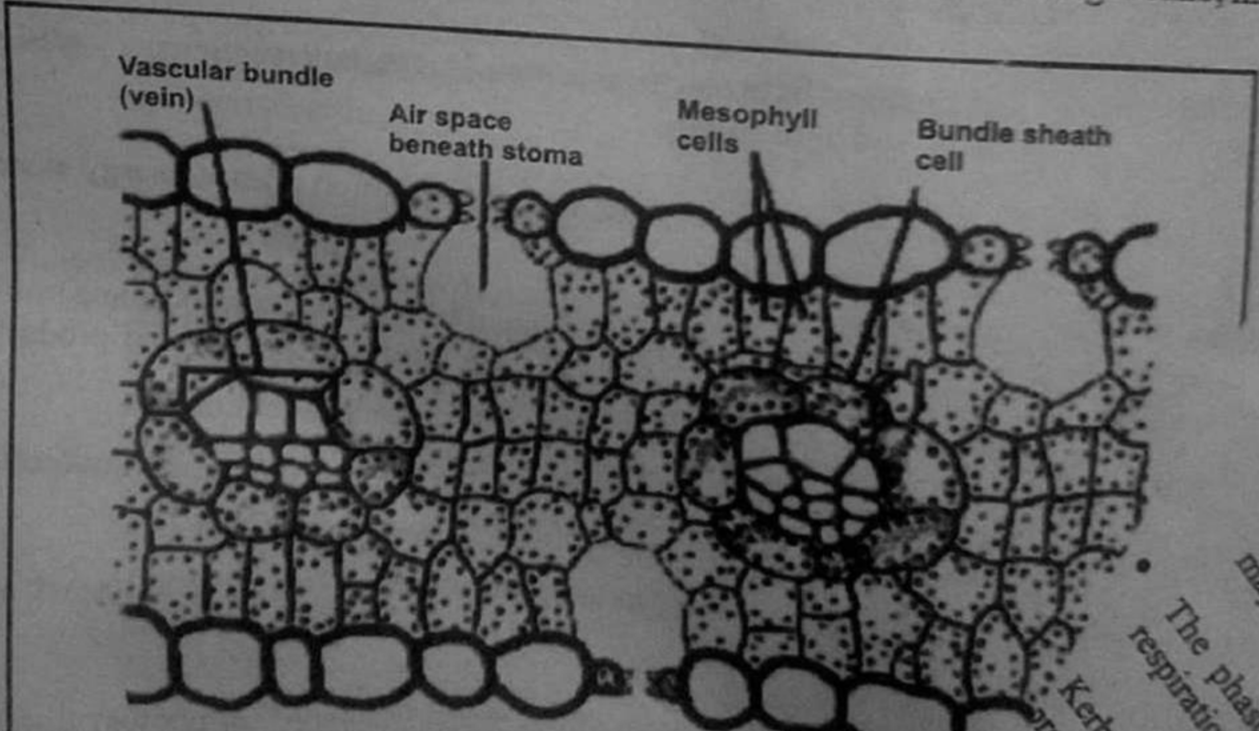


Fig: 4.15 Portion of a cross section of a leaf with C_4 photo

In C_4 plants the rate of photosynthesis remains high
are closed and temperature is high. The rate of CO_2 fixation
to C_3 plants. C_4 cycle is basically an adoptability of C_4 plan
in dry and hot condition and to reduce the rate of photores

KEY POINTS

- Bioenergetics is the study of those processes by means of which living organisms store, use and release energy.
- Photosynthesis is a process in which the green plants convert light energy into chemical form.
- The organic molecules of food are broken down and their energy isreleased in the process ofrespiration.
- ATP is a key molecule of biological world which, is the main source ofenergy.
- Photosynthesis has two sets of reactions. During light reactions ATP and $NADH_2$ are produced, as end products and these reactions need sunlight.

ducts of light reactions are used in the dark reactions, which
ed light energy.

ctive reactions of respiration release energy stored

anaerobic (fermentation).In anaerobic
are produced and its end products
CO_2.

aerobic and anaerobic

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of photosynthesis,
a place of CO_2 and
ary days when stomata
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EXERCISE

A. Choose the correct answer to the following questions.

1. The ultimate source of energy for maintenance of life on earth is:
   a. carbohydrate
   b. ATP
   c. sun
   d. mitochondria
2. In which compartment of the plant cell do the light-independent reactions of photosynthesis take place?
   a. Thylakoid
   b. Stroma
   c. Outer membrane
   d. Mesophyll
3. What would happen if the process of photosynthesis stops on earth?
   a. There will be more food
   b. No problem to living organisms
   c. No life on earth possible
   d. Living organisms will start using direct energy from sun
4. Identify in the following which is not a limiting factor for photosynthesis.
   a. light intensity
   b. temperature
   c. concentration of carbon dioxide.
   d. concentration of oxygen
5. Which of the following molecule is regenerated from phosphoglyceraldehyde in Calvin cycle?
   a. Phosphoglyceric acid
   b. Plastoquinone
   c. Ribulose biphosphate
   d. CO_2
6. The end products of non-cyclic electron pathway is:
   a. ATP
   b. $NADPH_2$
   c. ATP and $NADPH_2$
   d. $FADH_2$
7. The final electron acceptor in non-cyclic electron pathway is:
   a. ATP
   b. NADP
   c. $FADH_2$
   d. ADP
8. ATP generated within the Krebs cycle is called:
   a. photophosphorylation
   b. oxidative phosphorylation
   c. substrate-level phosphorylation
   d. electron transport chain
9. The electron carriers of chloroplast are present in:
   a. matrix of stroma
   b. inter-membrane space
   c. within the thylakoid space
   d. within its thylakoid

EXERCISE

10. In a eukaryotic cell the Krebs cycle occurs in:
   a. cytosol
   b. nucleus
   c. chloroplast
   d. mitochondria
11. Within the mitochondria the proton gradient develops across the:
   a. outer membrane
   b. inner membrane
   c. matrix
   d. inter membrane space
12. Which of the following generates more energy in aerobic respiration?
   a. Glucose
   b. Triglyceride
   c. Protein
   d. Sucrose
13. Phosphoenol pyruvate carboxylase is used in C4 Plants to :
   a. Fix CO_2
   b. Fix O_2
   c. Reduce RuBP
   d. Reduce pyruvate molecule

B. Write short answers to the following questions

1. Define glycolysis.
2. What is photorespiration?
3. What do you mean by chemiomosis?
4. State the role of carbondioxide as one of the raw materials of photosynthesis.
5. Differentiate between the absorption spectra of different photosynthetic pigments.
6. What is the main difference between cyclic and non cyclic photo

C. Write in detail the answers of the following questions.

1. Describe the role of sunlight in the process of photosynthesis.
2. Give an account of the events of non-cyclic electron pathway.
3. Write down the main steps of Calvin cycle.
4. Write a detailed note on the various steps of Kreb's cycle.
5. What is photorespiration and what are its disadvantages?

Projects:

- Develop the graphical interpretation of the wavelengths of light along with the percentage absorption by chlorophyll 'a' and 'b'.
- Develop a flow chart for explaining the events of the light-independent reactions.
- Draw the flow charts showing the events of glycolysis and Krebs cycle.
- Illustrate the net energy output during glycolysis, oxidation of pyruvate and Krebs cycle.