4

BIOENERGETICS

After completing this lesson, you 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).
- Draw the molecular structure of chlorophyll, showing the porphyrin head and the phytol tail.
- Draw the Z-scheme for explaining the events of the light-dependent reactions.
- Extract the leaf pigments and separate them by paper chromatography.
- 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 G3P in photosynthesis and respiration.
- Outline the cellular respiration of proteins and fats and correlate these with that of glucose.
- 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.
- 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 C_4 photosynthesis as an adaptation evolved in some plants to deal with the problem of photorespiration.

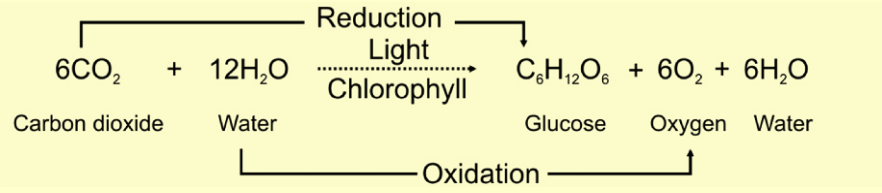
Living things cannot grow, reproduce, or exhibit any of the characteristics of life without a ready supply of energy. All metabolic reactions involve energy transformations. So the quantitative study of energy relationships in biological system is called **bioenergetics.** Biological energy transformations obey the laws of thermodynamics. You have got an introduction about bioenergetics in IX-X biology course.

This chapter deals with the most fundamental bioenergetics processes i.e., photosynthesis and respiration. You already have the general concept of these processes. The detailed learning would foster the skills of analysis and evaluation. This chapter also develops the basic concepts of photorespiration, the process that reduces plants productivity.

4.1 PHOTOSYNTHESIS

Chemically photosynthesis is a "redox" process in which CO_2 (an oxidized form of carbon) is reduced into glucose (a reduced form of carbon). Water acts as reducing agent which is oxidized into oxygen during this process. Bio-energetically photosynthesis can be defined as an energy conversion process in which energy poor molecules i.e., CO_2 and H_2O are transformed into energy rich molecule such as glucose. The extra energy is absorbed in the form of sunlight by the photosynthetic pigments.

The overall reaction of photosynthesis can be summarized as follows:



This process involves the interaction of sunlight, pigments, water and carbon dioxide.

4.1.1 Role of Light

Sunlight is an electromagnetic form of energy. The full range of electromagnetic radiation in the universe is called **electromagnetic spectrum.** Visible light is only a small part of the spectrum between 380ηm to 750ηm which is not only seen by naked eye but is also effective for the process of photosynthesis.

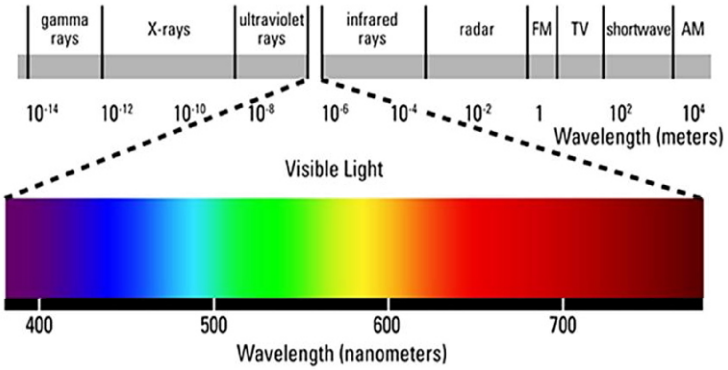


Fig. 4.1 Electromagnetic spectrum

The effectiveness of a particular wavelength of light for the process of photosynthesis primarily depends upon its absorption in plant body. As different wavelengths (colours) of visible light are differently absorbed by various photosynthetic pigments, therefore, each wavelength has its own effectiveness for the process of photosynthesis. If a plant is illuminated in different colours of light one by one, the rate of photosynthesis is measured and the data obtained in this

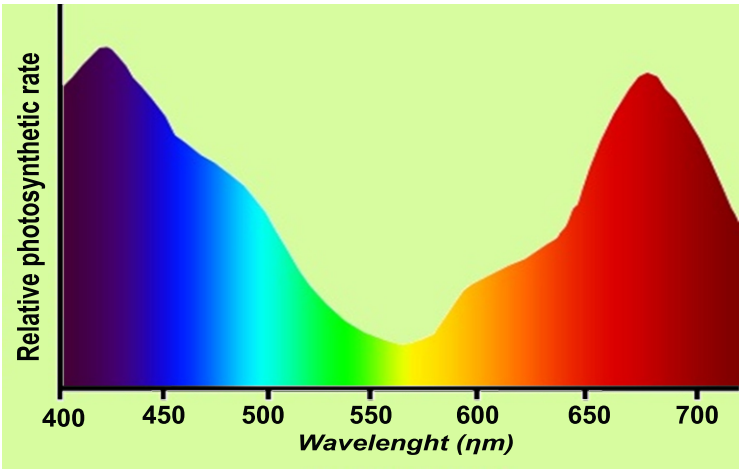


Fig. 4.2 Action spectrum of photosynthesis

way is plotted in a graph, you will see that the rate of photosynthesis will be variable in different colours of light. Such a graph which shows the effectiveness of different wavelength of light for the process of photosynthesis is called **action spectrum**. Analysis of action spectrum indicates that blue (430ηm) and red (670ηm) wavelengths of light are the most effective for the process of photosynthesis.

4.1.2 Role of Photosynthetic Pigments

Pigment is any substance that absorbs light energy. All the wavelengths which are absorbed by a pigment are disappeared. A particular pigment shows only those wavelengths which are reflected back. All the pigments that take part in photosynthesis are embedded in thylakoid membranes (grana lamellae) within chloroplasts. Higher plants have two major group of pigments i.e., chlorophyll and carotenoids.

Science Titbits

The rate of photosynthesis is directly proportional to the CO_2 consumed or O_2 released therefore; it can be measured by measuring the amount of CO_2 consumed or by measuring the amount of O_2 released during the process in a specific time.

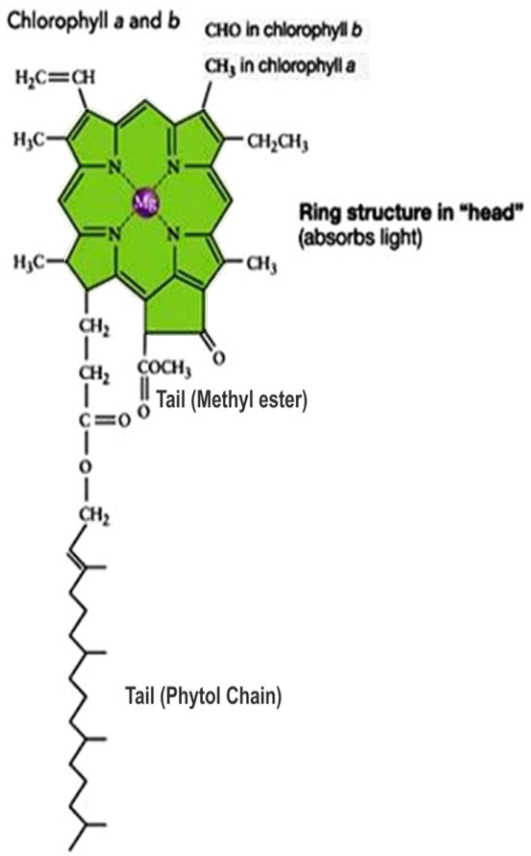


Fig 4.3: Structure of chlorophyll

Chlorophyll

Chlorophylls absorb mainly violet, blue, orange and red wavelengths. Green and yellow are least absorbed and reflected. Two major types of chlorophyll are Chlorophyll-a and Chlorophyll-b. Chlorophyll-a is a bluish green pigment which is found in all photosynthetic organisms except photosynthetic bacteria. Chlorophyll-b is yellowish green pigment which is also found in all photosynthetic organisms except brown, red algae and photosynthetic bacteria. Algae also have some other form of chlorophylls i.e., Chl-c, Chl-d and Chl-e while photosynthetic bacteria have yet another type of chlorophyll i.e., bacteriochlorophyll.

Molecular formula of chlorophyll a and b:

Chlorophyll a = $C_{55}\ H_{72}\ O_5\ N_4\ Mg$

Chlorophyll b = $C_{55}\ H_{70}\ O_6\ N_4\ Mg$

A molecule of chlorophyll consists of a head and two tails. The head is composed of a **porphyrin ring** with Mg in the centre. The porphyrin ring further consists of four pyrrole rings (each pyrrole ring contains four carbons and one nitrogen atom). The nitrogen atoms of **pyrrole rings** interact with central Mg atom. The pyrrole rings also contain different groups around them. The only difference between chlorophyll-a and chlorophyll-b is that chlorophyll-a has methyl group (-CH_3) on 2nd pyrrole ring whereas, chlorophyll-b has

aldehyde group (-CHO) at this point. The head of chlorophyll is hydrophilic in nature. It is exposed on the surface of thylakoid membrane. It is light absorbing part of chlorophyll.

The two side chains in the chlorophyll molecule are called tails. Side chains are phytol and methyl ester **The chlorophyll tails** are hydrophobic in nature. They are embedded into the thylakoid membranes and serve to anchor the chlorophyll molecule in the membrane.

Carotenoids

Carotenoids are terpenoid lipids, which are yellow, orange, red or brown pigments. They absorb light strongly in the blue-violet range. They are seen in leaves before leaf fall, present in some flowers and fruits. The carotenoids act as accessory pigment along with chlorophyll-b as they absorb light energy and then transfer it to the chlorophyll-a. Therefore, they protect the chlorophyll-'a' from excess of light. They also attract insects, birds and other animals for pollination and dispersal.

There are two types of carotenoids: carotenes and xanthophylls. The **carotenes** are orange red pigments, composed of isoprenoid units and are found in all photosynthetic eukaryotes. The most widespread and important carotene is β (beta) carotene. **Xanthophylls** are yellow in colour and are also composed of isoprenoid units. Lutein is widely distributed xanthophylls which is responsible for yellow colour of foliage in autumn.

4.1.3 Absorption Spectrum

The absorption of different colours of light by a particular pigment can be determined by the help of spectrophotometer. The data of spectrophotometer is represented by a graph. Such a graph which shows the absorption of different colours of light by a particular pigment is called **absorption spectrum** of the pigment.

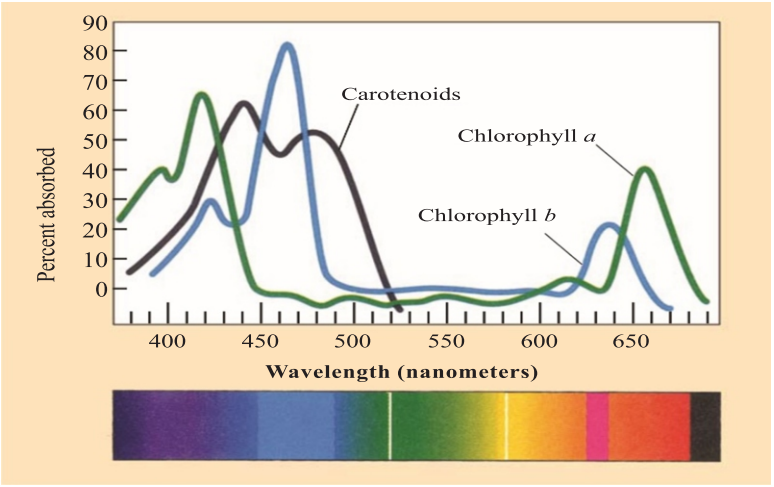


Fig: 4.4: Absorption spectra of different pigments

The absorption spectra of different pigments indicate that they absorb different wavelengths of visible light and these wavelengths are not absorbed at the same rate. The main photoreceptors are chlorophyll a and b and both show more absorption in violet blue (400ηm to 470ηm) and orange-red (630ηm to 660ηm) regions of the visible spectrum. On the other hand carotenoids show more absorption at 430ηm to 500ηm.

4.1.4 Arrangements of Pigments (Photosystems)

For efficient absorption and utilization of light energy, the photosynthetic pigments are arranged in the form of clusters in thylakoid membranes. These clusters are called **photosystems.** The peripheral part of photosystem is called **antenna complex** which

consists of accessary pigments such as chlorophyll-b and carotenoids. The central part of photosystem is called **reaction centre** which contains only chlorophyll-a and associated proteins. Since chlorophyll-a generally has an optimal absorption wavelength of 660ηm, it associates with different proteins in each type of photosystem to slightly shift its optimal wavelength, producing two distinct photosystem types i.e., photosystem-I (PS-I) and photosystem-II (PS-II). The chlorophyll-a in the reaction centre of PS-I can absorb maximum 700ηm wavelength of light, hence called P700. Similarly, the chlorophyll-a in the reaction centre of PS-II can absorb maximum 680ηm wavelength of light, hence called P680. The photosystems are named for the order in which they were discovered and not for the order in which they occur in the thylakoid membrane.

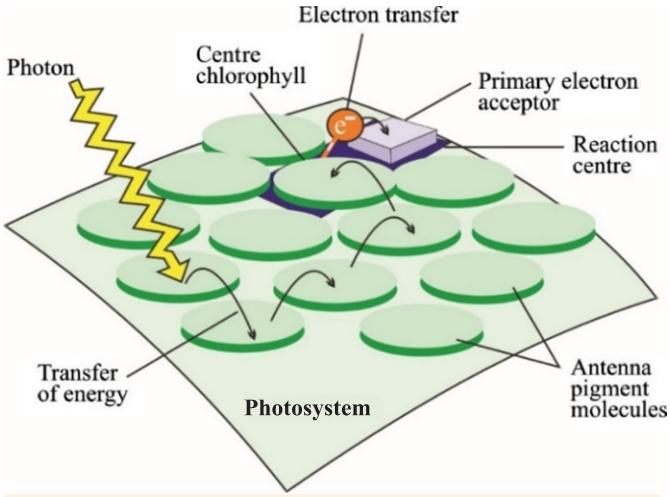


Fig: 4.5: Structure of photosystem

As chlorophyll-a can only absorb light of a narrow wavelength, it works with the pigments of antenna complex to gain energy from a larger part of the spectrum. The pigments absorb light of various wavelengths and pass along their gained energy to chlorophyll-a of the reaction centre. When the energy reaches the chlorophyll-a its electrons become so excited that they escape and move to a nearby electron transport chain. In this way chlorophyll molecule becomes oxidized.

$$\text{chlorophyll (reduced form)} \xrightarrow{\text{light energy}} \text{chlorophyll (oxidized form)} + e^- \text{ electron}$$

The electron transport system plays an important role in generation of ATP by the conversion of light energy into chemical energy.

4.1.5 Role of Carbon Dioxide in Photosynthesis

Carbon dioxide acts as carbon source for the synthesis of organic compounds in photosynthesis. Plants are therefore known as autotrophs because they use inorganic compounds for the synthesis of their organic compounds. Carbon dioxide is utilized in the dark or light independent reaction (Calvin cycle) of photosynthesis. Air contains about 0.03 to 0.04 percent of carbon dioxide. Land plants use this atmospheric carbon dioxide for photosynthesis. Dissolved carbon dioxide, bicarbonates and carbonates are present in water, which are used by aquatic photosynthetic organisms as carbon source.

4.1.6 Role of Water in Photosynthesis

Water is one of the raw materials for photosynthesis. Water acts as hydrogen and electron donor in photosynthesis. It replaces the electron lost by the P680 during

photosynthesis. $2H^+$ ions are taken up the $NADP^+$ to form NADPH. The oxygen which is produced is released in atmosphere.

This role of water in photosynthesis was first reported by **Van Niel** in 1930. He hypothesized that plants split water as a source of hydrogen, releasing oxygen as a byproduct. This observation was based on investigations of photosynthesis in bacteria that make carbohydrates from carbon dioxide, but do not release oxygen.

Neil's hypothesis was confirmed in 1940, when for the first time ^{18}O in biological research was used. In first experiment water was made of ^{18}O. The water tagged ^{18}O was added to an alga suspension. The oxygen, evolved during photosynthesis, was found to be radioactive. It was separated and identified. In another experiment carbon dioxide with tagged ^{18}O was added. The oxygen evolved contained none of the isotopes. Thus the source of evolved oxygen was proved to be water. In the following summary, red denotes labelled atoms of Oxygen ^{18}O.

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

Carbon dioxide — Water — Glucose — Water — Oxygen

$$6C\mathbf{O_2} + 12H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} C_6H_{12}O_6 + 6\mathbf{H_2O} + 6O_2$$

Carbon dioxide — Water — Glucose — Water — Oxygen

4.1.7 Mechanism of photosynthesis

The process of photosynthesis has been divided into two phases. The first phase is called light dependent phase (light reaction) because it can take place only in the presence of light. The light-dependent phase occurs in the thylakoid membranes. In this phase light energy is used to make ATP (assimilating power) and NADPH (reducing power); whereas, water and oxygen are supposed to be input and output respectively. The second phase of photosynthesis is called the light independent phase (dark reaction) because it can take place whether light is present or not. This phase actually requires the products of light reaction i.e., ATP and NADPH. Since these products are available in day therefore, dark reaction also occurs in day time. In this phase CO_2 acts as input which is converted into glyceraldehyde-3-phosphate (G3P), the output of this phase. The ATP is hydrolyzed to

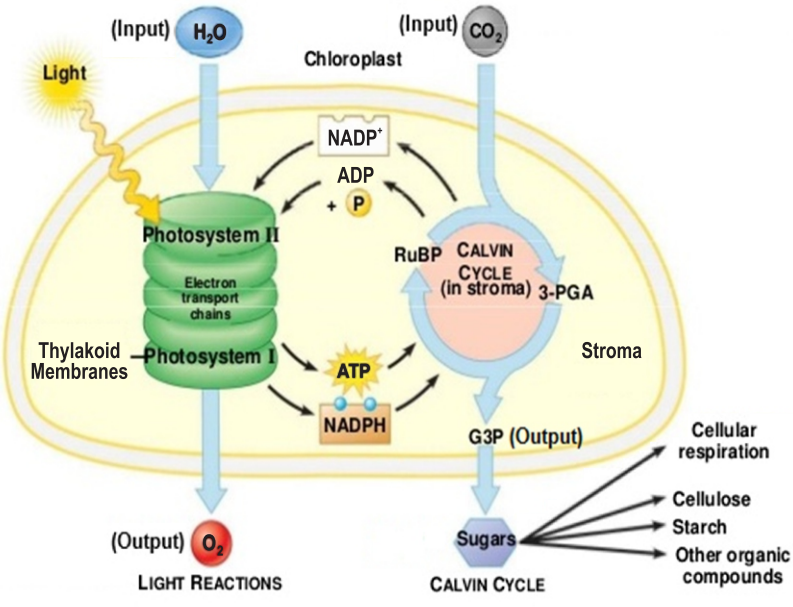


Fig: 4.6: An overview of photosynthesis

ADP and Pi (H_3PO_4) and its energy is incorporated in this phase; whereas, NADPH provides energized electron and hydrogen for the formation of G3P, which is an energy rich molecule.

4.1.8 Light Dependent Phase (Light Reaction)

Light dependent phase of photosynthesis involves the absorption of light by the photosystems, excitation and flow of electrons through an electron transport chain, chemiosmotic synthesis of ATP, and reduction of $NADP^+$ to NADPH. The flow of excited electrons through an electron transport chain during light reaction is of two different types i.e., non-cyclic and cyclic. In non-cyclic electron flow, the excited electrons after leaving a

$$ADP + Pi \longrightarrow ATP$$

particular photosystem do not comeback; these electrons after losing their energy are incorporated into another molecule. On the other hand, in cyclic electron flow, the excited electrons after leaving a particular photosystem finally comeback to their photosystem again. The most important event in light reaction is the production of ATP.

This production of ATP during light reaction is called **photophosphorylation** and the mechanism is called **chemiosmosis.** There are two types of photophosphorylation.

(a) Non-cyclic photophosphorylation

It is predominant pathway of light reaction in higher plants that occurs in routine. In this process both photosystems i.e., PS-I and PS-II are utilized and two electron transport chains are involved. When PS-II absorbs light, its excited electrons after flowing through an electron transport chain are transferred to PS-I. Similarly, the excited electrons which are liberated from PS-I are finally accepted by $NADP^+$. Therefore it is called non-cyclic electron flow. The events of non-cyclic photophosphorylation are continuous but here they are discussed in steps for convenience.

Absorption of light by PS-II and excitation of its electrons

When just two photons strike the antenna complex of PS-II, the two electrons become excited and begin to move along the atoms of different pigments within photosystem. Ultimately, the absorbed energy reaches the reaction centre of PS-II (P680) and causes its two electrons to be excited. These excited electrons are captured by the **primary electron acceptor** of PS-II and leave two "electron holes" in the photosystem behind making chlorophyll a strong oxidizing agent.

Photolysis of water

The electron holes of photosystem must be filled so that in the presence of water splitting enzyme reactions can proceed. When water reacts with oxidized state of chlorophyll in photosystem, it breaks up into $2H^+$ ions, $2e^-$ and $½O_2$. Since this breakdown occurs in the presence of sunlight therefore, it is termed as photolysis of water. The electrons released from water are used to fill the "electron holes" of PS-II.

$$H_2O \xrightarrow{\text{Photolysis of water}} 2H^+ + 2e^- + ½\ O_2$$

Electron flow from PS-II to PS-I

The excited/energized electrons which have been released from PS-II and captured by primary electron acceptor now begin to flow to PS-I through an electron transport chain. The electrons move from primary electron acceptor to the **plastoquinone (PQ)**. From PQ the electrons flow through a complex of the **cytochromes (Cyt)** which consist of **Cyt-b_6** and **Cyt-f**.

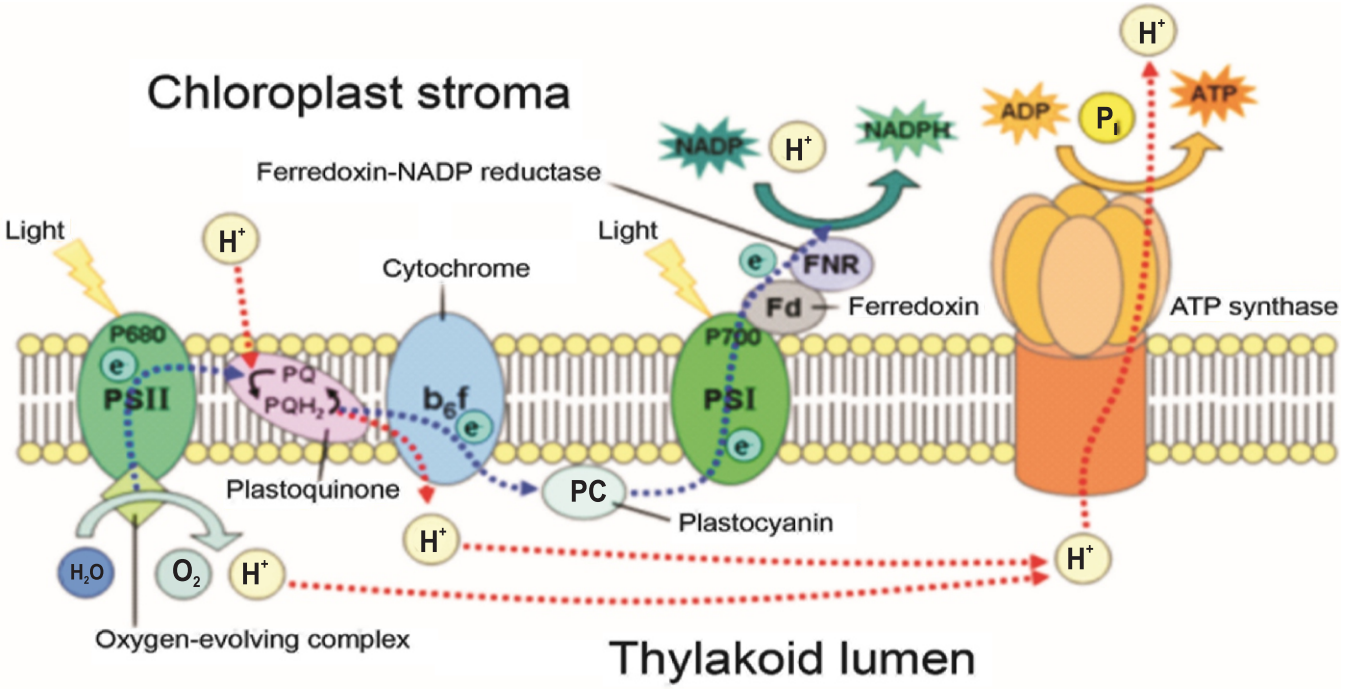


Fig: 4.7: Chemiosmotic synthesis of ATP during light reaction

The cytochrome complex is not only an electron carrier but it also works as proton pump. The electron flow through the cytochrome complex stimulates it to pump the protons from stroma to the thylakoid inner space. In this way the energy of flowing electrons is transformed into a gradient of protons (H^+) in the thylakoid inner space. The proton gradient activates an enzyme in thylakoid membrane called **ATP synthase** which not only moves the protons back into the stroma but also catalyzes a reaction in which ADP and Pi are combined to form ATP (photophosphorylation). This whole mechanism which involves flow of electron, pumping of protons and generation of ATP by thylakoid membranes is called **chemiosmosis.** This ATP, generated by light reactions will provide chemical energy for the synthesis of sugar during Calvin cycle. The energized electrons after losing their energy, move from cytochrome complex to the **plastocyanin (PC)** and finally incorporated into the PS-I

Absorption of light by PS-I and excitation of its electrons

On the other hand, when P700 in the reaction centre of PS-I molecule absorbs two photon of light, electrons are boosted to a higher energy level. P700 molecule passes these excited electrons to a primary electron acceptor of PS-I, creating “electron holes”. The electron holes of P700 are filled by the pair of electrons received from the P680 (photosystem II) via electron transport chain.

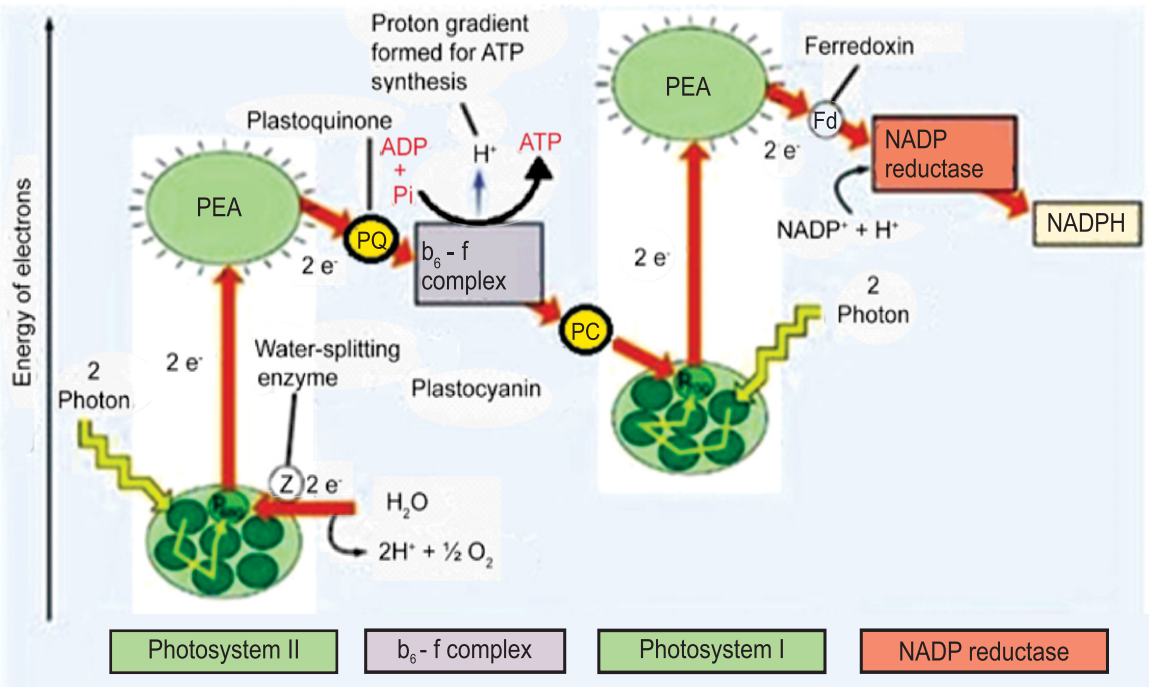


Fig: 4.8: Non-cyclic photophosphorylation (Z Scheme)

Electron flow from PS-I to $NADP^+$

The primary electron acceptor of photosystem I passes the photoexcited electrons to a second electron transport chain. The electrons are accepted by **ferredoxin (Fd).** It is an iron containing protein. An enzyme called **NADP reductase** (flavoprotein enzyme) transfers the electrons from Fd to $NADP^+$. $NADP^+$ combines with electrons and hydrogen ions to form NADPH (reduced). The NADPH will provide reducing power for the synthesis of sugar in the Calvin cycle.

$$NADP^+ + 2e^- + 2H^+ \longrightarrow NADPH + H$$

The path of electron transport through the two photosystems during non-cyclic photophosphorylation is known as **Z-Scheme** due to its conceptual zigzag shape.

(b) Cyclic photophosphorylation

The rise in NADPH and deficit of ATP may stimulate a temporary shift from a non-cyclic to cyclic electron flow until ATP supply catches up the demand. In this mechanism only PS-I is utilized. It absorbs energy in the form of photons. When energy reaches the **reaction centre** of PS-I the electrons are boosted up to higher energy level. Such excited electrons are first captured by primary electron acceptor of PS-I, then they move through an electron transport chain containing ferridoxin, cytochrome b_6-f complex and plastocyanin. When electrons are passed from cytochrome b_6-f complex an ATP is generated by chemiosmosis. Finally, the electrons after losing the energy return back to P700 chlorophyll in PS-I reaction centre. There is no production of NADPH, no occurrence of photolysis of water and therefore, no release of oxygen.

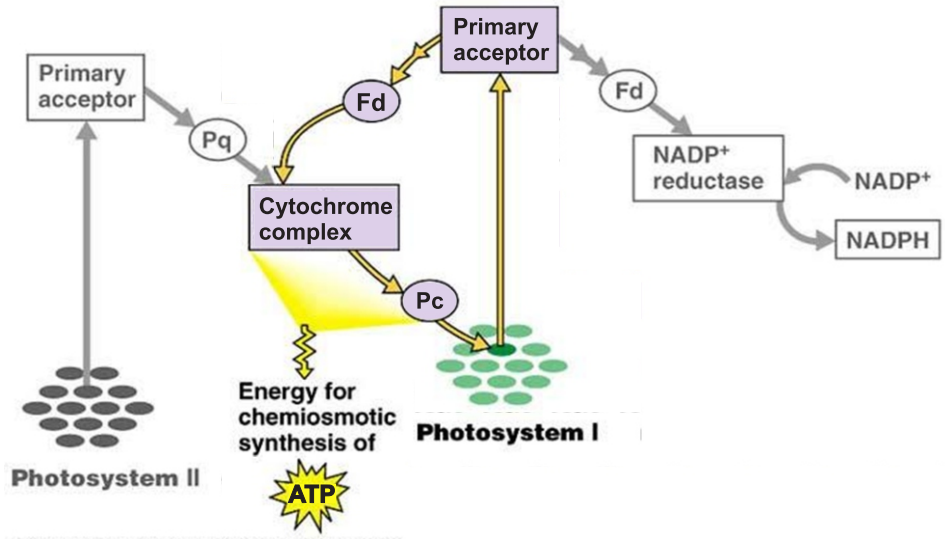


Fig: 4.9: Cyclic photophosphorylation

4.1.9 Light Independent Phase (Dark Reaction)

The light independent phase (dark reaction) takes its name from the fact that light is not directly required for these reactions to occur. This phase requires the availability of NADPH, ATP (the products of light reaction) and CO_2. In this phase of photosynthesis, NADPH is used to reduce carbon dioxide while ATP is used to incorporate energy. Finally, CO_2 is converted into a phosphorylated triose carbohydrate i.e., glyceraldehyde-3-phosphate (G3P) which are later on used to make glucose. Dark reaction generally involves a complicated metabolic pathway, the Calvin cycle or C3 pathway. However, in some plants, in addition to Calvin cycle another metabolic pathway is also involved, called **C4 pathway.** The plants in which only Calvin cycle occurs during dark reaction are called **C3 plants.**

Calvin cycle

Calvin cycle term is applied to the series of metabolic reactions in which CO_2 is reduced to produce G3P. (These reactions have been explored by **Melvin Calvin** and co-workers at the University of California. Melvin Calvin won the Nobel Prize in 1961 for this work). The Calvin cycle can be divided into three phases, carbon fixation, reduction and regeneration of carbon dioxide acceptor i.e., RuBP.

Carbon fixation

One of the key substance in this process is a five carbon phosphorylating sugar called **ribulose bisphosphate (RuBP).** It is generally referred as **CO_2 acceptor** because it is capable of combining with carbon dioxide with the help of Ribulose bisphosphate (RuBP) carboxylase/oxygenase also known as **RuBisCO.** Three intermediate molecules of six carbons are formed during this reaction. These molecules are unstable and exist for such a short time that, they cannot be isolated. Each six carbon breaks down to form two molecules of 3-phosphoglycerate (3-PGA), a phosphorous containing compound with three

carbon atoms. Since, the carbon of inorganic compound (CO_2) becomes the part of organic compound (RuBP) during this phase, hence, it is called **carbon fixation.** As the first stable compound in the Calvin cycle is a three carbon compound (3-PGA) that is why Calvin cycle is also known as **C3 pathway.**

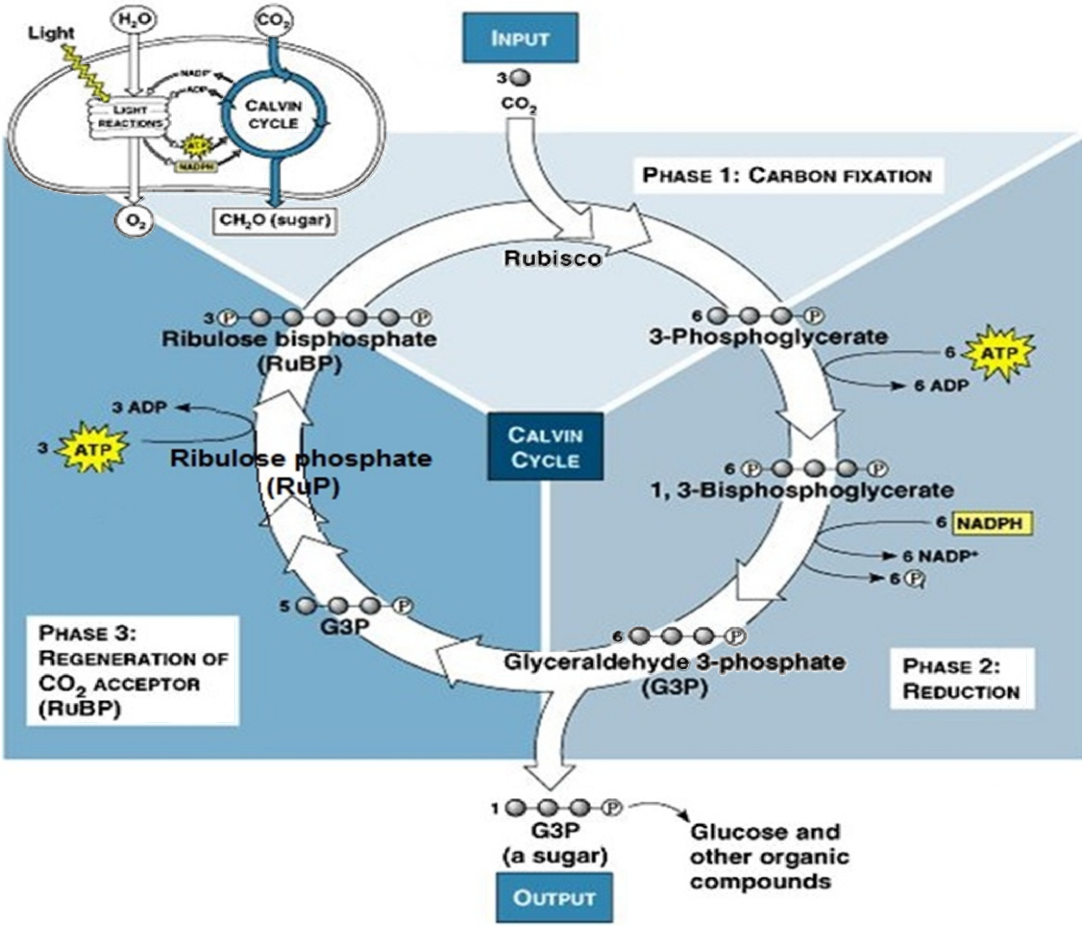
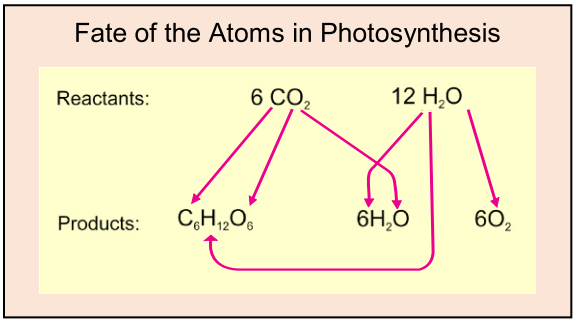


Fig 4.10: Calvin cycle

Reduction

In this phase six molecules of 3-phosphoglycerate (3-PGA) react with six ATP molecules, a phosphate from each ATP is transferred to each 3-PGA. In this way, 3-PGA molecules are changed into 1,3-Bisphosphoglycerate. These molecules are then reduced by the hydrogen of NADPH and finally glyceraldehyde 3 phosphate (G3P) molecules are produced. During this reduction process a phosphate group from each 1,3-Bisphosphoglycerate molecule is also given off. There are total six molecules of G3P are produced in this phase but only one molecule is released from the cycle while rest of the five molecules are used to regenerate the CO_2 acceptor molecules in the next phase.



Regeneration of CO_2 acceptor

Five molecules of G3P from the previous phase are used to regenerate the RuBP (CO_2 acceptor) in this phase. These five molecules each containing three carbon atoms undergo a series of reactions in which three molecules of ribulose phosphate (RuP) each containing five carbon atoms are produced. When three molecules of RuP react with three molecules of ATP, a phosphate group from each ATP is transferred to each RuP. Ultimately RuP are converted into RuBP which again participate in the next cycle.

The whole process of Calvin cycle indicates that there are three molecules of CO_2, six molecules of NADPH (reducing power) and nine molecules of ATP (assimilating power) are used to release just one molecule of G3P form the cycle. However, in order to produce a glucose molecule, two molecules of G3P are required. The overall process of Calvin cycle can be represented as:

$$3CO_2 + 6NADPH + 9ATP \longrightarrow G3P + 3H_2O + 9ADP + 9Pi + 6\ NADP^+$$

4.2 CELLULAR RESPIRATION

In biological systems oxidation-reduction is a chemical reaction usually involves the removal of hydrogen atom from one molecule and the gain of hydrogen atom by another molecule. Cellular respiration is a series of complex oxidation-reduction reactions by which living cells obtain energy through the breakdown of organic matter.

4.2.1 Kinds of Cellular Respiration

There are two kinds of respirations: aerobic respiration and anaerobic respiration. Aerobic respiration takes place in the presence of abundant atmospheric oxygen, whereas, anaerobic respiration occurs in the absence of oxygen. The organic molecule that generally undergoes breakdown in cellular respiration in order to release energy is glucose, therefore, glucose is supposed to be **respiratory fuel.** The initial breakdown of glucose in both aerobic and anaerobic respirations is quite same, in which it is broken down into two molecules of **pyruvates**. This common step of aerobic and anaerobic respirations is called **glycolysis**. The pyruvates undergo in different respiratory pathways depending upon the availability of oxygen and the kind of organism. If oxygen is available, the further breakdown of pyruvates takes place aerobically and the final products are carbon dioxide and water with the release of large amount of energy i.e., 36 ATPs (in eukaryotes) or 38 ATPs (in prokaryotes). If oxygen is absent, then the pyruvates are broken down anaerobically and the final products are either lactic acid or ethanol and carbon dioxide with release of very small amount of energy i.e., just 2 ATPs.

4.2.2 Mechanism of Anaerobic Respiration

Anaerobic respiration takes place in many microorganisms (bacteria, yeast), muscle cells of vertebrates and in the cells of higher plants. Anaerobic respiration is incomplete breakdown of glucose in the absence of oxygen. It is also known as **fermentation.** There are two pathways of anaerobic respiration depending upon the nature of final products i.e., lactic acid fermentation and alcoholic fermentation.

Lactic acid fermentation

It consists of **glycolysis** followed by the **reduction** of pyruvate by NADH to lactic acid. The pathway operates anaerobically because after NADH transfers its electron to the pyruvate, it is "free" to return and pick up more electrons during the earlier reaction of glycolysis. The overall equation can be represented as:

$$C_6H_{12}O_6 + 2NAD^+ \longrightarrow 2C_3H_4O_3 + 2NADH + 2H^+$$

$$2C_3H_4O_3 + 2NADH + 2H^+ \longrightarrow 2C_3H_6O_3 + 2NAD^+$$

Lactic acid fermentation occurs in anaerobic bacteria and in the muscles of mammals as well as human during strenuous exercise when oxygen supply is exhausted. The accumulation of lactic acid causes muscles fatigue i.e., muscles become unable to contract and begin to ache.

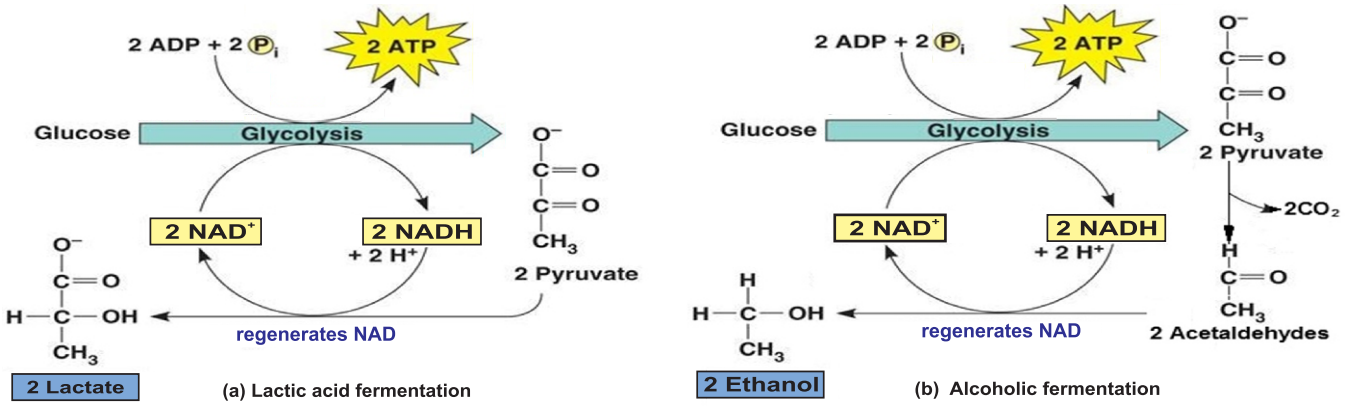


Fig: 4.11 Anaerobic respiration

Alcoholic fermentation

Alcoholic fermentation is found in yeast. It consists of **glycolysis** followed by the **decarboxylation** of pyruvate to acetaldehyde then **reduction** of acetaldehyde by NADH to ethyl alcohol or ethanol. This pathway also operates anaerobically because after NADH transfers its electron to the acetaldehyde, it is "free" to return and pick up more electrons during the earlier reaction of glycolysis. The overall equation can be represented as:

$$C_6H_{12}O_6 + 2NAD^+ \longrightarrow 2C_3H_4O_3 + 2NADH + 2H^+$$

$$2C_3H_4O_3 + 2NADH + 2H^+ \longrightarrow 2C_2H_5\text{-}OH + 2CO_2 + 2NAD^+$$

4.2.3 Mechanism of Aerobic Respiration

Aerobic respiration is a catabolic process which involves complete oxidative breakdown of organic food (especially glucose) into carbon dioxide and water with release of great deal of energy in the form of ATPs. It is predominant respiratory pathway in most of the organisms. Aerobic respiration is completed in four phases: glycolysis, oxidation of pyruvates, Krebs cycle and respiratory electron transport chain.

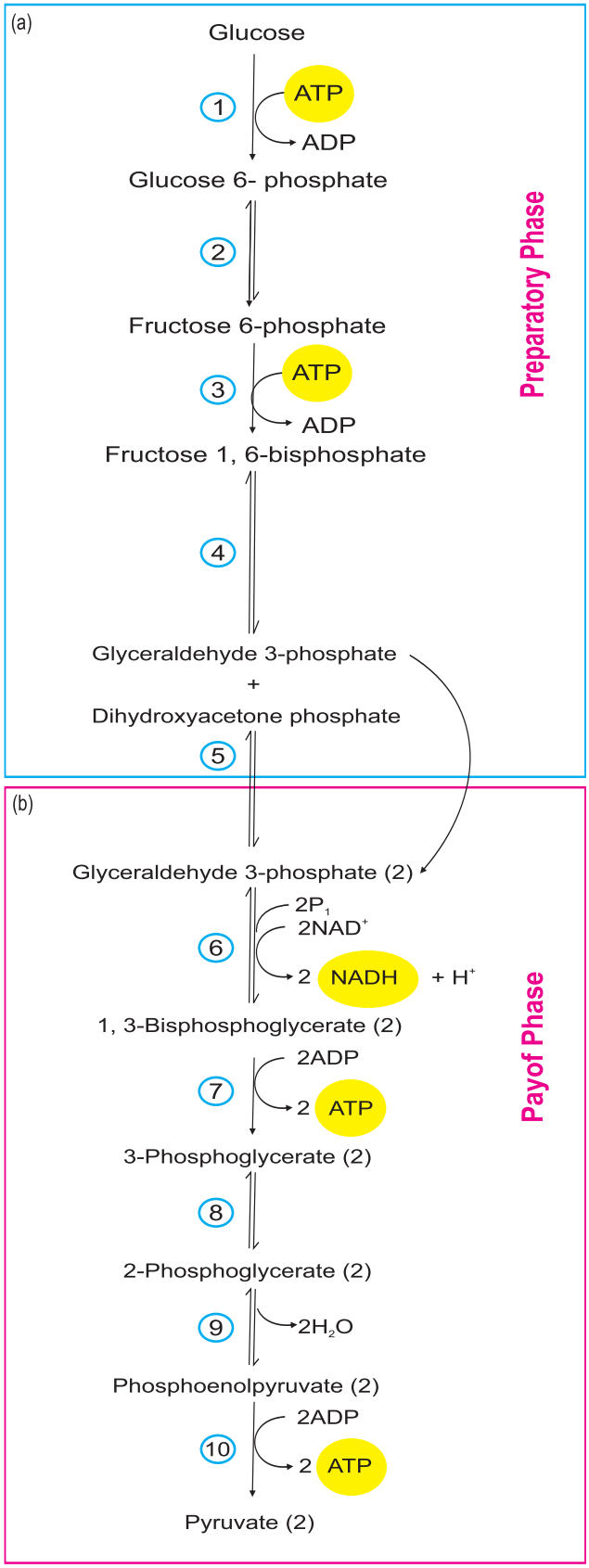


Fig: 4.13: Glycolysis

Glycolysis

Glycolysis is the process of breakdown of glucose or similar hexose sugar into two molecules of pyruvates through a series of enzymatic reactions releasing some energy (as ATP) and reduced coenzymes (as NADH). It occurs in the cytoplasm. It is completed in two phases i.e., preparatory phase and oxidative phase. **Preparatory phase** is an investment phase in which two ATPs are consumed. Its end products are two molecules of G3P. On the other hand **oxidative phase** is **pay off phase** in which not only ATPs are produced through substrate level phosphorylation but it also produces NADH which upon further oxidation in respiratory electron transport chain yields more ATPs. The whole glycolysis pathway takes place in the following sub steps.

1. Phosphorylation: When glucose reacts with ATP, a phosphate group from ATP is transferred to glucose. In this way glucose is phosphorylated to **glucose-6-phosphate**.

2. Isomerization: Glucose-6-phosphate is changed to its isomer **fructose-6-phosphate.**

3. Phosphorylation: When fructose-6-phosphate reacts with another ATP, it is phosphorylated to **Fructose-1**, **6-bisphosphate.**

4. Splitting: Now fructose-1, 6-bisphosphate splits up to form one molecule each of 3-carbon compounds, **glyceraldehyde 3-phosphate** (G3P) and **dihydroxyacetone 3-phosphate.**

5. Isomerization: The dihydroxyacetone 3-phosphate is ultimately changed into its isomer, the **glyceraldehyde 3-phosphate** (G3P). In this way preparatory phase is completed. Next phase of glycolysis is proceeded by two molecules of G3P, therefore, the remaining reactions occur twice.

6. Dehydrogenation and Phosphorylation:

NADH and accepts inorganic phosphate (Pi) to form **1, 3-bisphosphoglycerate.**

7. Formation of ATP: The direct synthesis of ATP from organic phosphorylated substrate is called **substrate level phosphorylation.** In this step a molecule of ATP is formed from 1, 3-bisphosphoglycerate which is changed into **3-phosphoglycerate.**

8. Isomerization: In this step position of phosphate group is changed from C3 to C2 of phosphoglycerate to form 2-phosphoglycerate.

9. Dehydration: In this step, 2-phosphoglycerate undergoes dehydration and is converted into **phosphoenol pyruvate** (PEP).

> Glycolysis is also called EMP pathway because it was discovered by three German scientists Embden, Meyerhof and Parnas.

10. Formation of ATP: Again a molecule of ATP is produced by **substrate level phosphorylation** when phosphoenol pyruvate loses phosphate group which is taken up by the ADP to form ATP in the presence of an enzyme (**pyruvate kinase)**. The phosphoenol pyruvate is finally converted into **pyruvate.**

4.2.4 Oxidation of Pyruvate

Pyruvates are produced in cytosol. Because pyruvate is a charged molecule, it must enter the mitochondrion via active transport with the help of the transport protein. On entering the mitochondria, pyruvates do not directly participate in Krebs cycle but they

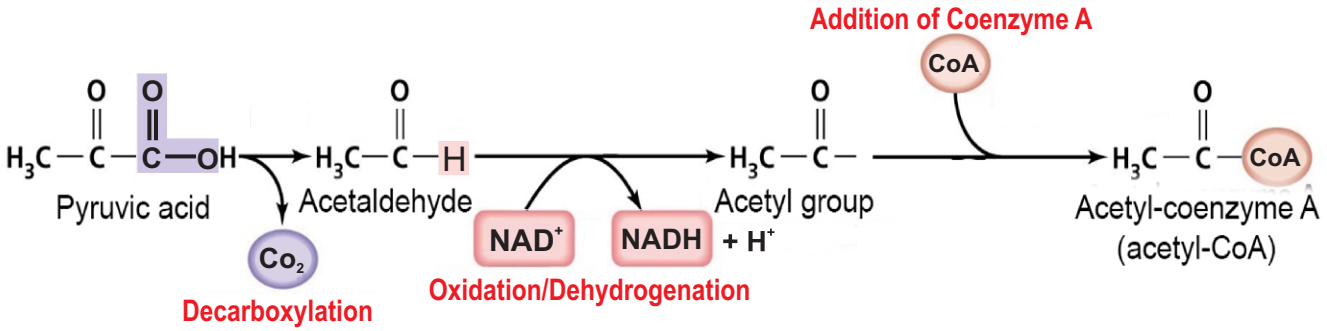


Fig: 4.14 Pathway of oxidation of pyruvate

undergo an intermediate phase, called **oxidation of pyruvate** or **link reaction** as it links the pathway of aerobic respiration that occurs outside the mitochondria with that occurs inside the mitochondria.

The oxidation of pyruvate takes place in three steps. First, it undergoes **decarboxylation** in which a molecule of CO_2 is removed from pyruvate to form **acetaldehyde.** Then NAD^+ removes hydrogen from acetaldehyde. As a result of this oxidation/ dehydrogenation a 2C fragment acetyl and NADH are produced. Finally, acetyl group is combined with coenzyme-A to form **acetyl CoA.**

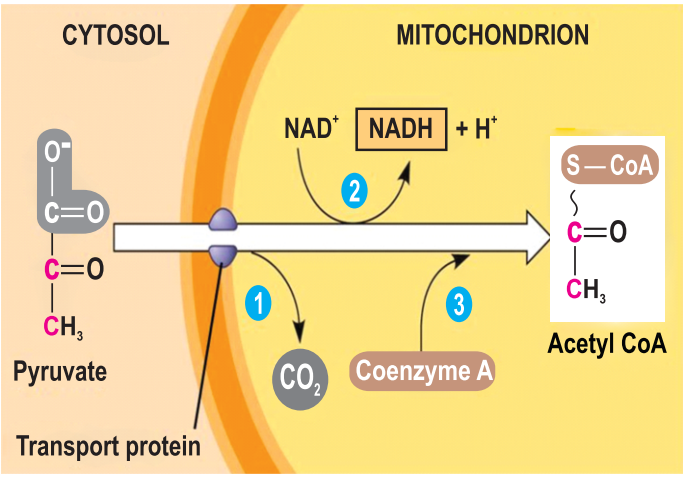


Fig: 4.15 Site of oxidation of pyruvate: Conversion of pyruvate to acetyl CoA, the junction between glycolysis and the citric acid cycle.

Science Titbits

A complex oxidation-reduction involves NAD or NADP. NAD and NADP act as intermediate in cellular reactions involving electron transfer. Many of the electrons removed from reduced carbon compounds in various enzyme-catalyzed reactions are transferred to NAD to produce NADH. When a molecule of NAD or NADP gains electrons and becomes reduced, a hydrogen ion combines with it as well. Thus the reduced form is symbolized as NADH or NADPH. In fact, another hydrogen ion becomes closely associated with each reduced molecule. Technically it is more accurate to represent the reduced form as NADH + H^+ or NADPH + H^+. For convenience, these reduced forms i.e., NADH + H^+ and NADPH + H^+ can be represented as $NADH_2$ and $NADPH_2$ respectively.

4.2.5 Krebs Cycle

This cycle was discovered by British scientist **Sir Hans Krebs**, therefore, called **Krebs cycle.** It is also called **Citric acid cycle** or **Tri carboxylic acid** (TCA) cycle because the first compound which is formed in the cycle is **citrate** (citric acid) that contains three carboxylic acid groups.

The Krebs cycle comprises following nine steps.

1. Synthesis

Acetyl CoA (2-carbon compound) and a water molecule combine with oxaloacetate (4-carbon compound) to form a 6-carbon compound called **citrate** (citric acid). It is the first product of Krebs cycle. CoA is liberated.

2. Dehydration

Citrate undergoes reorganization by the removal of a water molecule. The resulting compound is **cis-aconitate.**

3. Hydration

Cis-aconitate is converted into **isocitrate** with the addition of water. Actually, citrate and isocitrate are isomers of each other.

4. Oxidative decarboxylation

This is a two-step process, which involves oxidation/ dehydrogenation of isocitrate, followed by the **decarboxylation** to form **alpha-ketoglutarate**. The hydrogen and electrons which are released from isocitrate are taken up by NAD^+ to form NADH while the carboxyl group is released in the form of CO_2.

5. Oxidative decarboxylation and addition of CoA

α-Ketoglutarate again undergoes oxidative decarboxylation. The hydrogen and electrons which are released from **α-ketoglutarate** are taken up by NAD^+ to form NADH while the carboxyl group is released in the form of CO_2. Then, it combines with coenzyme A to form **succinyl CoA.**

6. Formation of ATP

Coenzyme A is removed from Succinyl CoA to form **succinate.** The reaction releases sufficient energy which is used to combine GDP and Pi forming GTP. GTP reacts with ADP to form ATP while GTP is again converted into GDP. In this way a molecule of ATP is generated in this reaction.

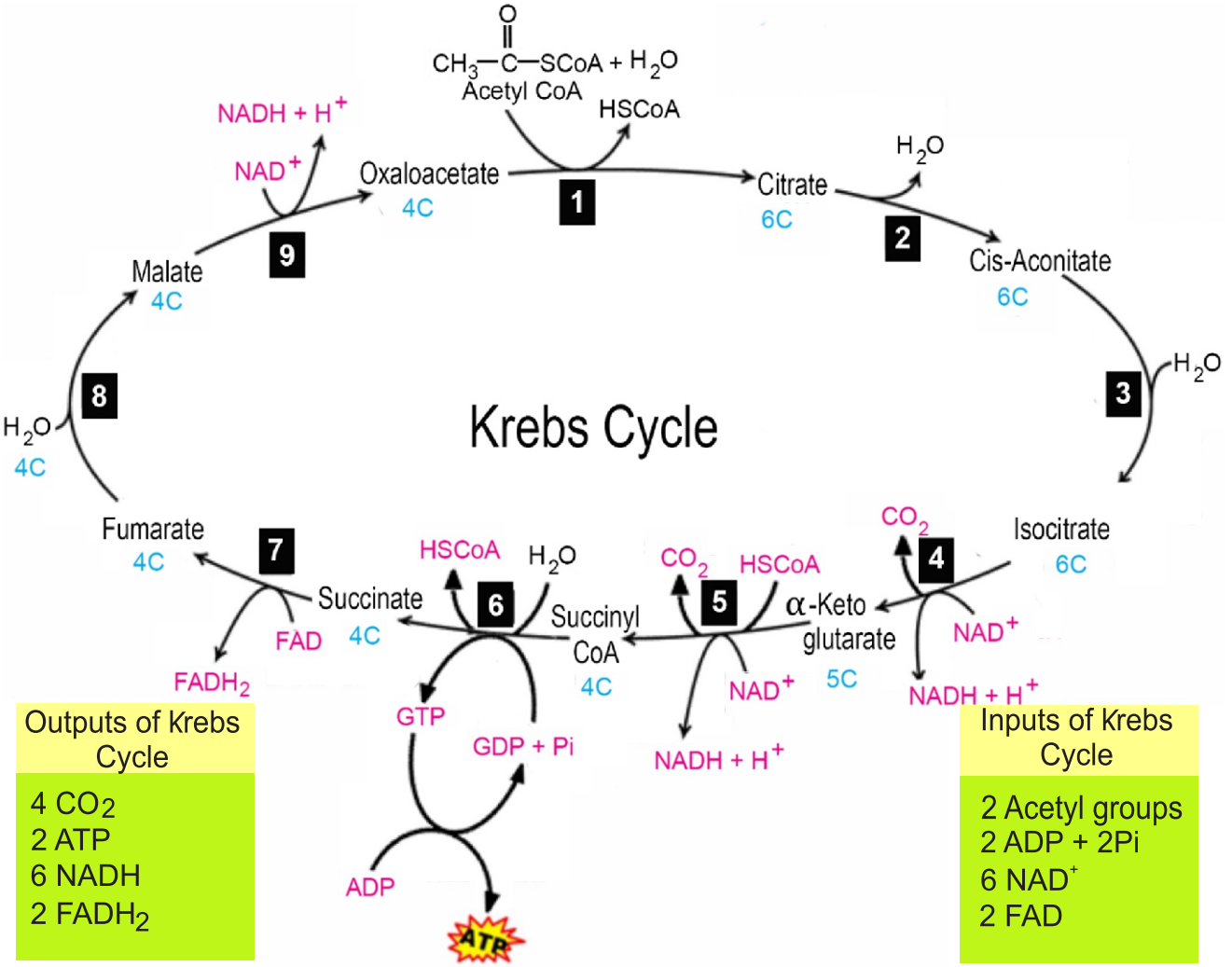


Fig: 4.16 Krebs cycle (Citric acid cycle or TCA cycle)

7. Dehydrogenation/oxidation

Succinate undergoes dehydrogenation/oxidation to form **fumarate.** The hydrogen and electrons which are released from succinate are taken up by FAD to form $FADH_2$.

8. Hydration

A molecule of water gets added to fumarate to form **malate.**

9. Dehydrogenation/oxidation

Malate undergoes dehydrogenation/oxidation to produce **oxaloacetate**. The hydrogen and electrons which are released from malate are taken up by NAD^+ to form NADH. Oxaloacetate picks up another molecule of acetyl CoA to repeat the cycle.

4.2.6 Electron Transport Chain (ETC)

After Kreb's cycle most of the energy of glucose is in the form of NADH and $FADH_2$, These two molecules enter into the electron transport chain. In this chain, the reduced NADH and $FADH_2$ are oxidized and their electrons are passed along a series of oxidation reduction reaction to the final acceptor i.e., molecular oxygen.

Components of electron transport chain

The components of electron transport chain include: (1) **NADH- dehydrogenase complex (I)**, (2) **FADH-dehydrogenase complex (II)** (3) **coenzyme Q** (4) **Cytochrome reductase complex (III)** (5) **Cytochrome-c** (6) **Cytochrome oxidase complex (IV).**

Passage of electron flow

NADH is oxidized when it reacts with **NADH- dehydrogenase complex (I).** Electrons now move to the **co-enzyme Q**. If $FADH_2$ is to be oxidized through ETC, it also hands over its electrons to coenzyme Q, via **FADH dehydrogenase complex (II).**

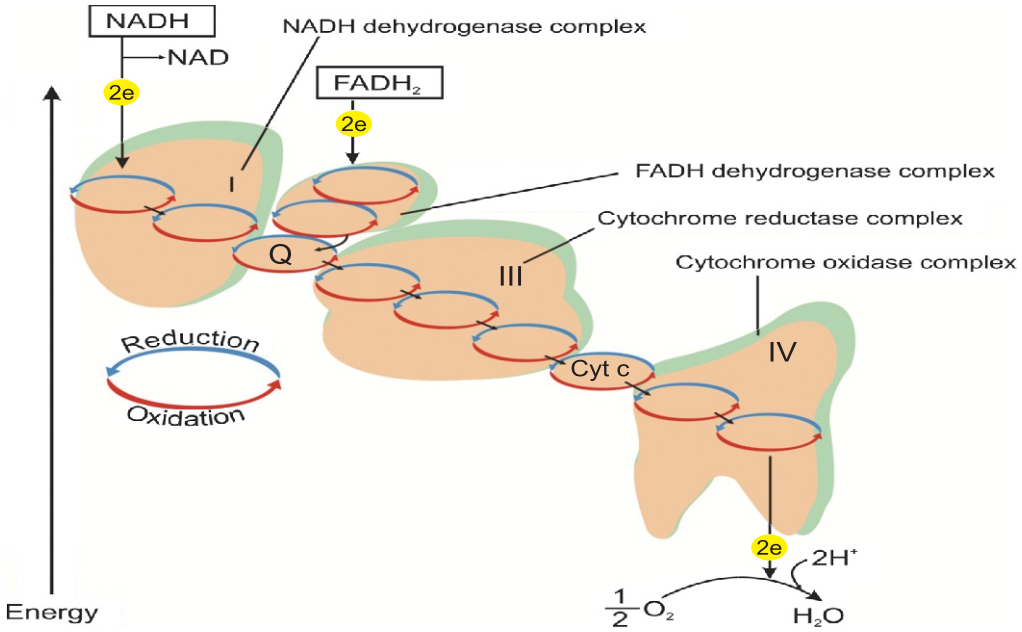


Fig: 4.17 Sequence of electron carriers in respiratory ETC

The flowing electrons from coenzyme **Q** are now transferred to **cytochrome reductase complex (III)** which hands over its electron to **cytochrome c**. Like co-enzyme Q, cytochrome c is also mobile carrier of electrons. Cytochrome c delivers the electrons to **cytochrome oxidase complex (IV).**

Finally, the electrons are transferred to oxygen. The oxygen is the ultimate acceptor of electrons. It becomes reactive. Each oxygen atom also picks up a pair of hydrogen ions from the aqueous solution forming water.

Science Titbits

Ubiquinone is not a protein, but a small molecule soluble in lipids and insoluble in water Cytochromes literally means "cell colour". The reduced cytochromes are pink in colour. They are protein plus pigment molecules containing iron. They can gain or lose an electron.

Energy released during passage of electrons from one carrier to the next is used to pump protons (H^+) from the mitochondrial matrix to the inter membrane space. There are three such sites, corresponding to three enzymes present in the electron transport chain i.e. NADH-dehydrogenase complex (I), cytochrome reductase complex (III) and cytochrome oxidase complex (IV).

The electron transport chain makes no ATP directly. Its function is to ease the fall of electrons from food to oxygen releasing energy in manageable amounts. How does the mitochondrion couple this electron transport chain and energy to ATP synthesis? The answer is a mechanism called chemiosmosis.

4.2.7 Chemiosmosis and Oxidative Phosphorylation

Oxidative phosphorylation is the synthesis of ATP molecules with the help of energy liberated during oxidation of reduced co-enzymes (NADH, $FADH_2$) produced in respiration. The enzyme required for this synthesis is called ATP synthetase.

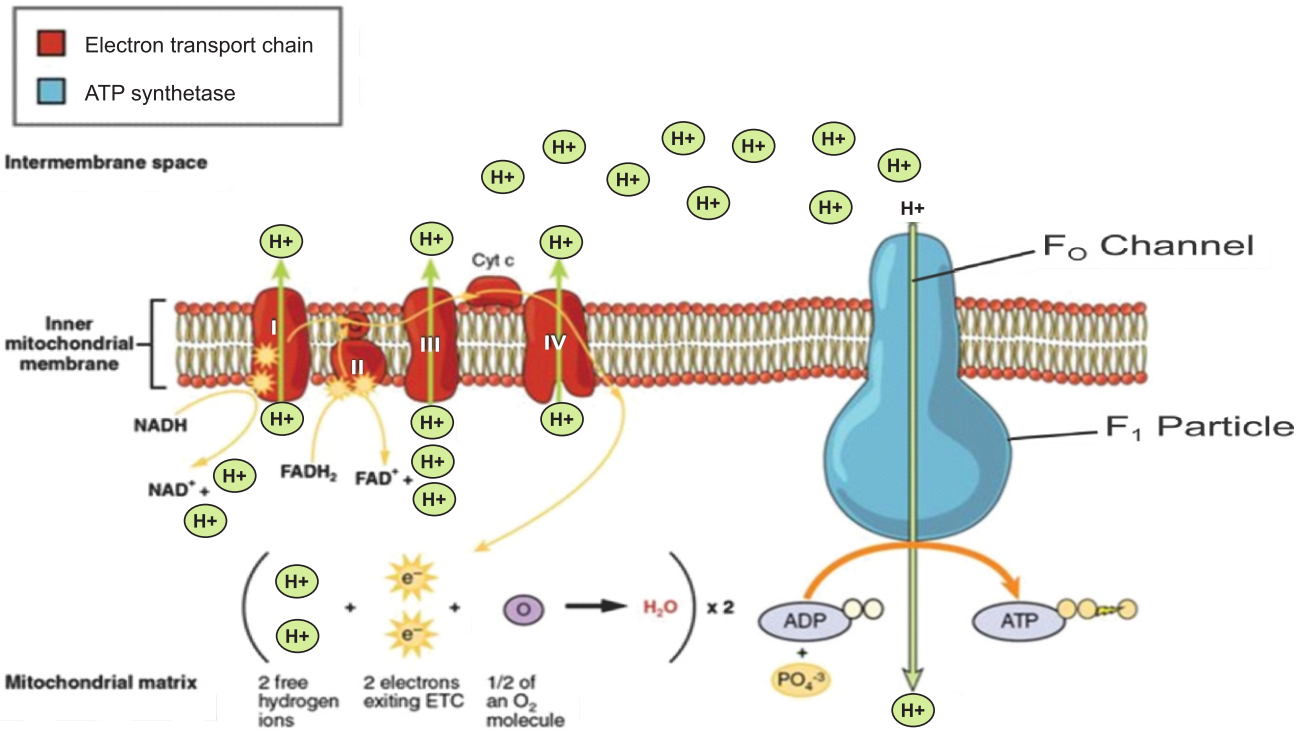


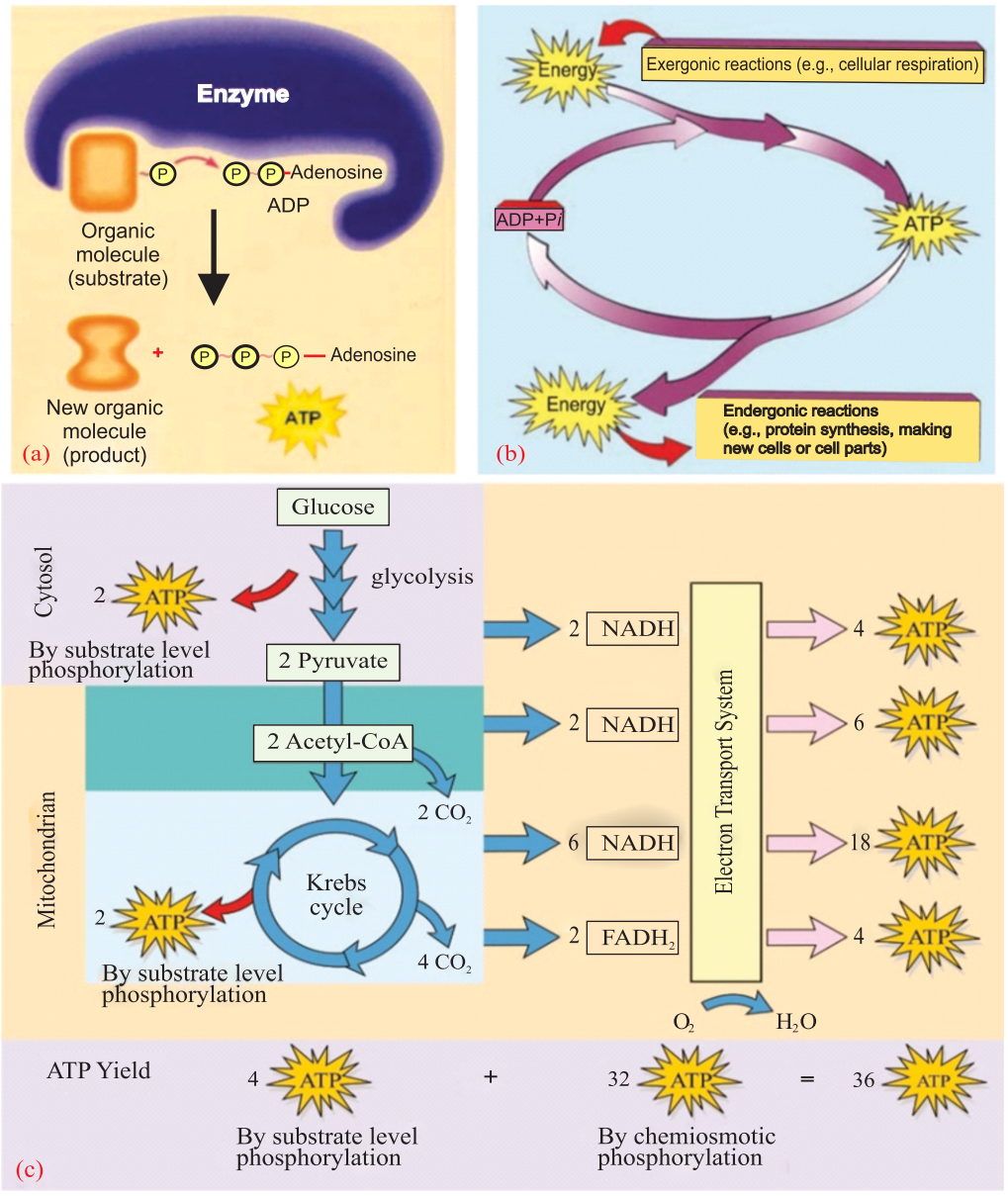
Fig: 4.18: Mechanism of chemiosmosis in respiratory electron transport chain

It is located in the inner mitochondrial membrane. It consists of two parts i.e., F_0 and F_1. F_0 is embedded in the membrane and involves in the movement of protons from inter-membrane space to mitochondrial matrix. F_1 or elementary particle is a head like part which is projected from the surface of membrane towards matrix. It catalyzes ATP synthesis by the combination of ADP and Pi. ATP-synthetase becomes active in ATP formation only when a proton gradient having higher concentration of H^+ or protons on the F_0 side as compared to F_1 side is established. The flow of protons through the F_0 channel induces F_1 particles to function as ATP-synthetase i.e., the energy of the proton gradient is used in attaching a phosphate to ADP by high energy bond. This produces ATP. Oxidation of one molecule of $NADH_2$ produces 3 ATP molecules while a similar oxidation of $FADH_2$ forms 2 ATP molecules. The theory of ATP production by this mechanism is called **chemiosmosis.**

4.2.8 Substrate Level Phosphorylation

The prime objective of cellular respiration is to generate ATPs. There are two ways to do this during aerobic respiration: chemiosmosis and substrate level phosphorylation, the former we have already discussed.

As far as substrate level phosphorylation is concerned, you are already familiar that the addition of inorganic phosphate to any organic molecule is called **phosphorylation** but, when phosphate is enzymatically transferred from an organic substrates molecule it is called **substrate level phosphorylation**. However, it accounts for only a small percentage of the ATP that a cell generates. It occurs at three occasions during aerobic respiration.



Note:

Actually, the two molecule of the NADH of glycolysis are produced in cytoplasm. These cannot be taken up by mitochondria because the mitochondrial membrane is impermeable for NADH. Therefore, at the time of their uptake only the energized electrons of NADH are transferred inside the mitochondrion by a complex mechanism. These electrons are received by two molecules of FAD^+ in the mitochondrial matrix to produce two molecule of $FADH_2$. Hence, four ATP molecules are produced instead of six. So, eukaryotes yield two less number of ATP than prokaryotes.

Fig:4.19: (a)Substrate level phosphorylation. (b) Because ATP is responsible for coupling many endergonic and exergonic reactions it is an important link between anabolism and catabolism in living cells. (c) ATP Budget in aerobic respiration

In glycolysis, substrate level phosphorylation occurs, when 1,3-bisphosphoglycerate is converted into 3-phosphoglycerate (7^{th} reaction) and when phosphoenol pyruvate is converted into pyruvate (10^{th} reaction). There are four ATPs produced by this mechanism during glycolysis but two of them are supposed to be consumed in preparatory phase so net product by substrate level phosphorylation is 2 ATP.

In Krebs cycle, substrate level phosphorylation occurs when succinyl CoA is converted into succinate. There are two molecules of ATP produced at this occasion. Since, ATP can be synthesized directly from the organic substrates of exergonic reactions (energy releasing reactions e.g., cellular respiration), therefore, it is said that substrate level phosphorylation couples the exergonic reactions with the synthesis of ATP. These ATP are then used to drive endergonic reactions (energy storing reaction e.g., protein synthesis). In this way, out of total 36 ATP which are produced during aerobic respiration in most of human cells, 4 ATP are the result of substrate level phosphorylation and remaining 32 ATP are produced by chemiosmosis through electron transport chain.

4.2.9 Importance of G3P

Glyceraldehydes 3-phosphate (G3P) is an important intermediate of respiration and photosynthesis. In respiration, G3P appears during glycolysis pathway which leads to the formation of pyruvate. In the Calvin cycle of photosynthesis, G3P molecules are converted into glucose phosphate within the chloroplast. Glucose phosphate is then converted to glucose, fructose, sucrose and starch.

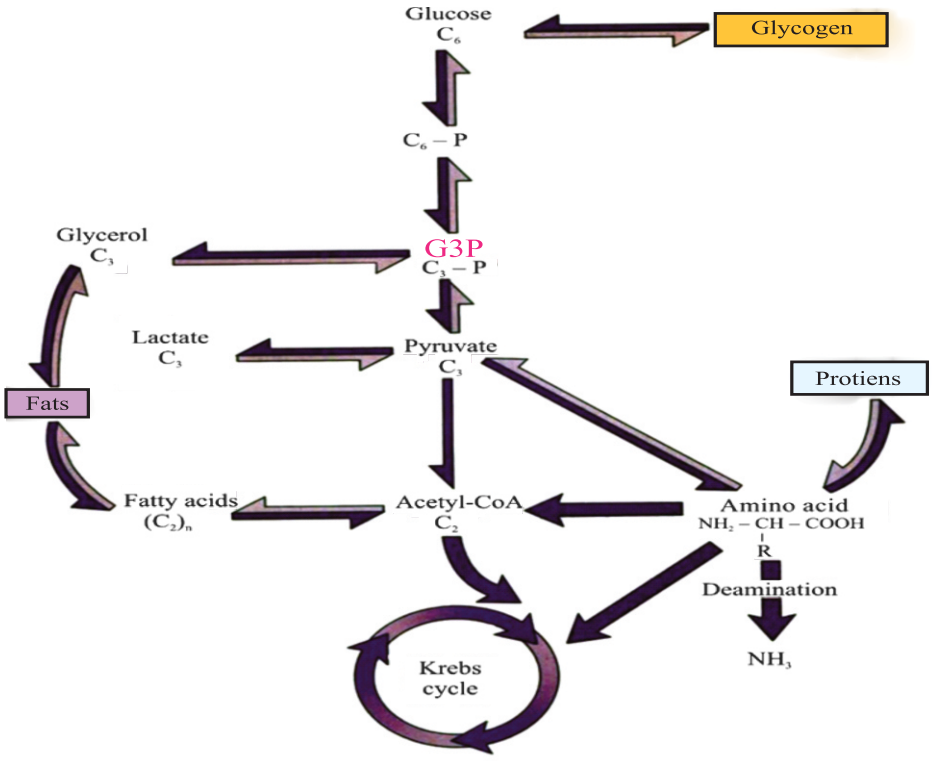


Fig: 4.20: The matabolic pool concept: When they are used as energy sources carbohydrates, fats and proteins enter degradative pathways at specific points. Degradation produces metabolites that can be used for synthesis of other compounds.

4.2.10 Cellular Respiration of Fats and Proteins

When a fat is used as an energy source, it breaks down to glycerol and three fatty acids. As figure 4.20 indicates, glycerol is converted to G3P, a metabolite in glycolysis. The fatty acids are converted to acetyl-CoA, which enters the Krebs cycle. An 18-carbon fatty acid results in nine acetyl-CoA molecules.

The hydrolysis of **proteins** results in amino acids whose R-group size determines whether the carbon chain is oxidized in glycolysis or the Krebs cycle. The carbon chain is produced in the liver when an amino acid undergoes deamination, i.e., the removal of the amino group. The amino group becomes ammonia (NH_3), which enters the urea cycle and becomes part of urea.

4.3 PHOTORESPIRATION

The respiratory activity that occurs in green cells in the presence of light resulting in release of carbon dioxide is termed as **photorespiration**. It needs oxygen and produce CO_2 and H_2O like aerobic respiration. However ATP is not produced during photorespiration.

4.3.1 Mechanism of Photorespiration

When the CO_2 levels inside the leaf drop to around 50 ppm (part per million), ribulose bisphosphate carboxylase/oxygenase (RuBisCO) starts to combine O_2 with RuBP instead of CO_2. The net result of this is that instead of producing two 3C molecules of phosphoglycerate (PGA), only one molecule of PGA and a toxic 2C molecule called **phosphoglycolate** are produced. The plant must get rid of the phosphoglycolate. First it immediately gets rid of the phosphate group, converting the molecule to **glycolate.**

$$RuBP + O_2 \longrightarrow Phosphoglycolate + Phosphoglycerate \longrightarrow Glycolate$$

The glycolate is then transported to the peroxisome and there converted to **glycine.** The glycine is then transported into the mitochondria where it is converted into **serine**. The serine is then used to make other organic molecules.

$$Glycolate \longrightarrow Glycine$$

$$2\ Glycine \longrightarrow Serine + CO_2$$

Effect of temperature on the activities of RuBisCO

Photorespiration is related to the functioning of the enzyme ribulose bisphosphate (RuBP) **carboxylase/oxygenase**. It is often called **RuBisCO** because it can have an oxygenase activity in addition to carboxylase activity. Its activity depends upon the relative concentration of O_2 and CO_2 in leaves. Photorespiration starts when the CO_2 levels inside a leaf become low. This happens on hot dry days when plant begins to secrete abscisic acid which causes closing of stomata to prevent excess water loss. If the plant continues CO_2 fixation in photosynthesis when its stomata are closed, the CO_2 will be used up and the O_2 released from photosynthesis will be prevented to release out of plant body. In this way, ratio of O_2 in the leaf will increase relative to CO_2 concentrations.

Disadvantages and Evolution of Photorespiration

Photorespiration costs the plant energy and results in the net loss of CO_2 fixation from the plant. Thus, it reduces the rate of photosynthetic process. In most plants,

photorespiration reduces the amount of carbon fixed into carbohydrate during photosynthesis by 25 percent. Photorespiration is not essential for plant. It is also observed that if photorespiration is inhibited chemically, the plant can, still grow. Furthermore, some plants are naturally resistant to photorespiration. Then why photorespiration exists? The common simple answer to this question is that the active site of RuBisCO is evolved to bind both carbon dioxide and oxygen. Originally it was not a problem as there was no oxygen in the atmosphere at the time of establishment of earth so the carbon dioxide binding activity was the only one used. The photorespiration started when the oxygen began to accumulate in the atmosphere.

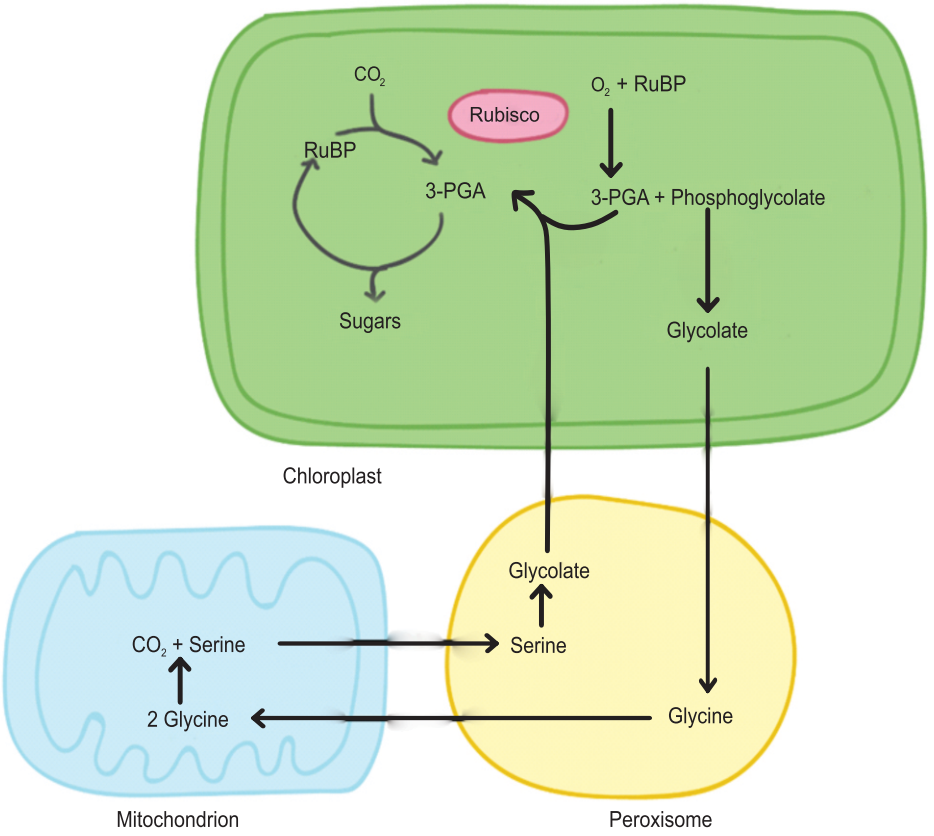


Fig: 4.21: Schematic representation of pathway involved in photorespiration in chloroplast, peroxisomes and mitochondria

Science, Technology and Society Connections

- **Analyze the impact of photorespiration on the agriculture yield in the tropic climates.**

Photorespiration decreases net photosynthesis because a portion of CO_2 fixed in photosynthesis escapes from the leave after it is fixed. Under certain conditions, up to 5% of the photosynthetic potential is lost in photorespiratory metabolism. Thus photorespiration reduces dry matter production and agricultural yield in tropical climate.

4.3.2 C_4 photosynthesis: An adaptation to the problem of photorespiration

Some plants which grow in tropical climate have an adaptation to the problem of photorespiration. They have an additional metabolic pathway in light independent phase of

photosynthesis beside Calvin cycle. This metabolic pathway is called Hatch-Slack cycle of C_4 pathway in which **phosphoenol pyruvate** (PEP) carboxylase is used instead of RuBisCO to fix CO_2 to phosphoenol pyruvate (a C_3 molecule), and the result is **oxaloacetate**, a C_4 molecule. It takes place in cytoplasm of mesophyll cells.

$$PEP + CO_2 \xrightarrow{\text{PEPcarboxylase}} \text{Oxaloacetate}$$

As the first product of CO_2 fixation is a 4-carbon compound oxaloacetate, so the plants are called C_4 plants e.g., maize, sugarcane, sorghum, etc. Oxaloacetate is then transported to the chloroplasts of mesophyll cells. It is then converted to another 4-C compound, the **malate**, with the help of NADH, produced in the photochemical phase. The malate is then transported to the chloroplasts of bundle sheath cells. Here malate is converted to **pyruvate** (C_3) with the release of CO_2. Thus concentration of CO_2 increases in the bundle sheath cells. These cells contain enzymes of Calvin cycle. Because of high concentration of CO_2, RubisCO participates in Calvin cycle and not in photorespiration. Sugar formed in Calvin cycle is transported into the phloem. Pyruvate generated in the bundle sheath cells re-enters mesophyll cells and regenerates phosphoenol pyruvate (PEP) by consuming one ATP.

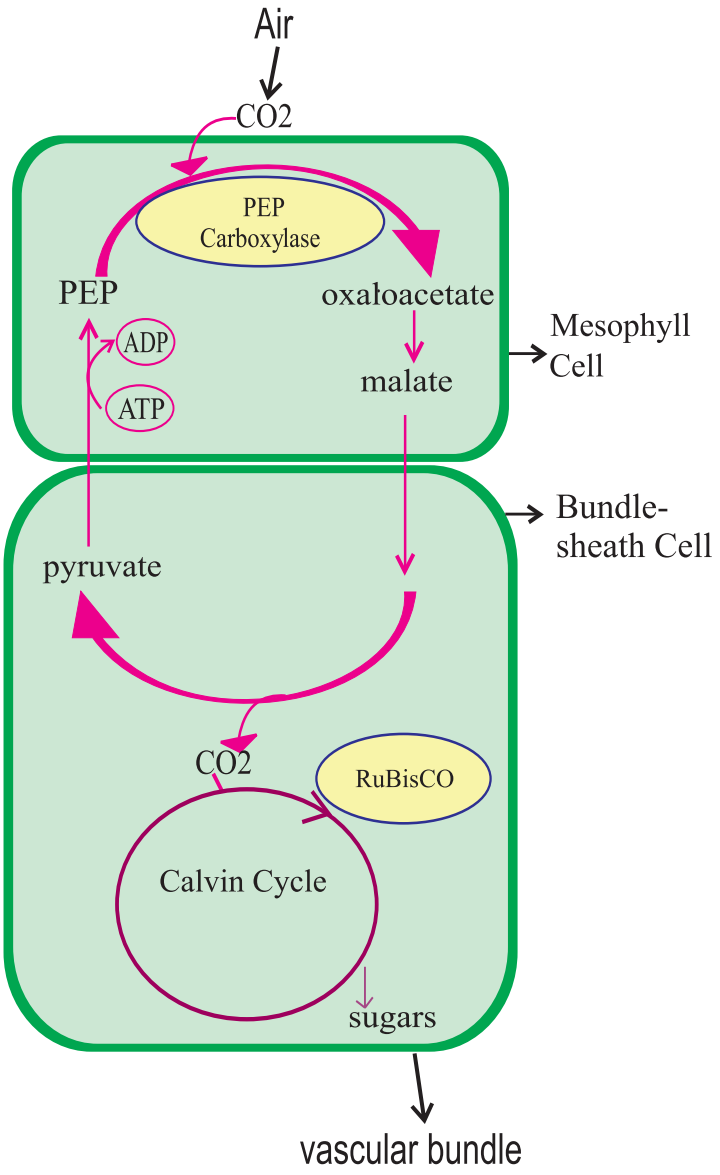


Fig. 4.22: C_4 photosynthesis

Exercise

MCQs

1. Select the correct answer

(i) Removal of the source of carbon dioxide from photosynthesizing chloroplasts results in rapid changes in the concentration of certain chemicals. Which one of the following represents the correct combination of concentration changes?

	ATP	Ribulose bishposphate	Phosphoglyceric acid (PGA)
A	decreases	decreases	increases
B	decreases	increases	no change
C	increases	increases	decreases
D	increases	no change	decreases

(ii) What are the products of the light reactions in photosynthesis?

(A) ATP and NADP (B) ATP, $NADPH_2$ and oxygen

(C) ATP, PGA and $NADH_2$ (D) ATP, PGA and oxygen

(iii) During the light dependent stage of photosynthesis, the photoactivated pigment removes an electron from the hydroxylation derived from the water molecule. The fate of the free hydroxyl radical is that it

(A) is broken down into oxygen and a free radical of hydrogen

(B) is used to raise the activation level of chlorophyll by donating a positive charge

(C) is used to produce adenosine triphosphate from adenosine diphosphate

(D) reduces carbon dioxide to sugar

(iv) Carbon dioxide labeled with ^{14}C has been used to identify the intermediate compounds in the Calvin cycle, the light-independent stage in photosynthesis. Which compound would be the first to contain the ^{14}C?

(A) glucose (B) PGA (C) RuBP (D) starch

(v) The rate of photosynthesis of a freshwater plant is measured using five spectral colours. Which sequence of colours would give an increasing photosynthetic response?

Smallest ⟶ Largest response					
A	blue	green	yellow	orange	red
B	green	yellow	orange	red	blue
C	red	orange	yellow	green	blue
D	yellow	green	orange	blue	red

(vi) During dark reactions the three carbon atoms of 3-PGA are derived from

(A) RuBP only (B) CO_2 only

(C) RuBP + CO_2 (D) RuBP + CO_2 + PEP

(vii) Chlorophyll is soluble in

(A) water (B) organic solvent

(C) water and organic solvent (D) not in any solvent

(viii) Photorespiration takes place only in

(A) root (B) mitochondria

(C) green parts of the plant (D) all cells of the plant

(ix) In C_4 plants, fixation of CO_2 occurs in

(A) palisade tissue (B) cortex of stem

(C) spongy mesophyll and bundle of sheath (D) phloem tissue

(x) ATP synthesis during light reactions is

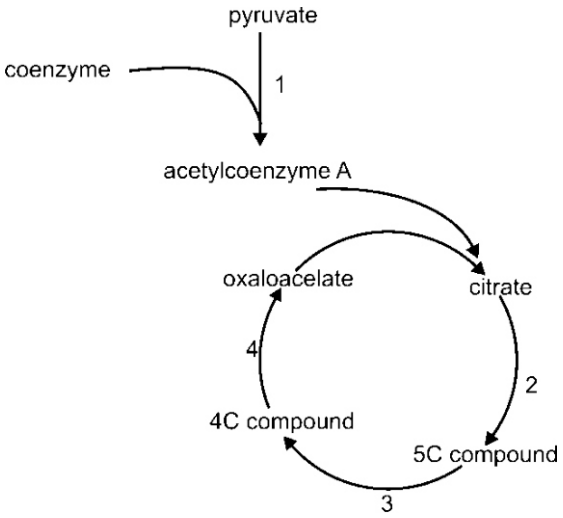
(A) oxidative (B) photolysis

(C) substrate phosphorylation (D) photophosphoryation

(xi) In C_3 plants first stable product of photosynthesis during dark reaction is

(A) PGA (B) G3P (C) RuBP (D) oxaloacetate

(xii) The diagram shows the Krebs cycle. At which numbered stages does decarboxylation take place?



(A) 1 and 2 (B) 1, 2 and 3

(C) 1, 3 and 4 (D) 1, 2, 3 and 4

Short Questions

2. What is electromagnetic spectrum?
3. Explain ‘action spectrum’ of photosynthesis.
4. What are the types of chlorophyll?
5. What is the importance of carotene?
6. Describe ‘absorption spectrum’ in photosynthesis.
7. What is photosystem? Explain.
8. What is the role of carbon dioxide in photosynthesis?
9. How it was confirmed that ‘plants split water as a source of hydrogen releasing hydrogen as a byproduct?
10. What is the importance of G3P?
11. What is the effect of temperature on the activities of RuBisCO?
12. What are the disadvantages of photorespiration?
13. How photorespiration evolved?
14. Write the differences between:

(a) chlorophyll a and chlorophyll b
(b) carotene and xanthophyll
(c) action spectrum and absorption spectrum
(d) absorption spectrum of chlorophyll a and b
(e) antenna complex and reaction centre
(f) photosystem I and photosystem II
(g) light dependent reaction and light independent reaction of photosynthesis
(h) oxidative phosphorylation and photophosphorylation
(i) cyclic photophosphorylation and non-cyclic photophosphorylation
(j) C_4 carbon fixation and C_3 carbon fixation
(k) lactic acid fermentation and alcoholic fermentation
(l) Calvin cycle and Krebs cycle
(m) oxidative phosphorylation and substrate level phosphorylation

Extensive Questions

15. What is photosynthesis? Explain the role of light in photosynthesis.
16. Describe the structure of chlorophyll.
17. Write a note on the photosynthetic pigment carotene.
18. Explain the arrangement of photosystems.
19. Describe the role of water in photosynthesis.
20. Describe the mechanism of photosynthesis.
21. Explain in detail the light dependent phase of photosynthesis?
22. Explain in detail the light independent phase of photosynthesis?
23. Describe cyclic photophosphorylation.
24. Describe Calvin cycle.
25. Describe the kinds of cellular respiration.
26. Give an account of 'Glycolysis'.
27. Explain oxidation of pyruvate.
28. Explain Krebs cycle.
29. Explain electron transport chain.
30. Explain chemiosmosis and oxidative phosphorylation.
31. Describe substrate level phosphorylation.
32. Give an account of photorespiration in plants.
33. Explain that C_4 photosynthesis is an adaptation to the problem in photorespiration.

About the Content Authors

Prof. Jawaid Mohsin Malick

Prof. Jawaid Mohsin Malick was born on 8th February 1945 in the province of Bihar. Malick is the title given to his ancestor Syed Ibrahim by the King Muhammad Tughlaq. Syed Ibrahim was a saint, the commander in chief of the army and conqueror of Bihar. Syed Ibrahim is the descendent of Hazrat Ghos-e-Azam, Syed Abdul Qadir Jilani (رحمة للهعليه) at the seventh generation. The ancestors of Syed Ibrahim migrated from Iraq to Afghanistan and settled in the village 'But Nagar' near Ghazni. Prof. Jawaid served as lecturer in Quaid-i-Azam College and Notre Dame College Dhaka. He is a former head of the department of Zoology, F.G. Postgraduate College, H-8,Islamabad where he served for more than twenty five years. He is also a former Principal, Federal Government College, H-9 , F-10/4 Islamabad, and Director Colleges and Director Administration, Federal Directorate of Education, Islamabad. He did his post-graduation in Zoology with specialization in Entomology from Dhaka University, East Pakistan (former). He taught various classes for more than forty five years in various capacities. He has also worked as Education Officer, in Nigeria for four years. He has successfully completed the 61st advance course in administration and development held in 1996 at National Institute of Public Administration (NIPA), Karachi. In 1995, he was awarded a shield by the honourable Mr. Rafiq Tarrar, the then President of Pakistan, for his services to humanity.

He published four research papers in Science Journals of Pakistan on Butterflies of Pakistan. He has contributed articles on science and sports in Urdu and English dailies of Islamabad. He is co-author and managing author of more than forty five textbooks on General Science and Biology as well as Biology Practical Notebooks. He has travelled to Singapore, Thailand, Indonesia, India, Bangladesh, UAE, Saudi Arabia, Egypt, Italy, Holland, UK, Qatar, USA and Nigeria. He has also served as a National Consultant, Science Education, JICA sponsored project for the promotion of Student Centred and Inquiry Based (SCIB) learning, National Institute of Science and Technical Education, Ministry of Education, Islamabad.

Dr. Sarwat Jawaid

Dr. (Mrs.) Sarwat Jawaid is the daughter of Prof.J.M.Malick. She has served as Medical Officer (Burn Centre) in Pakistan Institute of Medical Sciences, Islamabad. She did her graduation in Medicine from Isra University Hyderabad (2005) and Master in Public Health from Sarhad University, Peshawar (2009). She is a co-author of Biology textbooks of grade 9, 10, 11 and 12 as well as practical notebooks. She has also written a thesis on "Effect of health awareness programme in the reduction of burn injuries incidence among the community of Islamabad territory".

Prof. Abid Ali Mughal

Prof. Abid Ali Mughal is serving as Assistant Professor and Head of Biology Department, Islamabad Model College for Boys, H-9, Islamabad. He started his teaching career as lecturer in Botany at F. G. Degree College for Men, Wah Cantt in 2003. Before that he had also served as Research Fellow in Plant physiology and Biotechnology divisions of Nuclear Institute of Agriculture, Tandojam Dist. Hyderabad, which is an agricultural research centre of Pakistan Atomic Energy Commission. He did his M.Sc. (Hons), Botany in 2002 from University of Sindh, Jamshoro and was awarded Gold Medal. He did M.Phil. Biotechnology from Quaid-i-Azam University in 2009. His field of specialization is Plant physiology and genetic engineering. He is Principal Author of Textbook of Biology for Grade-12 according to National Curriculum 2006, published by Khyber Pakhtun Khua Textbook Board Peshawar. He has also been Resource Person in the demonstration and laboratory sessions of Teacher's Training Workshop on "Laboratory Methods in Biology", held at Department of Animal Science, Quaid-e-Azam University Islamabad. He is now Ph.D Research Scholar in the Department of Environmental sciences, University of Arid Agriculture, Rawalpindi.