

Unit 6: Bioenergetics

Long Questions

DESCRIPTIVE QUESTIONS

Q1. Define Bioenergetics. How ATP is used as cell energy currency?

Ans. Definition: Bioenergetics is the study of how **energy flows** through living systems.

Explanation: It explores the processes through which cells **store** and **expend** energy. The processes of photosynthesis and respiration help to understand some of the principles of bioenergetics. Photosynthesis acts as an **energy-capturing** while respiration as an **energy-releasing** process.

ATP

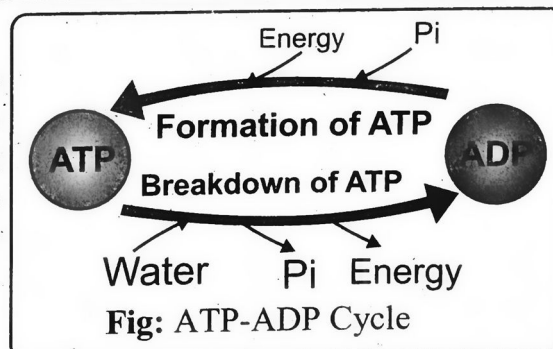
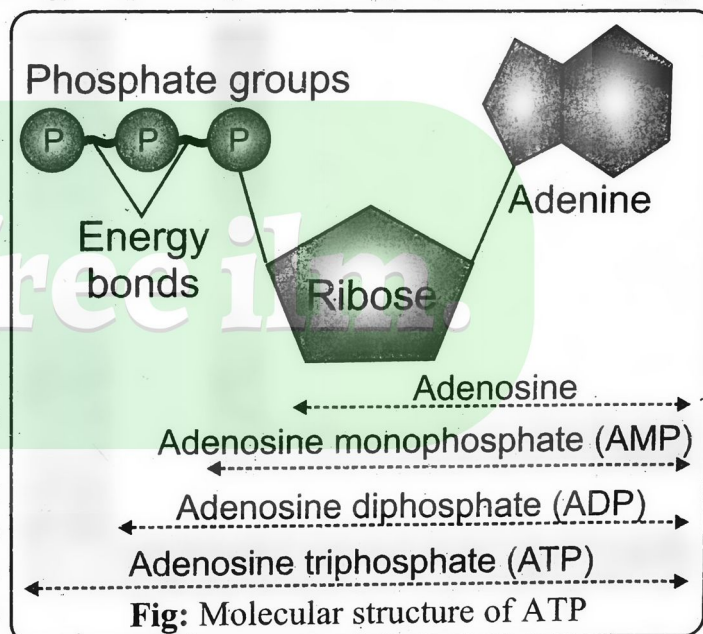
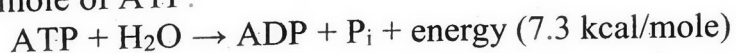
★**Discovery of ATP:** ATP was discovered in 1929 by **Karl Lohmann**. In 1941, the Nobel prize winner **Fritz Lipmann** proposed that ATP is the main energy-transfer molecule in the cell.

The energy currency of cells

Cells use a special energy currency for their reactions. This currency is actually a nucleotide called **adenosine triphosphate (ATP)**. When cells store energy, they make ATP. When cells need energy, they break ATP. A molecule of ATP has **three subunits** i.e. **adenine**, (a nitrogen containing base); **ribose** (a five-carbon sugar) and **three phosphate groups**.

ATP-ADP Cycle

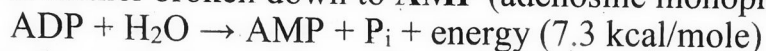
The **covalent bonds** between two phosphates are high-energy bonds. When one of these bonds is broken, inorganic phosphate (P_i) separates and energy is released. The breaking of one phosphate bond releases about **7.3 kcal** (7,300 calories) per mole of ATP.



★ **Note:** All questions and paragraphs marked with a star ★ are explanations of the Box Information provided in the textbook.

In common energy reactions only the outer **P-P high energy bond** breaks. When this happens, **ATP** becomes **ADP** (adenosine diphosphate) and one P_i is released.

In some cases, **ADP** is further broken down to **AMP** (adenosine monophosphate) and P_i :



Cells get energy from the **oxidation of food**. They store this energy by combining ADP with P_i to form ATP. So, we can summarize that ATP is made during energy-releasing processes and it is broken down during energy-consuming processes. In this way ATP transfers energy between metabolic reactions.

PHOTOSYNTHESIS

Q2. Define photosynthesis. What is role of light and carbon dioxide in process of photosynthesis?

Ans. Photosynthesis

Definition: Photosynthesis involves the use of **light energy** that is absorbed and converted into chemical energy by photosynthetic pigments.

★ In this process the energy-poor inorganic compounds of carbon (i.e. CO_2) are reduced to energy-rich carbohydrates.

Equation: Photosynthesis in plants can be summarized as:



Explanation: Carbon dioxide, water and light are the reactants while **glucose** and **oxygen** are the products. Water appears on both sides of the equation because water is used as reactant in some reactions and released as product in others. However, there is no yield of water.

★ **Compensation Point:** Photosynthesis uses the **products of respiration** and **respiration** uses the products of photosynthesis. Photosynthesis occurs only during day time but respiration goes on day and night.

In Dark: During darkness, leaves and other parts respire and utilize oxygen and release carbon dioxide.

Dawn and dusk: At dawn and dusk, when **light intensity** is **low**, the rate of photosynthesis and respiration may be equal for a short time. Thus, the oxygen released from photosynthesis is just equal to the amount required for cellular respiration. Also, the carbon dioxide released by respiration is just equal to the amount required by photosynthesizing cells. At this moment there is no net gas exchange between leaves and atmosphere. This is termed as compensation point.

At noon, when the **light intensity increases**, the rate of photosynthesis also **increases**. At this time, there is more requirement of carbon dioxide. Respiration alone cannot supply this carbon dioxide. Similarly, the oxygen produced during photosynthesis is more than the need of the respiring cells. So, the result is the net release of oxygen coupled with the uptake of carbon dioxide.

Role of Light: Light plays a crucial role in photosynthesis, providing the energy required to drive the **chemical reactions** that transform simple molecules into complex organic compounds. Light energy is absorbed by **chlorophyll**. The absorbed light energy is converted into **chemical energy**, which is in turn stored in organic compounds in the form of **C-H bond** energy.

Role of Carbon Dioxide

Sugar is formed by the **reduction of CO_2** by using **ATP** and **NADPH**. In this way, CO_2 acts as the source of carbon for making sugars. Carbon dioxide enters the leaves through stomata and gets dissolved in water absorbed by the cell walls of mesophyll cells. **Stomata** are found

in large numbers in leaves. The entry of CO_2 into the leaves is dependent upon the opening of stomata.

★ **Source of CO_2 :** About 10% of total photosynthesis is carried out by terrestrial plants, the rest occurs in oceans, lakes and ponds. Aquatic photosynthetic organisms use dissolved CO_2 , bicarbonates and soluble carbonates as carbon source. Land photosynthetic organisms use atmospheric CO_2 as carbon source.

Q3. Describe the role of water in photosynthesis through an experiment.

Ans. Role of Water

Water is the source of **hydrogen**, for the **reduction of CO_2** during photosynthesis. **Oxygen** released during **photosynthesis** comes from **water** and so water is an important source of atmospheric oxygen which most organisms need for aerobic respiration and thus for obtaining energy to live.

Contribution of Van Neil: In 1930s, **Van Neil** hypothesized that plant splits water as a source of hydrogen, releasing oxygen as a by-product. **Neil's hypothesis** was based on the investigations on photosynthetic bacteria that make carbohydrate from carbon dioxide, but do not release oxygen later confirmed by scientists during 1940s.

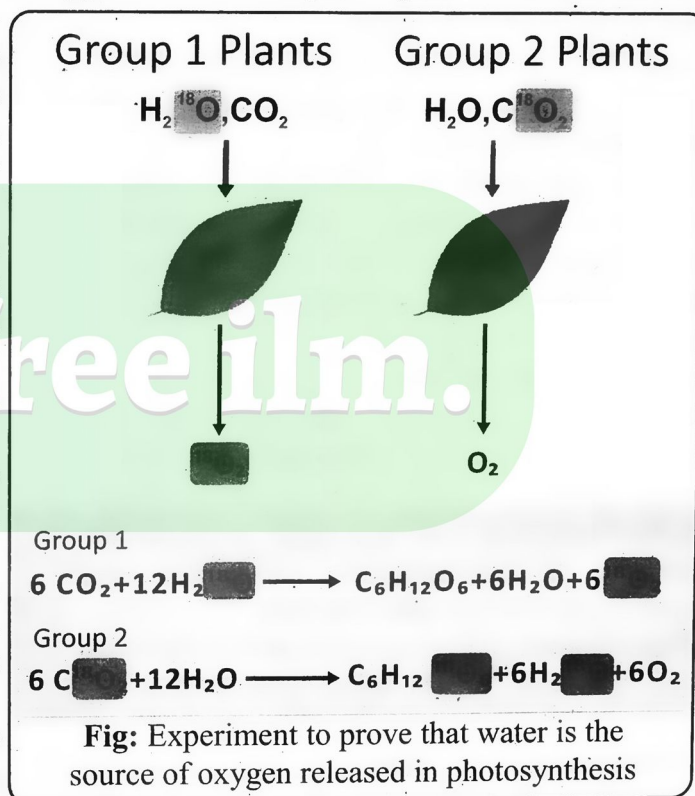
- An experiment was conducted in which **isotopic tracer (^{18}O) of oxygen** was used. In laboratory, scientists prepared water with **heavy-oxygen** i.e., H_2^{18}O .
- They also prepared carbon dioxide with heavy oxygen i.e., C^{18}O_2 .
- Experimental green plants in one group were given water H_2^{18}O and normal carbon dioxide i.e., C^{16}O_2 .
- Plants in the second group were given C^{18}O_2 and normal water i.e., H_2^{16}O . Both plants were given an environment to conduct photosynthesis.
- Oxygen released during photosynthesis of both plants was collected and tested.
- It was found that plants of first group produced ^{18}O but the plants of second group produced normal oxygen (^{16}O).

Q4. What are photosynthetic pigments? Explain chlorophyll molecule and accessory pigments as photosynthetic pigments?

Ans. Photosynthetic pigment

Photosynthetic pigments are present in **thylakoid membranes**. These pigments capture light energy necessary for photosynthesis. Some of the pigments are **chlorophyll a**, **chlorophyll b**, **xanthophylls**, **carotenes**.

Role of photosynthetic pigments: Different pigments absorb light of different wavelengths (colours). Light behave like a stream of particles called **photons**. Pigment molecules absorb one photon at a time. When a pigment molecule absorbs a photon, its electrons move to higher energy level, so, it becomes energy-rich or excited.



★ **Wavelength of photon:** Short wavelength photons (**blue**) have a higher energy than long wavelength (**red**) photons. More energetic photons (shorter wavelength) promote electrons to higher energy levels.

Bacteriochlorophylls

Chlorophyll is a lipid molecule. Chlorophylls are of different kinds. Chlorophyll a, b, c and d are found in plants and algae, while the others are found in photosynthetic bacteria and are known as **bacteriochlorophylls**.

Parts: A molecule of chlorophyll consists of two parts i.e., a **hydrophilic head** and a **hydrophobic tail**.

Head: The head is made of porphyrin ring, which further consists of four pyrrole rings (5-sided N-containing compounds). The four pyrrole rings are held together by a magnesium atom in the centre. In chlorophyll-a, the second pyrrole ring has **methyl (CH₃) group** while in chlorophyll-b, it has **aldehyde (CHO) group** at the same spot. The porphyrin ring of chlorophyll absorbs light.

Tail: The tail is made of long hydrocarbon chain. It anchors the molecule in the thylakoid membrane.

Light Absorption: Chlorophyll absorb mainly **violet-blue** and **orange-red** wavelengths of light. Green wavelengths are least absorbed by chlorophyll and are transmitted or reflected.

Accessory Pigments

Accessory pigments include all the pigments, other than **chlorophyll-a**, which can gather light for photosynthesis.

Chlorophyll-b is an accessory pigment and others are **carotenoids** (carotenes and xanthophylls) and **phycobilins**.

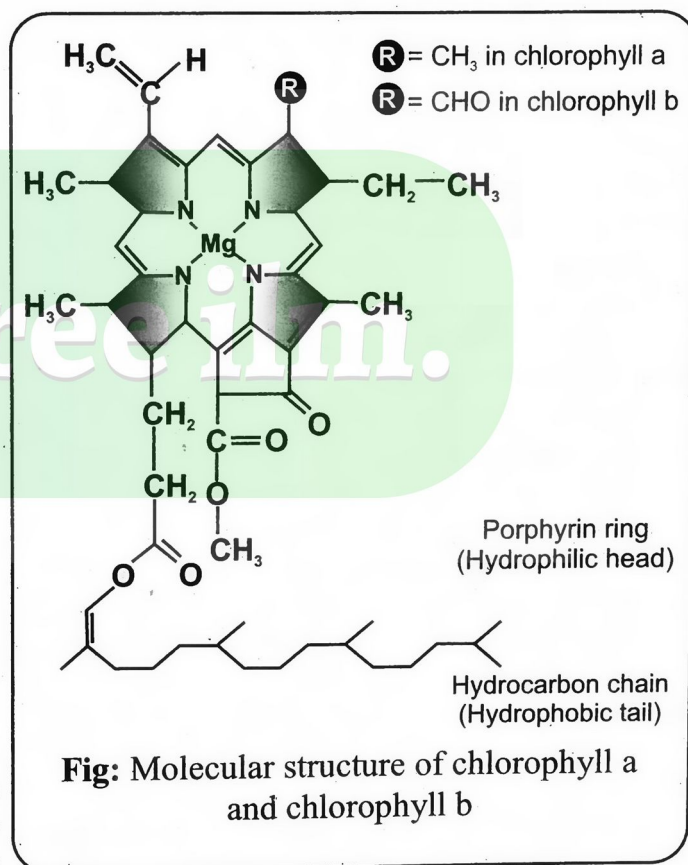
Occurrence: Chlorophyll b and carotenoids are found in plants while phycobilins are found in the red algae and cyanobacteria.

Absorption of light: When accessory pigments absorb light, they pass on the energy towards chlorophyll a. It is generally believed that the order of transfer of energy in plants is;

Carotenoids → Chlorophyll b → Chlorophyll a

Q5. Describe the action and absorption spectrum of light.

Ans. Action spectrum: Photosynthetic pigments absorb **different wavelengths** of light at different rates. Moreover, the different wavelengths are also differently effective in photosynthesis. The **effectiveness** of different wavelengths of light is determined in terms of **action spectrum**. For getting action spectrum of light, a plant is illuminated with different colours of light one by one. While providing each colour, the rate of photosynthesis is measured by measuring the amount of oxygen emitted from leaves. The data is plotted in a

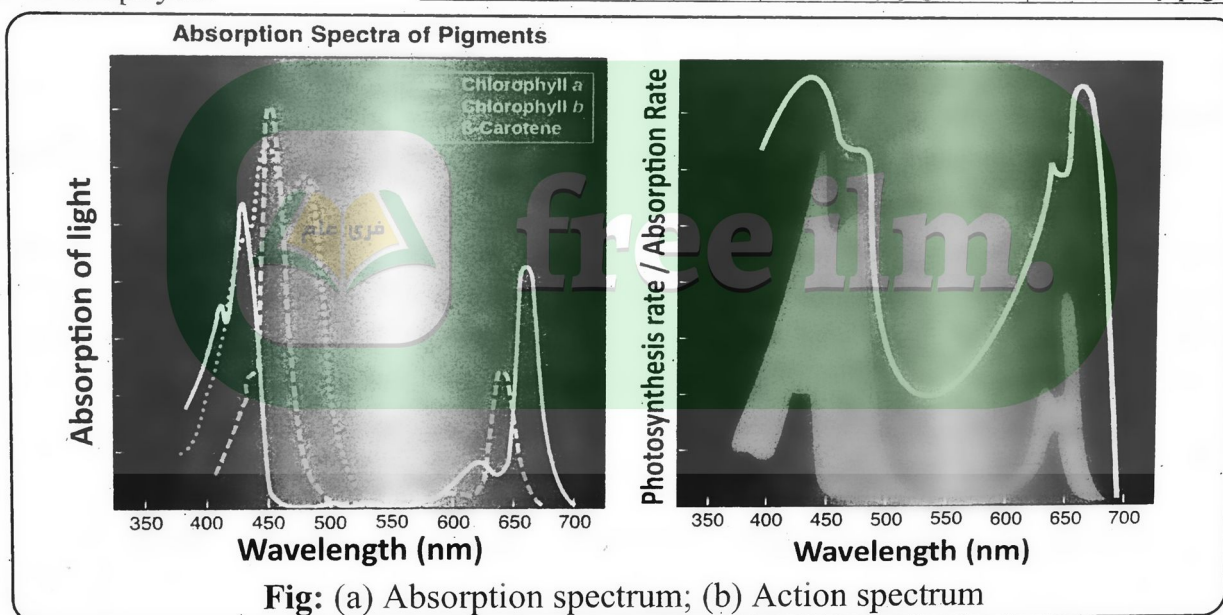


graph called action spectrum. The first action spectrum was made by a German biologist, T.W. Engelmann in 1883. He worked on the photosynthetic pigments of *Spirogyra*. When the cells of a filament of *Spirogyra* were illuminated with different wavelengths of light, maximum photosynthesis occurred in the cells which received blue and red spectrum of light and so maximum oxygen was emitted from these cells.

Absorption Spectrum: A graph showing different wavelengths absorbed by a pigment, is called absorption spectrum of the pigment. Absorption spectrum of chlorophylls indicates that absorption of **blue light (430 nm)** and **red light (670 nm)** is maximum. Absorption peaks of carotenoids are different from those of chlorophylls. Action spectrum of photosynthesis also shows that **blue** and **red** parts lights are the most effective. This means that the action spectrum of photosynthesis coincides with the absorption spectrum of photosynthetic pigments.

Some wavelengths not absorbed by **chlorophyll-a** are very effectively absorbed by **chlorophyll-b** and vice-versa. Such differences increase the range of light absorbed by both chlorophylls.

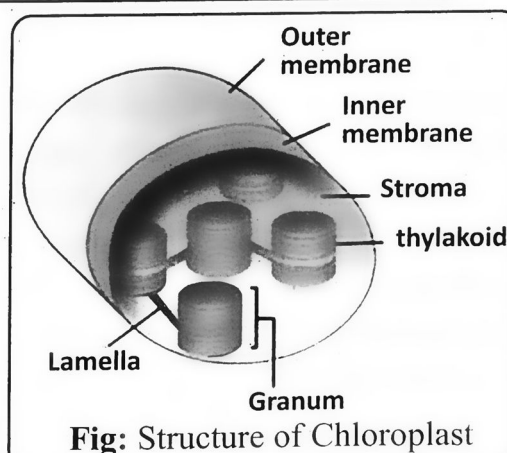
Features	Chlorophyll-a	Chlorophyll-b
Absorbance	430 nm	455 nm
Colour	Blue – Green	Yellow – Green
Role in photosynthesis	Primary pigment	Accessory pigment



Q6. What are photosystems? Give their structure. / Describe how photosynthetic pigments are organized in thylakoid membrane?

Ans. Definition: For efficient absorption and utilization of solar energy, photosynthetic pigments are organized into clusters, called **photosystems**. These photosystems are embedded in **thylakoid membranes** of chloroplasts.

Components: Photosystems contain photosynthetic pigments and the carriers of **electron transport chain**. Each photosystem consists of a light gathering '**antenna complex**' and a '**reaction centre**'.



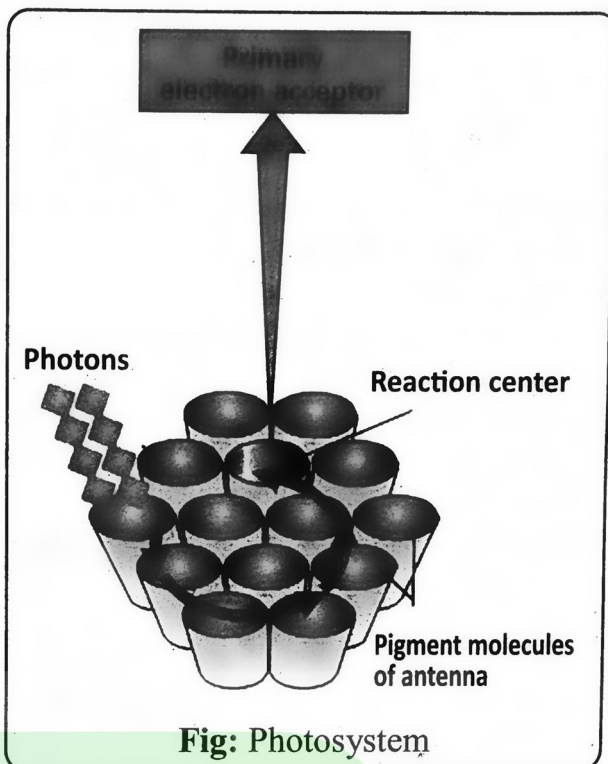
Antenna Complex: Antenna complex has many **pigment molecules** which **capture** light energy and pass the excitation energy (in the form of high-energy electrons) to the reaction centre.

Reaction Centre: The reaction centre has one or more molecules of **chlorophyll-a**, which pass the **high-energy electrons** to a primary electron **acceptor**. The electron acceptor passes them on to the series of electron carriers, collectively called **electron transport chain**.

Types: In chloroplast, there are two photosystems, **photosystem-I**, (PS-I) and **photosystem-II** (PS-II). These are named so in order of their discovery.

PS-I: PS-I has **P₇₀₀ chlorophyll-a** molecule in its reaction centre and it absorbs maximum light of 700 nm.

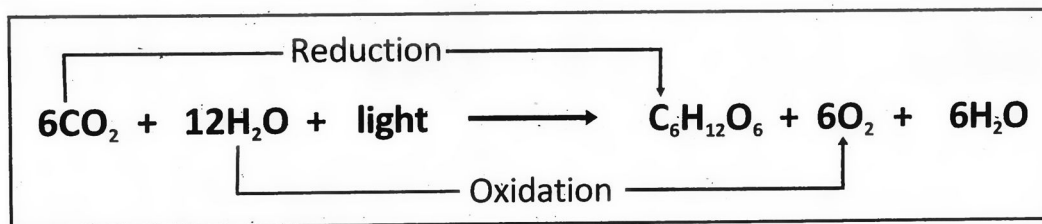
PS-II: The reaction centre of PS-II has **P₆₈₀ chlorophyll-a**, which absorbs best the light of 680 nm.



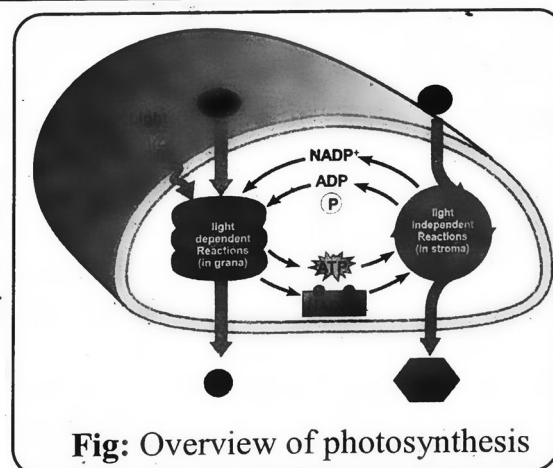
Q7. How photosynthesis is a redox reaction? Explain.

Ans. Mechanism of photosynthesis

Photosynthesis is a **redox (oxidation-reduction) process**. As indicated in the photosynthesis equation below, when water molecules are split apart, they are actually oxidized (they lose electrons and hydrogen ions) and yield oxygen. Meanwhile, **CO₂** is reduced to sugar as electrons and hydrogen ions are added to it. In this way oxidation and reduction go hand in hand.



However, it is not a simple, single – step process. Rather, it is a **complex metabolic pathway** consisting of a series of reactions. The **light-dependent reactions** take place on the thylakoid membranes of the **grana** while the **light-independent reactions** take place in the **stroma** of the chloroplasts.



Q8. Give detail of the events that capture light and convert it into chemical energy during light dependent reactions? Illustrate Cyclic Photophosphorylation.

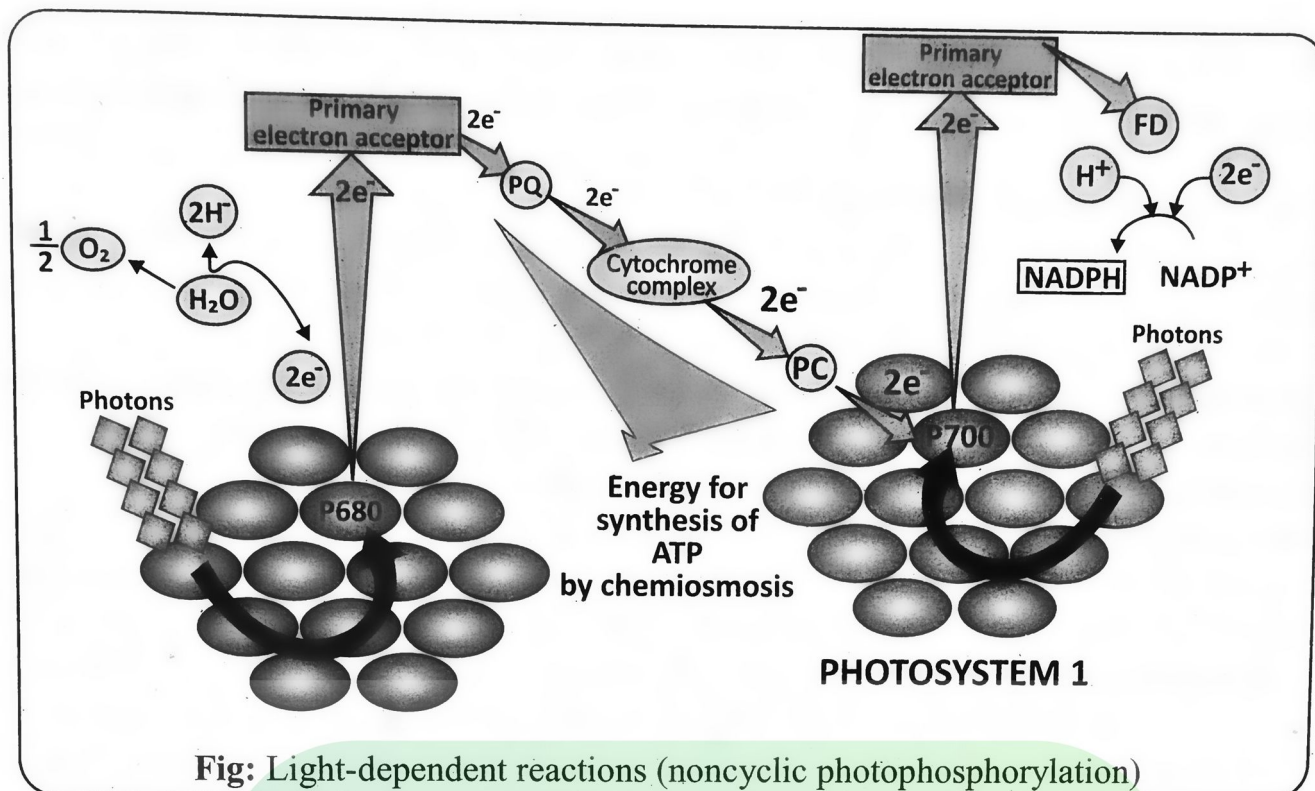
Ans. Light Dependent Reactions

The key events in the light-dependent reactions of photosynthesis are (1) the **absorption** of light energy by photosynthetic pigments, (2) the **excitation** of electrons by that energy, and (3) the formation of **ATP** and **NADPH**.

Photophosphorylation: The formation of ATP is the most important step of **light-dependent reactions**. It is called **photophosphorylation**. This process is either non-cyclic photophosphorylation or cyclic photophosphorylation.

Non-Cyclic Photophosphorylation: It is the usual way of the production of ATPs during light-dependent reactions. In non-cyclic pathway, both photosystems i.e., **PS-I** and **PS-II** participate and two electron chains are involved. It happens in the following way:

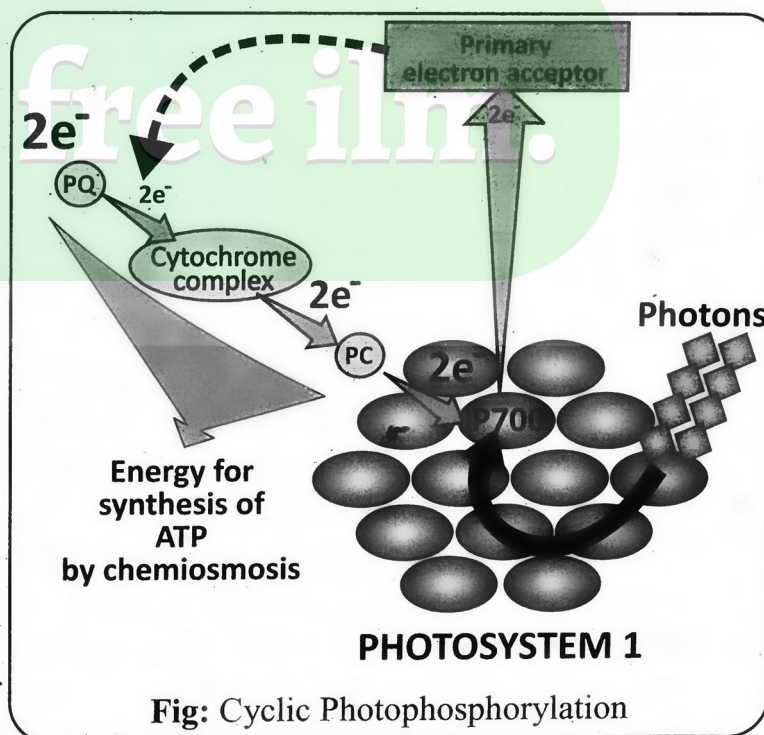
1. **Absorption of light by PS-II:** When light falls on PS-II, the energy level of chlorophyll molecules of its antenna centre rises. Two excited electrons move from them and pass to different chlorophyll molecules. The excited electrons reach **P₆₈₀ chlorophyll** present in the reaction centre. Due to energy boost of P₆₈₀ chlorophyll, its two excited electrons pass to the primary electron acceptor of photosystem-II. Due to it, an electron "hole" is created in **P₆₈₀ chlorophyll**, which has become a strong oxidizing agent.
2. **Photolysis of water:** The electron "hole" in chlorophyll molecule is filled by the electrons from water. When water molecule reacts with oxidized chlorophyll in PS-II, it breaks into two hydrogen ions, an oxygen atom (which immediately combines with another oxygen to form O₂), and two electrons. These two electrons fill the "hole" in P₆₈₀ chlorophyll. This water splitting step of photosynthesis is called **photolysis**. The oxygen produced during photolysis is the main source of atmospheric oxygen.
3. **Electron flow from PS-II to PS-I:** In step 1, the photoexcited electrons of P₆₈₀ chlorophyll were received by primary electron acceptor of PS-II. Now, these electrons carriers called **plastoquinone (PQ)**, cytochrome complex and **plastocyanin (PC)**. As electrons move down the chain, their energy goes on decreasing and is used by thylakoid membrane to produce ATP through the process of chemiosmosis.
4. **Absorption of light by PS-I:** In the next step light energy is absorbed by PS-I. The energy level of its chlorophyll molecules boosts to very high level. The excited electrons of **P₇₀₀ chlorophyll** of the reaction centre pass to the primary electron acceptor of PS-I. The electrons coming from PS-II fill the electron "hole" of P₇₀₀ chlorophyll of PS-I.
5. **Electron flow from PS-I to NADP⁺:** The primary electron acceptor of PS-I passes the photoexcited electrons to a second electron transport chain. These electrons are received by ferredoxin (FD). An enzyme **NADP reductase** transfers these electrons from FD to NADP⁺. When NADP⁺ gets two electrons and an H⁺ ion, it is reduced to NADPH. This reaction stores the high-energy electrons in NADPH.



So, the light energy gets converted into chemical energy (ATP and NADPH). The zigzag path taken by electrons through PS-II and PS-I and electron transport chains, is called **Z-scheme**.

Cyclic Photophosphorylation

Under certain conditions, photoexcited electrons of PS-I take an alternative path called cyclic electron flow. This path uses **PS-I** but not **PS-II**. These electrons cycle-back from primary electron acceptor of PS-I to **P₇₀₀ chlorophyll** via the electron transport chain. There is no production of NADPH and no release of oxygen. Cyclic flow however generates ATP. It happens when **Calvin cycle** slows down and NADPH accumulates in **chloroplast**.



Q9. Explain the mechanism of Chemiosmosis with the help of diagram.

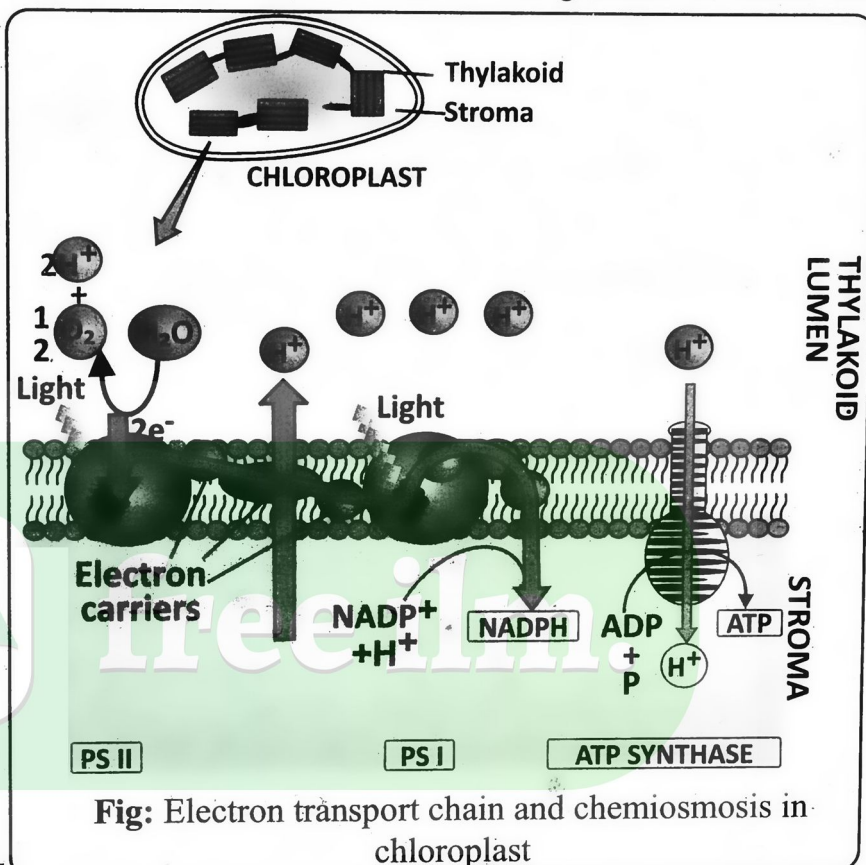
Ans. Chemiosmosis

This process uses the energy released from electron transport to synthesize ATP. During light-dependent reactions when electrons are transferred to the series of carriers of electron transport chain, it results in oxidation and reduction reactions. Electrons lose energy during this carrier-to-carrier

transport. **Chemiosmosis** is the mechanism in which **thylakoid membranes** couple these **redox reactions** with the synthesis of ATPs.

Process

- The energy released from electrons is spent for the active transport of H^+ ions from the stroma of chloroplast to its inner compartment (lumen).
- In this way many H^+ ions are deposited in the lumen. This H^+ ion gradient in lumen has potential energy.
- The H^+ ions diffuse back from lumen in stroma (from higher concentration in lumen to lower concentration).
- While diffusing, they pass through a special protein of the membrane of thylakoid cells. This protein is an enzyme called **ATP synthase**.
- This enzyme uses the energy yielded from the flow of H^+ ions to make a bond between **ADP** and **inorganic phosphate (Pi)**.
- So, ADP is converted into ATP and energy is packed in it.
- ★ The electron transport chains in mitochondria and chloroplasts generate ATP by the same mechanism of chemiosmosis.



Q10. Explain Calvin cycle? / Illustrate light independent reactions of photosynthesis in terms of paragraph and illustrate in terms of Calvin cycle.

Ans. Light – Independent Reactions

Light-independent reactions are a series of reactions which happen in the stroma of chloroplast. These reactions use carbon from CO_2 , energy from ATP, and hydrogen ions from NADPH to construct energy-rich sugar molecules. These are also called **dark reactions**. These reactions can occur in the absence as well as in the presence of light, as long as ATP and NADPH are available.

Discovery: The details of dark reactions were discovered by **Melvin Calvin** and his colleagues at the University of California. That is why, the dark reactions are also called the **Calvin cycle**. Calvin was awarded **Nobel Prize** in **1961** for this work.

Phases: The Calvin cycle is divided into the following phases.

Phase I: Carbon Fixation

Carbon fixation refers to the initial incorporation of CO_2 into organic material. An enzyme known as **ribulose biphosphate carboxylase** (or **Rubisco**; probably the most abundant

protein on Earth) combines three molecules of CO_2 with three molecules of a **five-carbon sugar** named **ribulose biphosphate (RuBP)**. It results in the formation of **six molecules** of a three-carbon compound called 3-phosphoglyceric acid (3-PGA) or 3-phosphoglycerate.

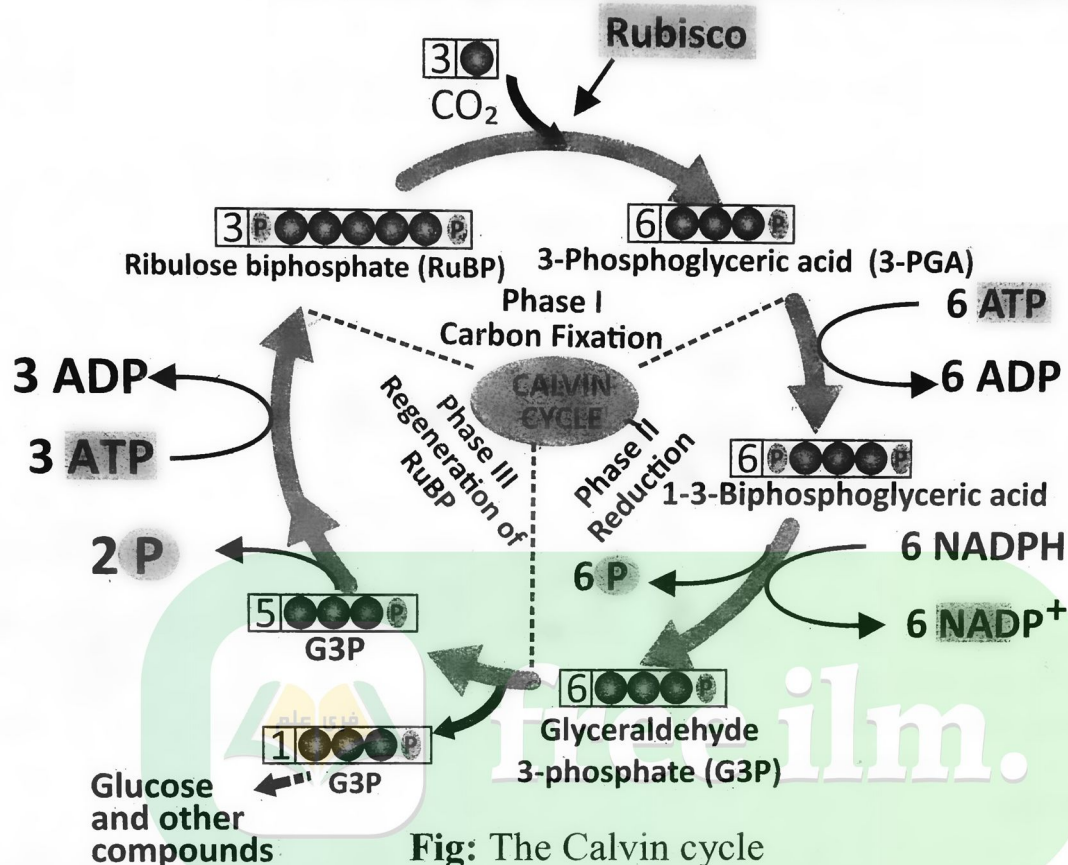


Fig: The Calvin cycle

Phase II: Reduction

In this phase, six phosphate groups are taken from **six ATPs** and added to molecules of **3-PGA**. In this way, each 3-PGA changes into **1, 3-biphosphoglyceric acid**. Each 1,3-biphosphoglyceric acid is then reduced to **Glyceraldehyde 3-phosphate (G3P)**. **NADPH** provides hydrogen for this reduction. During this step, phosphate groups are also detached from **1,3-biphosphoglyceric acid**.

In this way, six molecules of **G3P** are produced, out of which one molecule leaves the cycle. It combines with another G3P and makes glucose, which may be then converted to other carbohydrates.

★ **G3P in Glycolysis:** G3P is the same three-carbon sugar which is formed in glycolysis (first phase of cellular respiration) by the splitting of glucose.

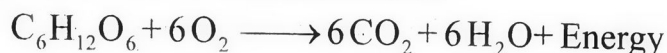
Phase III: Regeneration of RuBP

Through a series of reactions, **five molecules of G3P** are converted into three molecules of **Ribulose phosphate (RuP)**. One phosphate group is added to each RuP to make three molecules of RuBP by using three ATPs of light reactions. These RuBP receive CO_2 again and the cycle continues.

Q11. What is cellular respiration? Give its types.

Ans. Definition: Cellular respiration is the universal process by which organisms **break down** complex carbon containing compounds (e.g., glucose) to get useable energy.

Equation: Cellular respiration can be summarized as:



The arrangement of atoms in glucose has more stored energy while there is much less energy in the arrangement of atoms in CO_2 and H_2O . The reason is that there are many C-H bonds in glucose but there are no such bonds in CO_2 and H_2O .

The exchange of CO_2 and O_2 between the organism and its environment is called **external respiration** or breathing.

Step-by-step oxidation: Cellular respiration is the process by which energy is made available to cells in a **step-by-step oxidation** of food in the cells.

★ Many of the reactions that occur in your cells also occur in the cells of frog mice, planaria, mushrooms and radishes.

Respiratory Fuel: The basic events in cellular respiration in all cells are much similar. Almost all cells in all organisms use **glucose** as energy source. That is why, glucose is known as respiratory fuel.

Types: There are two main types of cellular respiration:

1. **Anaerobic respiration** (fermentation) takes place in the absence of oxygen.
2. **Aerobic respiration** takes place in the presence of oxygen.

In the first step of both these types, glucose is split into two molecules of pyruvic acid ($\text{C}_3\text{H}_4\text{O}_3$) in a process called glycolysis. The next reactions of pyruvic acid are different in anaerobic and aerobic respiration.

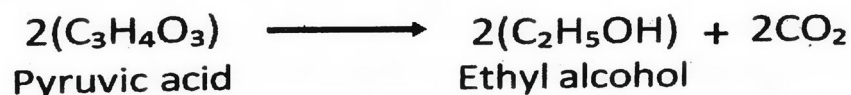
Q12. What happens with glucose in anaerobic respiration and how different organisms modify the end products?

Ans. Anaerobic Respiration: Anaerobic respiration happens in many **microorganisms** and in some cells of higher plants. It also happens in the muscle cells of vertebrates. In anaerobic respiration, glucose is not completely oxidized. This type of respiration yields relatively small amount of energy from glucose molecule. As a result of anaerobic respiration, one glucose molecule yields only two **ATPs** (only about 2% of the energy present in glucose). The energy in two ATPs is equivalent to **14.6 kcal**.

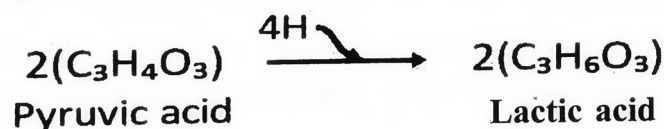
Types of Fermentation

Anaerobic respiration consists of **glycolysis** followed by the reduction of **pyruvic acid** by NADH to either **lactic acid** or alcohol and CO_2 i.e., it may again be classified as;

- a. **Alcoholic Fermentation:** In primitive **prokaryotic cells (bacteria)** and in some **eukaryotic** cells such as **yeast**, **pyruvic acid** is further broken down by alcoholic fermentation into alcohol ($\text{C}_2\text{H}_5\text{OH}$) and CO_2 .



- b. **Lactic acid Fermentation:** In lactic acid fermentation, each **pyruvic acid** molecule is converted into **lactic acid** $\text{C}_3\text{H}_6\text{O}_3$ in the absence of oxygen gas.



This form of anaerobic respiration occurs in **muscle cells of humans** and **other animals**. It happens during extreme physical activities, when oxygen cannot be transported to the cells as rapidly as it is needed. Many bacteria also use lactic acid fermentation to get energy.

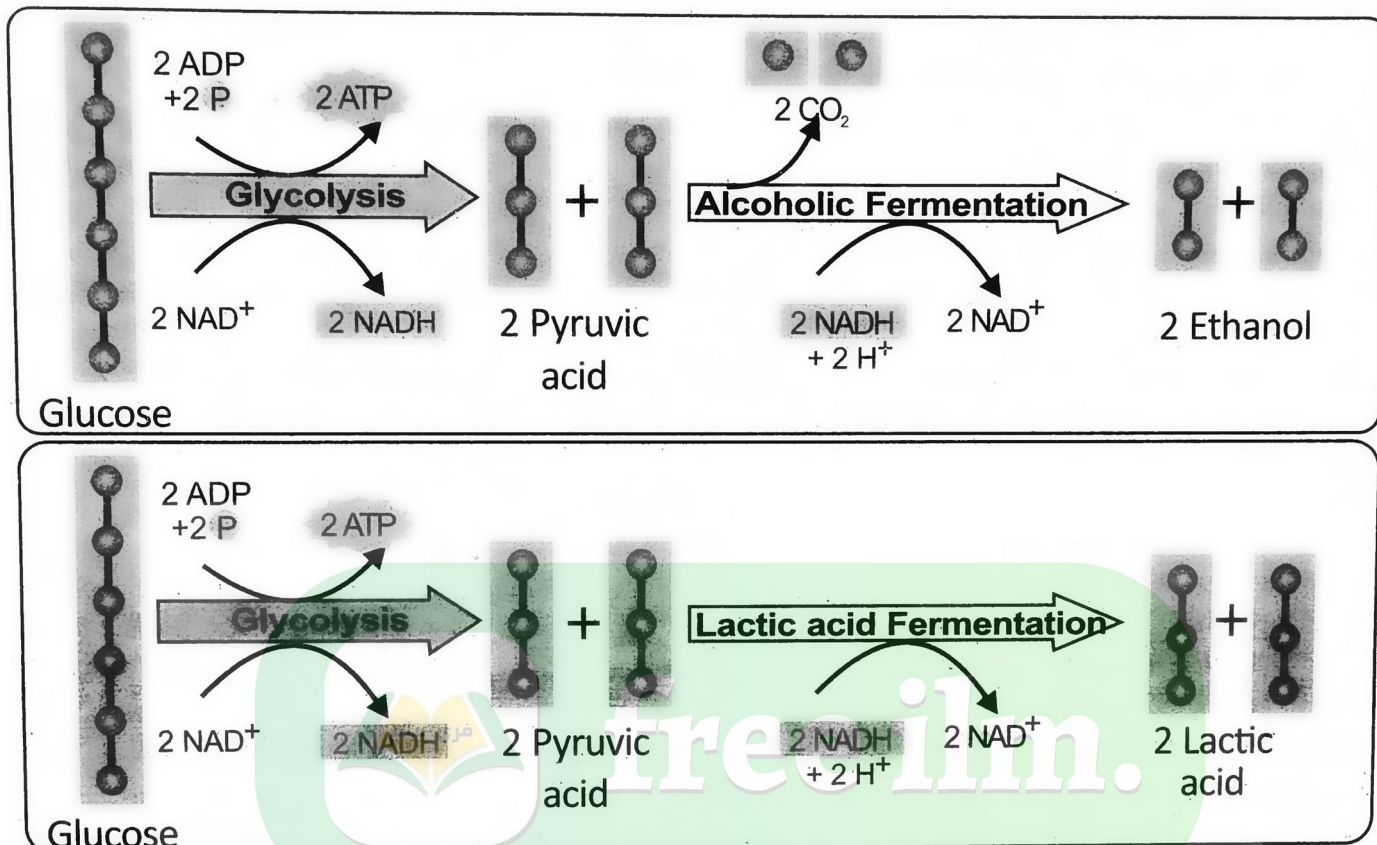


Fig: Alcoholic fermentation and lactic acid fermentation

Q13. What do you know about evolution of aerobic respiration? Also write its mechanism.

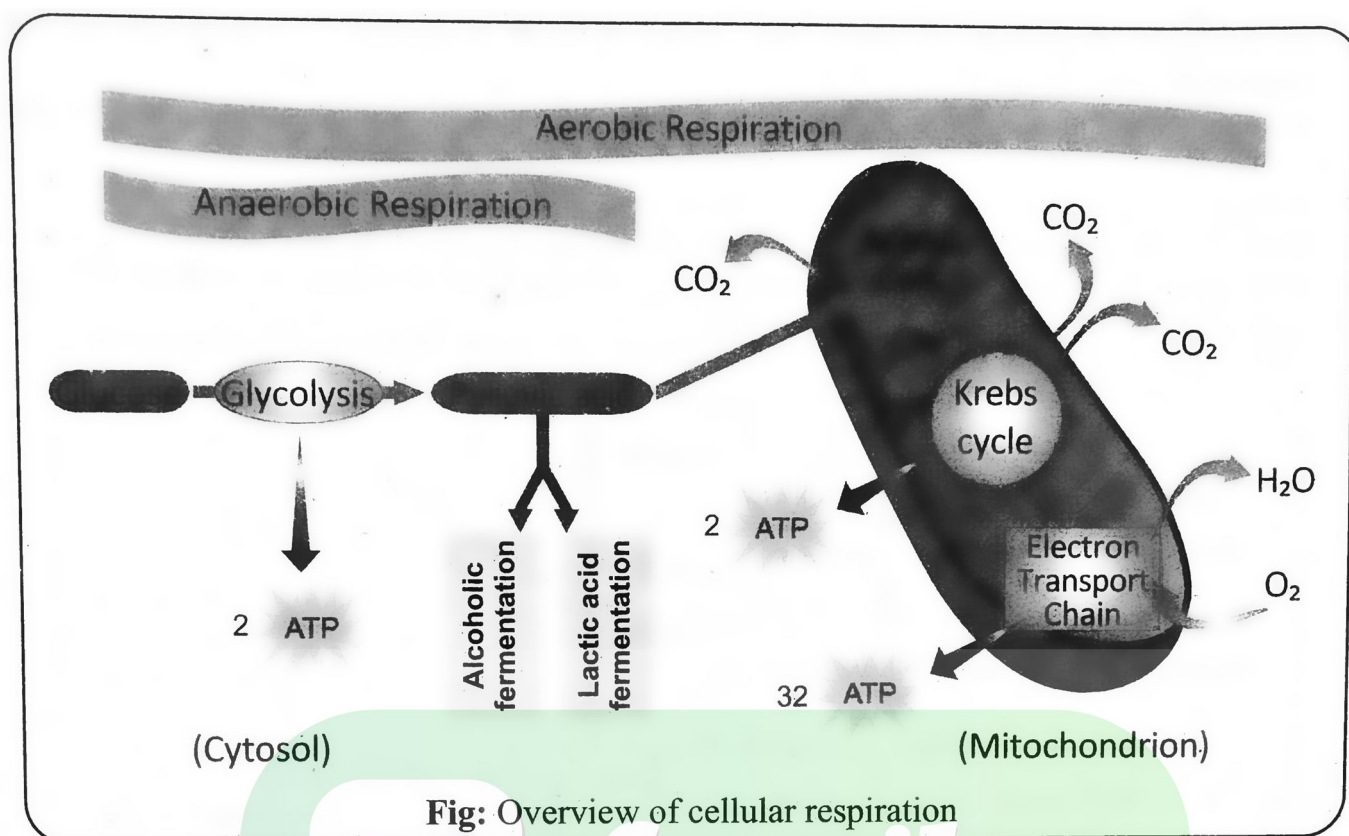
Ans. ★ Evolution of Aerobic Respiration

When life evolved on planet Earth free O_2 was not available. So, only anaerobic respiration was possible. But with the evolution of photosynthesis on Earth, molecular oxygen accumulated slowly in the atmosphere. The presence of free oxygen made **evolution** of aerobic respiration possible.

Mechanism: The complete breakdown of glucose molecule occurs only in aerobic respiration. During this process, glucose is broken down to pyruvic acid which is then completely oxidized to CO_2 and water and all the energy stored in its C-H bonds, is released.

Stages: Cellular respiration is a continuous process, but for study purposes we can divide it into four main stages.

1. Glycolysis
 2. Pyruvic acid oxidation
 3. Krebs cycle or citric acid cycle
 4. Electron transport chain and chemiosmosis
- Glycolysis** occurs in the cytosol and oxygen is not essential for this stage. The other three stages occur within **mitochondria** where the **presence of oxygen** is essential.



Q14. What is glycolysis? Explain how is glucose broken down to pyruvic acid in glycolysis?

Ans. Definition: Glycolysis is the **breakdown of glucose** into two molecules of **pyruvic acid**. Glycolysis takes place in both types of **respiration** i.e., anaerobic and aerobic.

Enzymes: The breakdown of glucose takes place in a series of steps, each catalysed by a specific enzyme. All these enzymes are found dissolved in the **cytosol**. In addition to the enzymes, **ATP** and **coenzyme NAD⁺** (nicotinamide adenine dinucleotide) are also essential. Glycolysis involves following reactions.

1. Preparatory Phase

It involves the expenditure of energy and the breakdown of glucose. It consists of the following steps;

- A phosphate group is transferred from ATP to glucose. As a result, glucose changes into **glucose 6-phosphate**.
- Glucose 6-phosphate is converted into its isomer called **fructose 6-phosphate**.
- Another ATP molecule transfers a second phosphate group to fructose 6-phosphate. So, it becomes **fructose 1, 6-biphosphate**.
- Fructose 1, 6-biphosphate is highly reactive and breaks into two molecules of three-carbon intermediates i.e., **glyceraldehyde 3-phosphate (G3P)** and **dihydroxy acetone phosphate (DAP)**. These are inter-converted and result in two molecules of G3P.

2. Oxidative Phase

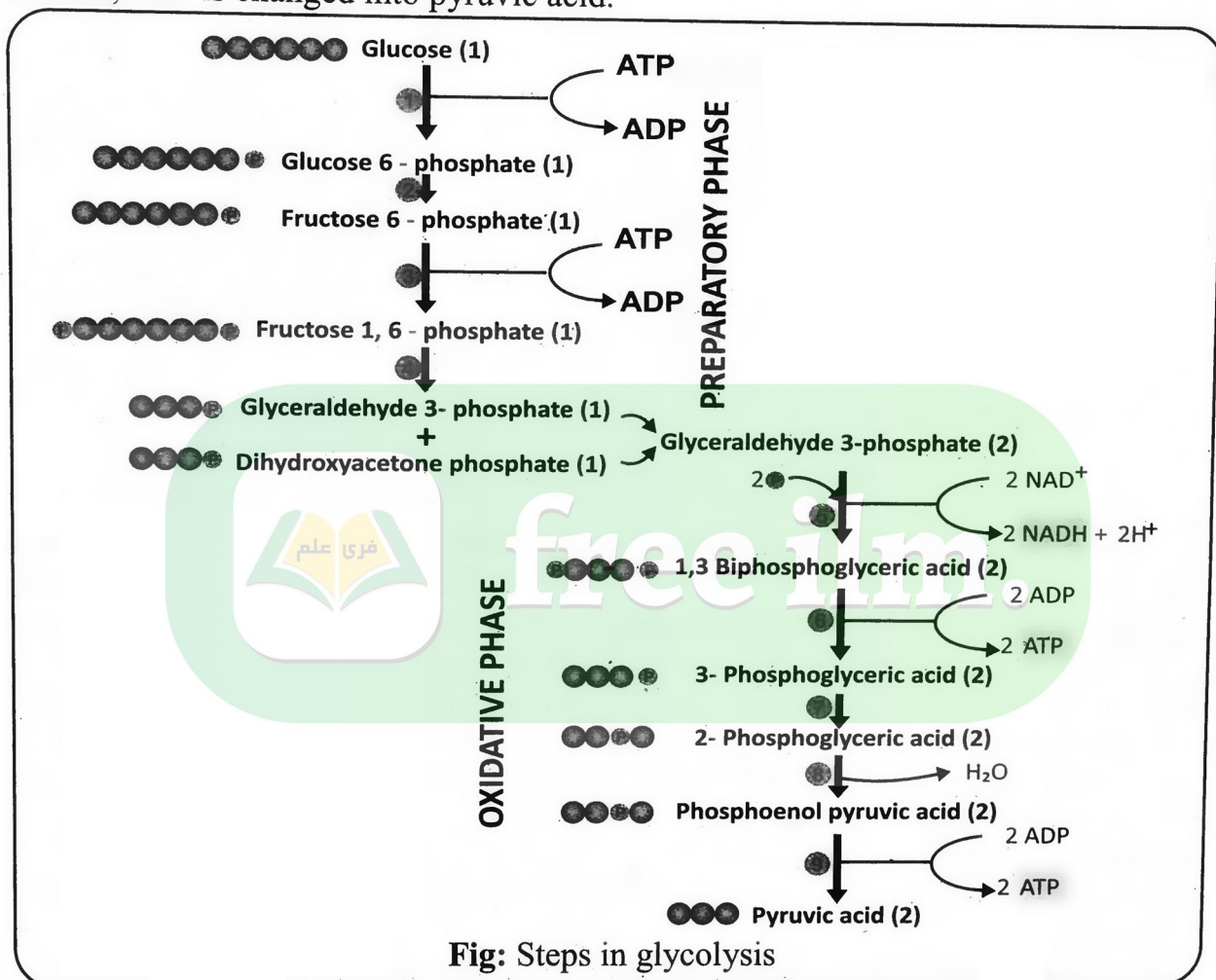
It involves the removal of hydrogen from **G3P** and packing of released energy in the form of ATP. It consists of the following steps:

Occurrence: Glycolysis occurs in cytosol and oxygen is not essential for it.

- Each G3P is oxidized to its acidic form. In this step, two hydrogen atoms (containing two high-energy electrons) are removed from **G3P** and transferred to **NAD⁺**. At the same time,

an inorganic phosphate group is also added to **G3P**. It results in a molecule of **1,3-biphosphoglyceric acid (1, 3-BPGA)**.

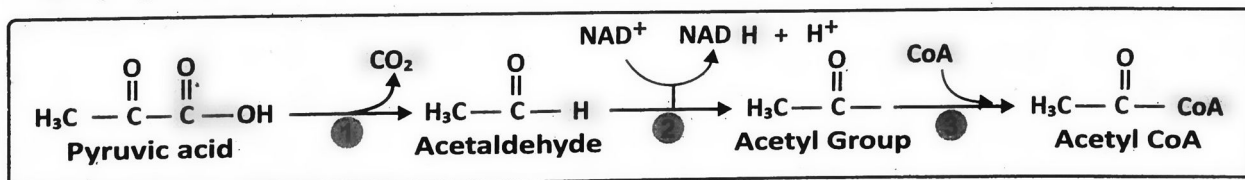
- The phosphate group is transferred from 1,3-BPGA to ADP. So, 1,3-BPGA changes into 3-phosphoglyceric acid (**3-PGA**). A molecule of ATP is also formed in this step.
- 3-PGA is converted to 2-phosphoglyceric acid (**2-PGA**).
- 2-PGA is dehydrated (water removed) into **phosphoenol pyruvic acid (PEP)**.
- PEP gives up its high energy phosphate to convert a second molecule of ADP to ATP. As a result, PEP is changed into pyruvic acid.



Q15. Explain pyruvic acid oxidation.

Ans. Pyruvic acid does not directly participate in **Krebs cycle**. It has to go through the following changes before entering the Krebs cycle.

- A molecule of **carbon dioxide** is removed from **pyruvic acid**. So, it changes into acetaldehyde.
- **Acetaldehyde** is oxidized (hydrogen is removed) to make **acetyl group**. A molecule of NAD⁺ is reduced to NADH.
- Acetyl group combines with coenzyme-A (CoA) to form **acetyl-CoA**.



Glucose enters cells from the tissue fluid by passive transport using a specific glucose carrier. The carrier can be controlled (gated) by hormones such as insulin.

Gluconeogenesis: Pyruvic acid can also be turned back into **glucose** by reversing glycolysis. This is called gluconeogenesis.

Q16. Explain Krebs Cycle. / Describe how Krebs cycle is the completion of oxidation of glycolytic products?

Ans. Krebs Cycle

This cycle was worked out by British biochemist, **Sir Hans Krebs** so it is called the **Krebs cycle**. It is also called the **citric acid cycle**, after the six-carbon citric acid molecule formed in its first step. All steps of the citric acid cycle occur in mitochondria. It involves following reactions.

- Pyruvic acid formed during glycolysis is first converted into Acetyl CoA. It now enters the cyclic series of chemical reactions of Kreb's cycle.
- Acetyl-CoA splits into **CoA** and **acetyl** group. The acetyl group combines with a four-carbon molecule, oxaloacetic acid. As a result, six-carbon **citric acid** is formed.
- Citric acid undergoes an oxidative decarboxylation reaction. It is decarboxylated (releasing a molecule of CO_2) and then oxidized (reducing an NAD^+ to NADH). So, a five-carbon molecule called **alpha-ketoglutaric acid** is formed.
- Alpha-ketoglutaric acid undergoes further oxidation and decarboxylation. It results in the formation of a four-carbon molecule i.e., succinic acid. **Succinic acid** joins with CoA and makes **succinyl CoA**.

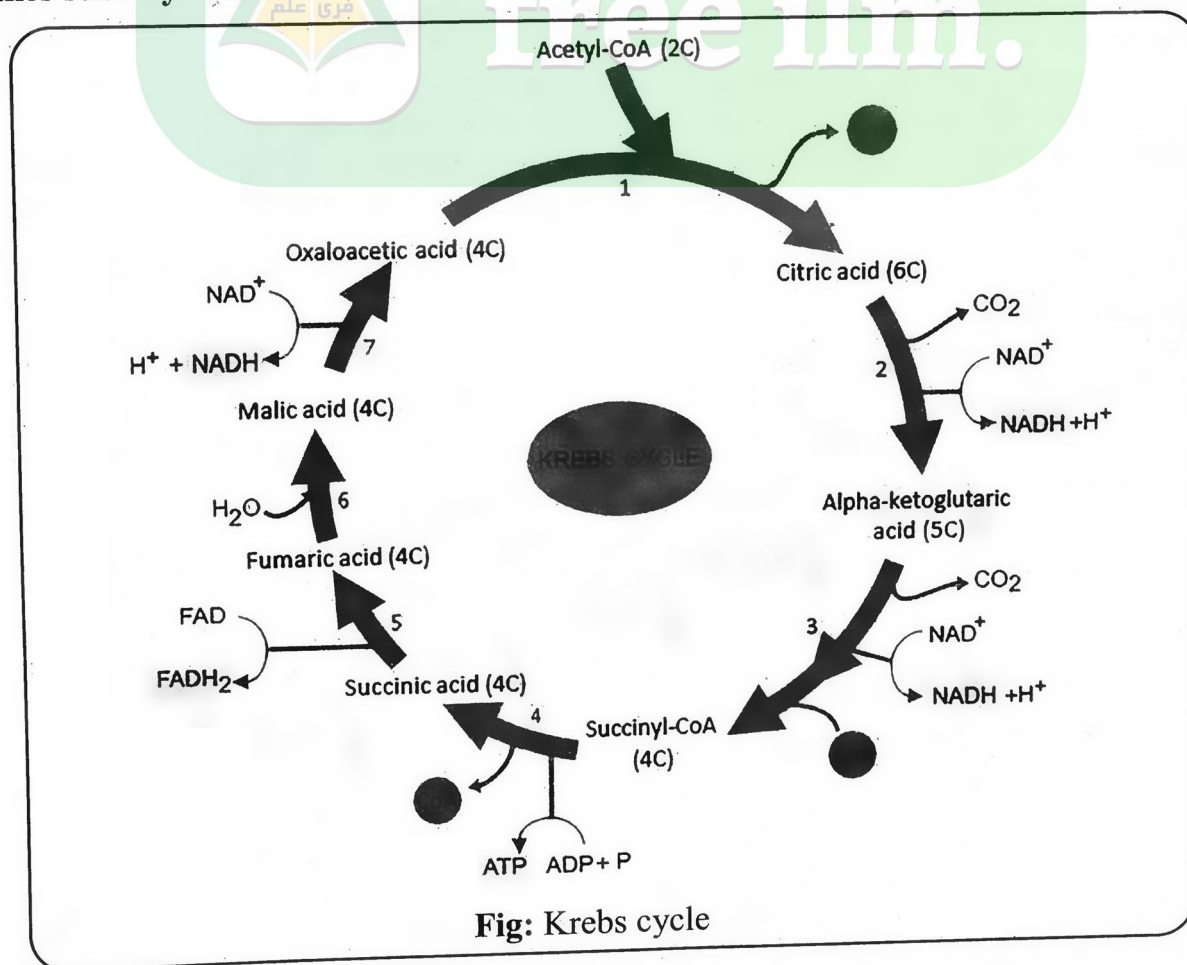


Fig: Krebs cycle

- The bond between succinic acid and CoA is a high-energy linkage. It again splits into CoA and succinic acid. The energy released in this reaction, is used in making a molecule of ATP.
- Succinic acid is oxidized to **fumaric acid**. When its two hydrogen atoms are removed, the free energy is not enough to reduce NAD^+ . So, a different electron acceptor i.e., the coenzyme flavin adenine dinucleotide (FAD) is used and is reduced to FADH_2 .
- In order to regenerate **oxaloacetic acid**, a molecule of water added to **fumaric acid** and it is changed to malic acid.
- **Malic acid** is oxidized to produce oxaloacetic acid. The hydrogen and electrons released from malic acid convert an NAD^+ to NADH . This completes the cycle and **oxaloacetic acid** is now free to bind to another molecule of **acetyl CoA** to initiate the cycle.

Q17. Explain Electron Transport Chain and Chemiosmosis. / Define chemiosmosis. How would you relate it with electron transport chain?

Ans. Electron Transport Chain

In electron transport chain the electrons are transferred from the reduced coenzymes i.e., NADH and FADH_2 to a series of electron carriers and finally to oxygen. After getting the electrons, the oxygen attaches with hydrogen ions and forms water.

The transfer of electrons to the series of carriers of electron transport chain results in oxidation and reduction reactions i.e., a carrier is oxidized when it loses electrons and next carrier transport.

Chemiosmosis: Chemiosmosis is the mechanism in which membranes are used to **couple** these **redox reactions** with the synthesis of ATPs.

Pathway of electrons: The electron transport chain of respiration is built in the inner membrane of the mitochondrion. At the start of electron transport chain, NADH is oxidized, and the released electrons are taken up by **coenzyme Q**. The reduced CoQ transports electrons to cytochrome 'b' which in turn transports them to **cytochrome 'c'**. Cytochrome 'c' then transports electrons to **cytochrome 'a' complex** (a complex of two cytochromes). This complex transports electrons to an atom of oxygen that is present at the bottom end of the chain.

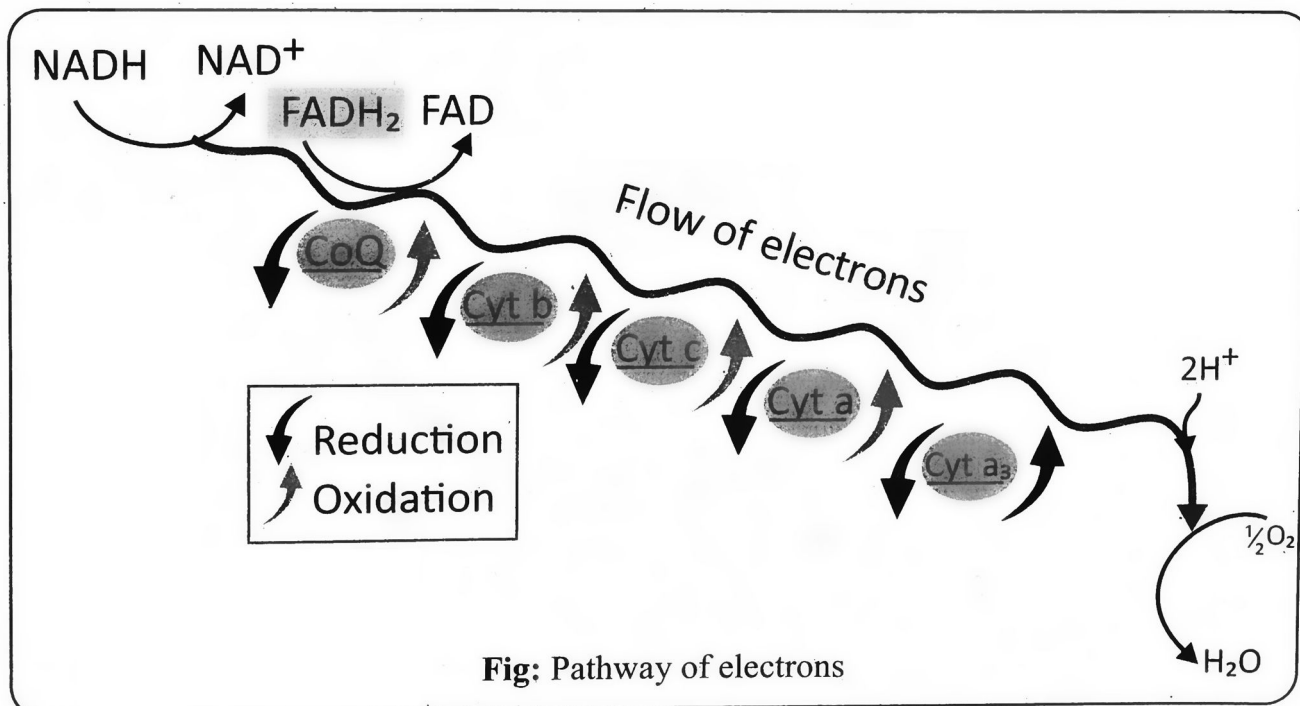


Fig: Pathway of electrons

Q18. How ATPs are synthesized in mitochondria?

Ans. Synthesis of ATP: As redox (reduction-oxidation) occurs, the energy released from the electrons is used for the **active transport** of H^+ ions from one side (the matrix of mitochondrion) of the membrane to the other (the inter-membrane space). In this way, many H^+ ions are deposited in the inter-membrane space. The resulting **H^+ ion** gradient stores potential energy. The H^+ ions diffuse back along their concentration gradient from the inter membrane space to the matrix.

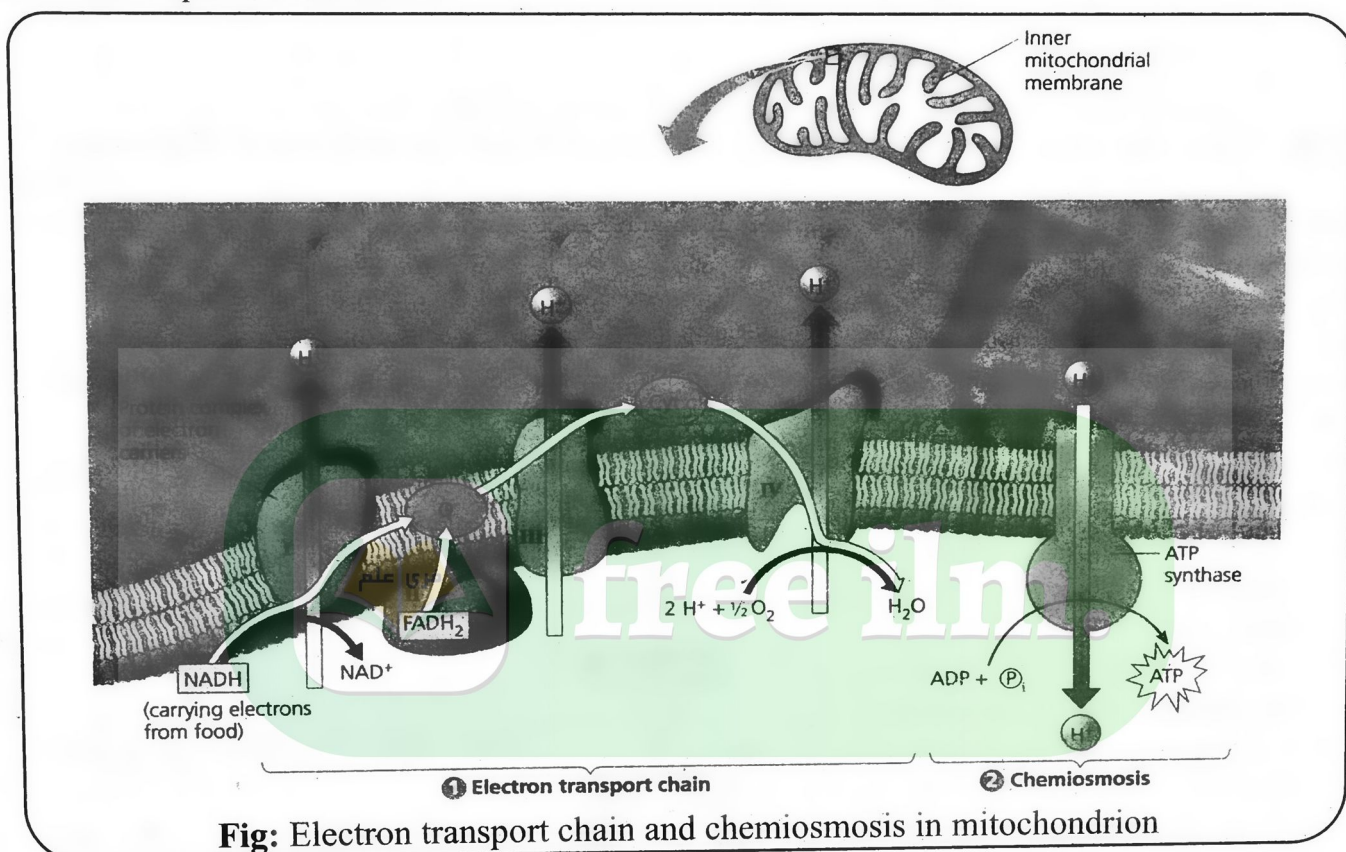
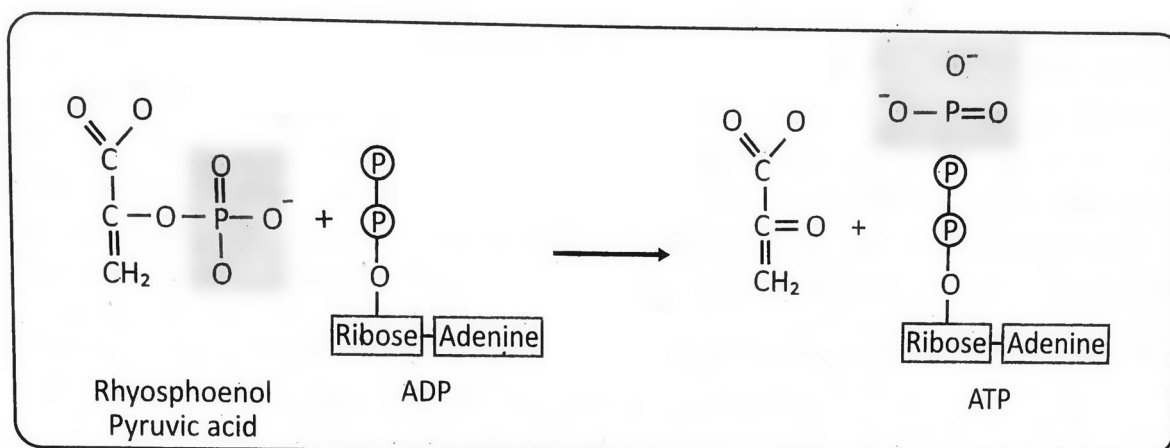


Fig: Electron transport chain and chemiosmosis in mitochondrion

On their way they pass through a special protein known as ATP synthase. As the H^+ ions move through this protein, their flow drives the synthesis of ATP. Oxidation of one molecule of NADH in electron transport chain produces three ATP. While oxidation of one FADH₂ produces two ATP. At the end, the two hydrogen ions are taken by the oxygen atom which has also taken two electrons to form water.

Q19. Explain substrate- level phosphorylation.

Ans. Cells generate ATP by **phosphorylation** i.e. adding a phosphate group to ADP. A cell has two ways to do this: chemiosmotic phosphorylation (chemiosmosis) and **substrate-level phosphorylation**. Substrate-level phosphorylation is much simpler than chemiosmosis. It does not involve any membrane or electron transport chain. In this process, an enzyme transfers a phosphate group from an **organic substrate molecule** to ADP. The products are a new organic molecule and a molecule of ATP. For example; during the last step of glycolysis, an enzyme transfers phosphate group from **phosphoenol pyruvic (PEP) acid** to ADP. As a result, ADP becomes ATP and PEP is changed into pyruvic acid. Substrate-level phosphorylation accounts for only a small percentage of the ATP that a cell generates. This reaction can be shown as:



Q20. Give the overview of the energy extracted from the oxidation of glucose.

Ans. The NADH and FADH_2 produced during **glycolysis** and **Krebs cycle** pass on their **energy-rich electrons** to the electron transport chain and ATPs are produced.

The NADH molecule generated in the Krebs cycle causes the production of three ATP molecules, during chemiosmosis, extracted from the aerobic oxidation of glucose

- Glycolysis takes place in cytoplasm and the NADH, produced during glycolysis, have to be transported across the **mitochondrial membrane**. It costs one ATP molecule per NADH. Thus each NADH of glycolysis produces two ATP molecules in the final balance sheet instead of three.
- Each FADH_2 molecule leads to the production of two ATP molecules.

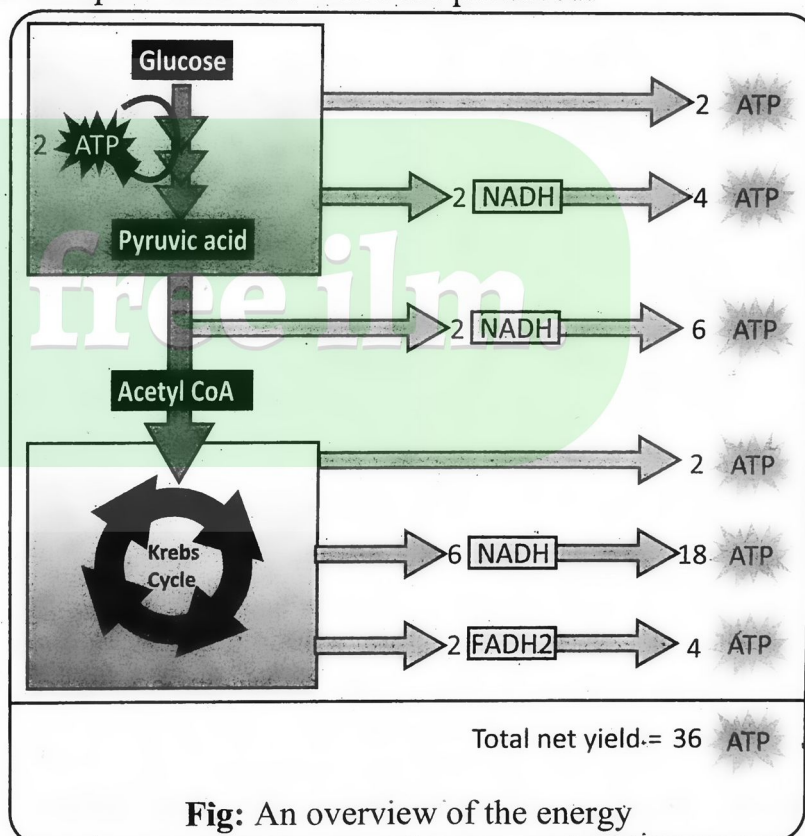
In this way, aerobic oxidation of glucose yields a net profit of **36 ATP molecules**.

While during the glycolysis of anaerobic oxidation only **2 ATP** molecules are generated. Thus, aerobic oxidation is **18 times more efficient** than anaerobic.

Q21. Through which ways proteins and fats enter cellular respiration?

Ans.

- Free glucose molecules** are not common in our diet. Rather, we consume sucrose and other disaccharides, starch, and **fats** and **proteins**.
- Proteins may also be used as fuel but they must be digested to their constituent amino acids.
- Typically, a cell uses most of the amino acids to make its own proteins.



- Some **amino acids** are deaminated (amino group detached) and then are converted to other organic compounds.
- These compounds are usually converted to **pyruvic acid**, acetyl CoA, or the organic acids in the Krebs cycle, and their energy is converted to ATP.
- **Lipids** are excellent cellular fuel because they contain many carbon-hydrogen bonds. They are first hydrolysed into glycerol and fatty acids.
- Glycerol is converted to **glyceraldehyde 3-phosphate**, an intermediate in glycolysis.
- While the fatty acids are changed into acetyl CoA. In this way both the fatty acids and the glycerol enter cellular respiration.

PHOTORESPIRATION

Q22. What is photorespiration? Explain its mechanism and disadvantages.

Ans. 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 produces CO_2 and H_2O like aerobic respiration. However, ATP is not produced during photorespiration.

Mechanism of Photorespiration

RuBP carboxylase (rubisco) catalyses the addition of CO_2 to RuBP to make phosphoglyceric acid (phosphoglycerate), which is further reduced to form glucose. However, when the relative concentration of CO_2 decreases and there is more oxygen in leaf cells, rubisco adds O_2 in RuBP instead of CO_2 . It results in the **breakdown of RuBP** into two molecules i.e., one phosphoglycerate and one phosphoglycolate (a two-carbon molecule).

Phosphoglycolate is converted into glycolate, which moves from chloroplast to peroxisome. Here, it is metabolized to glyoxylate by using O_2 . This reaction also produces toxic hydrogen peroxide (H_2O_2). **Glyoxylate** is then converted to glycine, which is transported to mitochondrion. Here, two molecules of glycine form a molecule

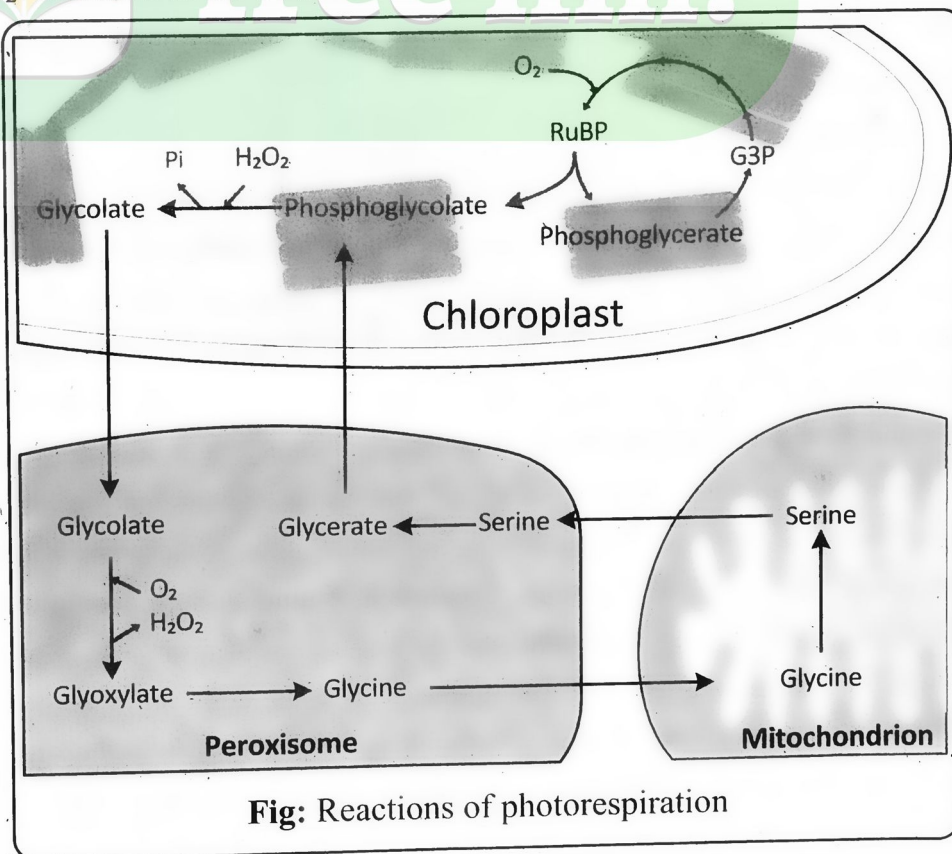


Fig: Reactions of photorespiration

of serine. Serine is then transported to peroxisome. Here, it is converted to glycerate. From peroxisome, glycerate moves to chloroplast, where it is changed to phosphoglycerate which can re-enter Calvin cycle.

Disadvantages of Photorespiration

- Plants that use Calvin cycle to fix carbon are called **C-3 plants**. When photorespiration occurs in these plants, they lose between a **25% to 50%** of their fixed carbon. It results in reduction in their yields.
- The rate of photorespiration also depends on temperature. At higher temperatures the oxidative activity of rubisco increases than its carbon fixing activity. In tropical climates, especially those in which the temperature is often above **28°C**, the problem is a severe and it has a major negative impact on agricultural yields.
- When photosynthesis first evolved, there was little oxygen in the atmosphere. So, there was little or no photorespiration. After millions of years, free O_2 accumulated in the atmosphere and competition started between CO_2 and O_2 for the same active site of rubisco. It led to the problem that photorespiration now poses.

Q23. How is the process of C-4 photosynthesis an adaptation to deal with the problem of photorespiration?

Ans. Adaptations to the problems of Photorespiration

Plants of warmer climates evolved the following two ways to deal with the problem of photorespiration.

C-4 Photosynthesis

Some plants including grasses (corn, sugarcane and sorghum) and about two dozen other plant groups run a special pathway called **C-4 photosynthesis** in addition to the normal Calvin cycle. In their leaves, the mesophyll cells have less air spaces. The enzymes of Calvin cycle are more deposited in specialized cells called **bundle-sheath cells**, which are impermeable to CO_2 .

During **C-4 photosynthesis** in mesophyll cells, CO_2 is attached with a 3-carbon molecule called phosphoenol pyruvic acid. It results in the formation of a four-carbon molecule oxaloacetic acid. Due to this first 4-C product, this process is called C-4 photosynthesis and the plants are called C-4 plants. **Oxaloacetic acid** is then converted to malic acid, by using NADH. Malic acid is broken down to pyruvic acid and CO_2 . These cells can hold CO_2 in them. So, concentration of CO_2 increases in these cells and they run Calvin cycle instead of photorespiration. Pyruvic acid produced in bundle sheath cells returns to mesophyll cell and is converted again to phosphoenol pyruvic acid by using ATP.

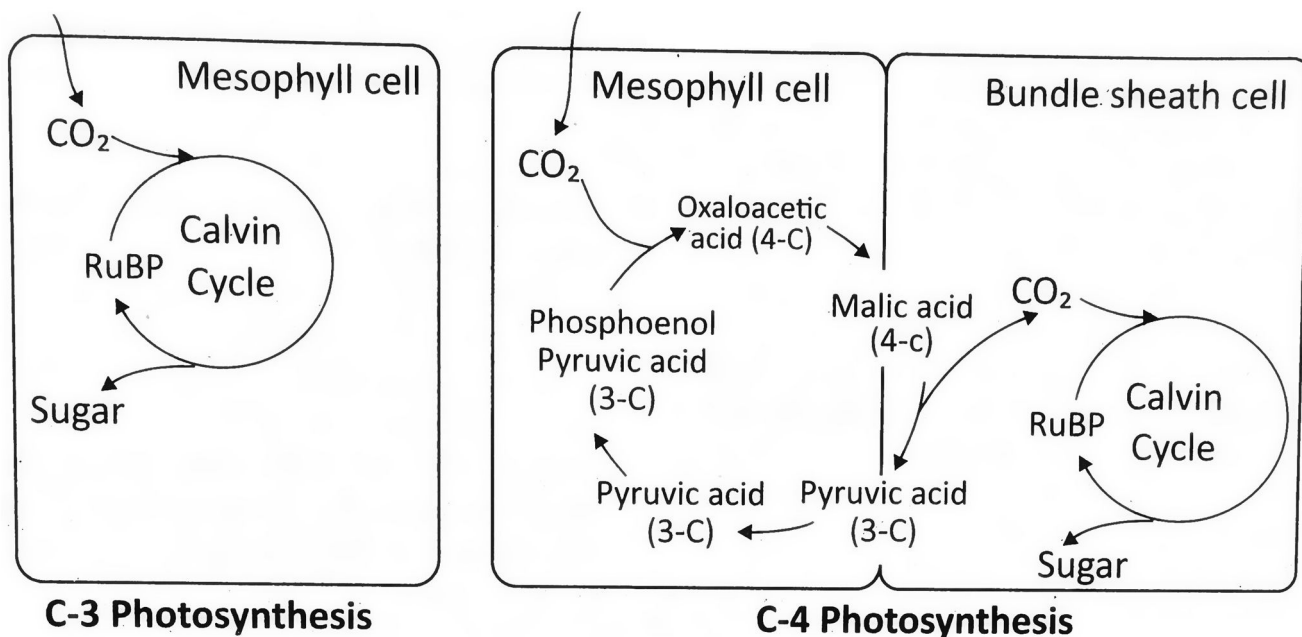


Fig: C-3 photosynthesis and C-4 photosynthesis

Q24. What is CAM metabolism?

Ans. In hot climates, many succulent plant such as **Cacti, pineapples** and some other plant groups perform Crassulacean acid metabolism or CAM (after the plant family Crassulaceae in which it was first discovered). In these plants, the stomata open during the night and close during the day. Closing stomata during the day prevents water loss and removal of CO_2 . So, rate of photorespiration is reduced due to high concentration of carbon dioxide. The carbon dioxide necessary for producing sugar is provided from organic molecules made the night before. Like C-4 plants, these plants use both C-4 and C-3 pathways.

