CHAPTER-4
BIOENERGETICS

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

Teacher's Point

Teachers would guide the students to draw the molecular structure of chlorophyll, showing the porphyrin head and phytol tail

Teacher's Point

Teacher would guide the students to develop the graphical interpretation of the wavelengths of light along with the percentage absorption by of chlorophyll a and b?

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.

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.

Q1. Explain cellular respiration of fats and proteins.

Ans: 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 indicates, glycerol is converted to PGAL, 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.

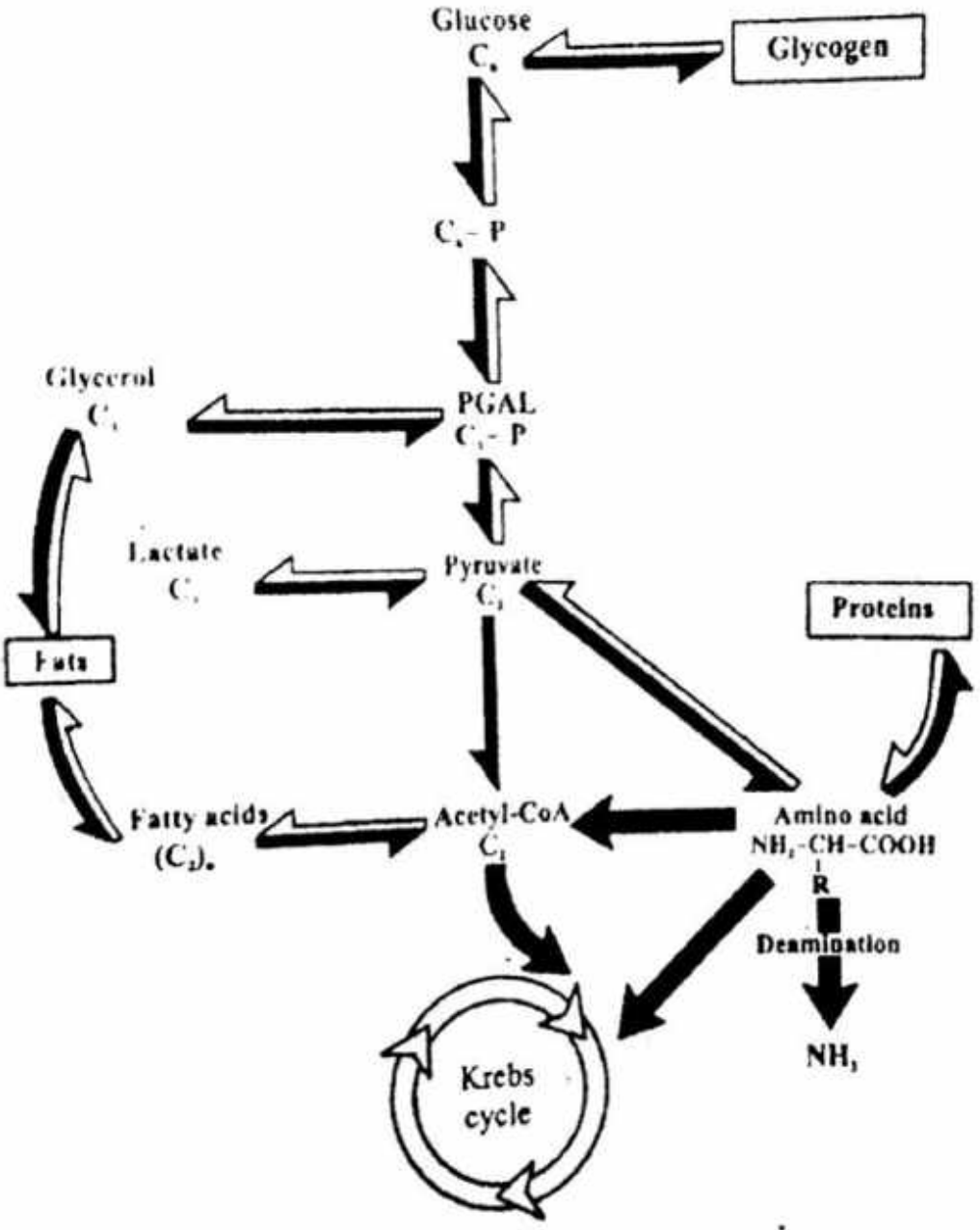


Fig. The matabolic pool concept: When they are used as energy sources carbohydrates, fats and proteins enter degradative pathways at specific points. Degradation produces metabolites that can be used for synthesis of other compounds.

Teacher's Point

Teachers would guide the students to:

- 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.

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.

Teacher's Point

Teachers would guide the student to justify why photorespiration is interference in the successful performance of the Calvin cycle.

Activity

Extraction of the leaf pigments and their separation by paper chromatography

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	increases

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(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 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

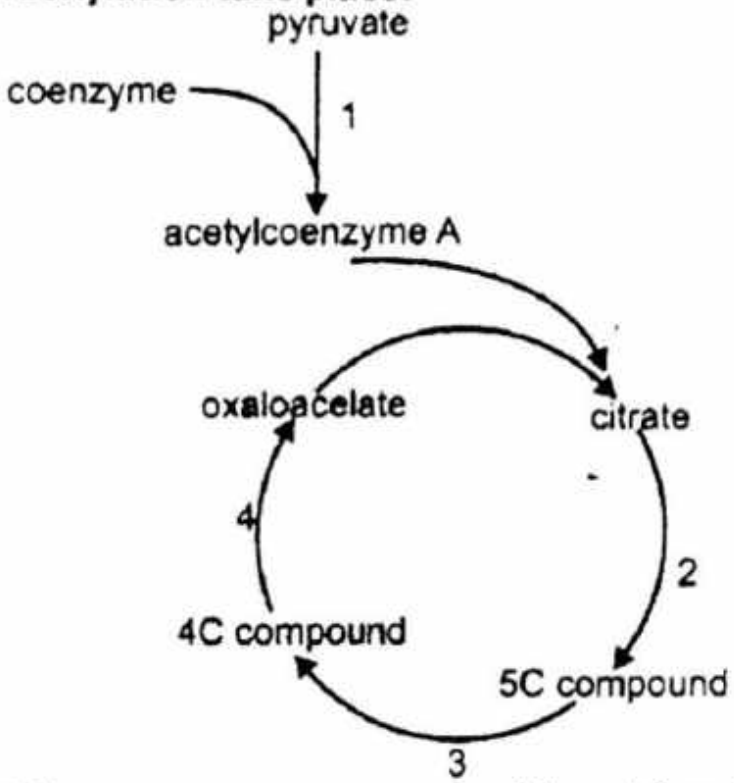
(x) ATP synthesis during light reactions is

(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) PGAL
(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

Answers

(i) C	(ii) B	(iii) A	(iv) B	(v) B	(vi) C
(vii) C	(viii) C	(ix) C	(x) D	(xi) B	(xii) B

SHORT QUESTIONS

2. What is electromagnetic spectrum?

Ans: Electromagnetic Spectrum:

Sunlight is an electromagnetic or radiant 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 380 ηm to 750 ηm which is not only seen by naked eye but is also effective for the process of photosynthesis.

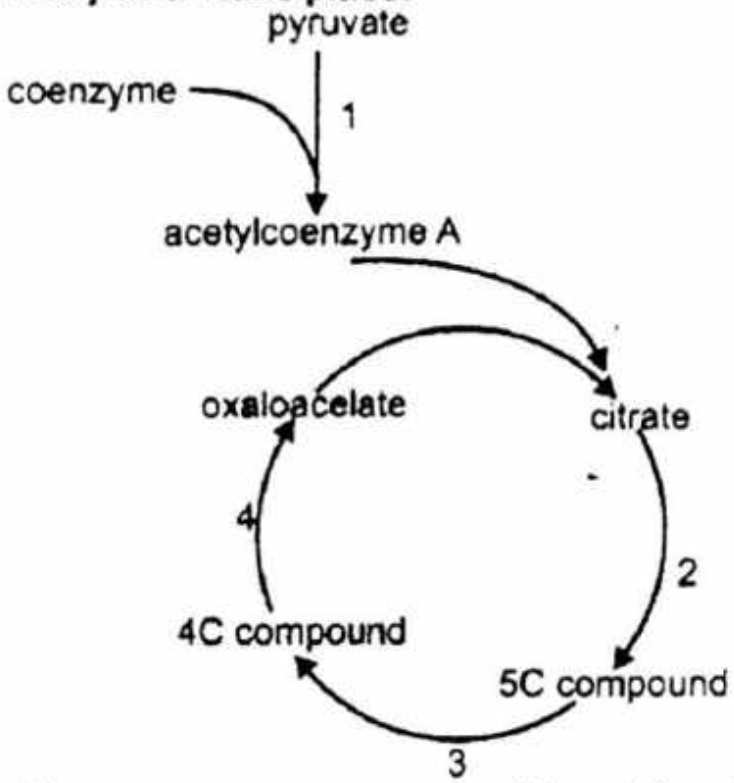
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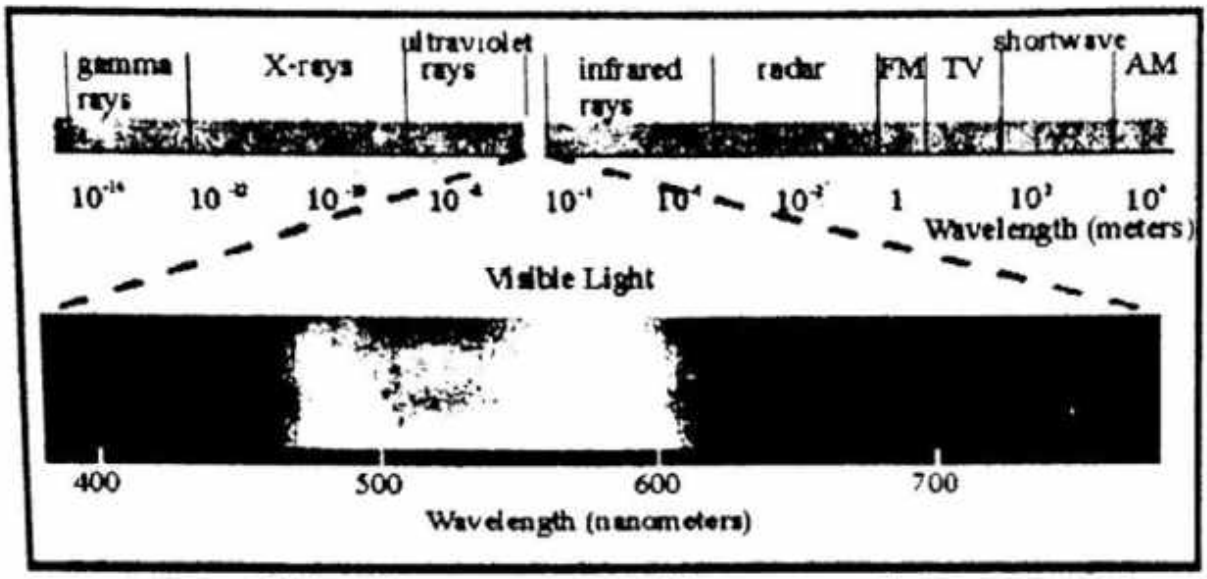
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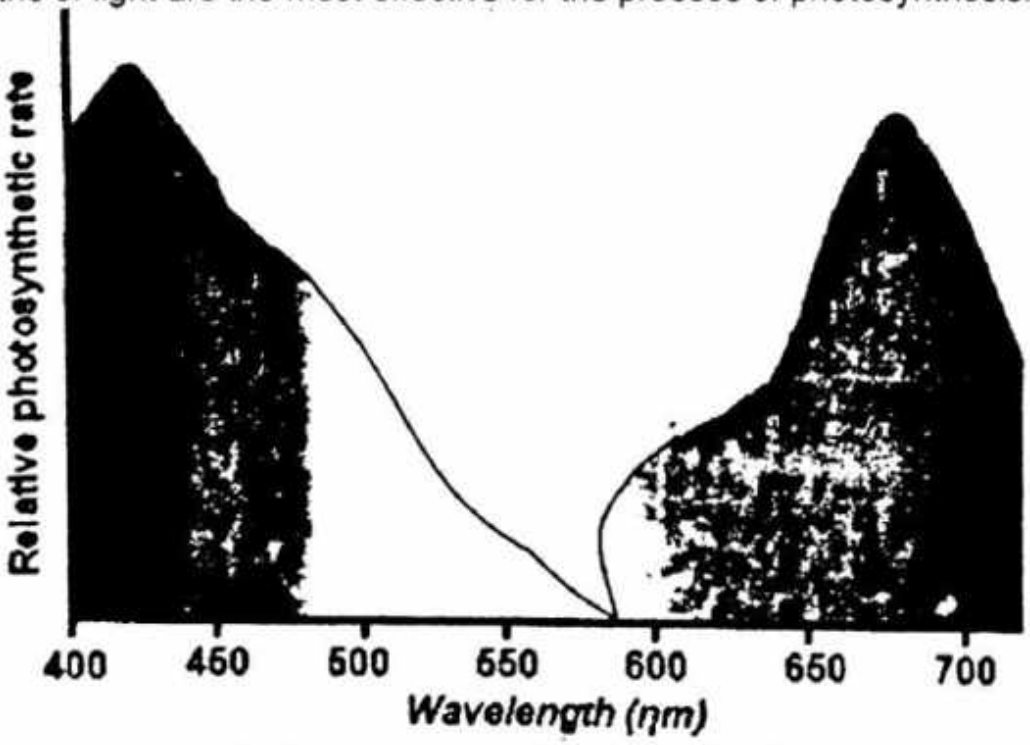
Electromagnetic spectrum

3. Explain 'action spectrum' of photosynthesis.

Ans: Action Spectrum:

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 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 (430 ηm) and red *(670 ηm)* wavelengths of light are the most effective for the process of photosynthesis.



Action spectrum of photosynthesis

An action spectrum is the rate of a physiological activity plotted against wavelength of light. It shows which wavelength of light is most effectively used in a specific chemical reaction. Some reactants are able to use specific wavelengths of light more effectively to complete their reactions.

4. What are the types of chlorophyll?

Ans: Types of Chlorophyll:

Two major types of chlorophyll are Chlorophyll-a and Chlorophyll-b

i. Chlorophyll-a:

Chlorophyll-a is a bluish green pigment which is found in all photosynthetic organisms except photosynthetic bacteria.

ii. Chlorophyll-b:

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

5. What is the importance of carotene?

Ans: Importance of Carotene:

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.

OR (Second Answer)

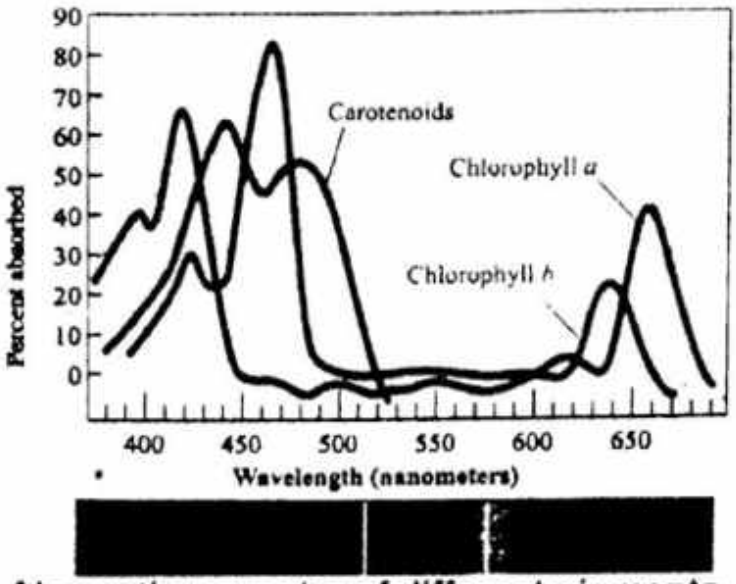
It gives yellow and orange fruits and vegetables their rich hues. Beta-carotene is also used to color foods such as margarine. In the body, beta-carotene converts into vitamin A (**retinol**). We need vitamin A for good vision and **eye health**, for a strong immune system, and for healthy skin and **mucous** membranes.

6. Describe 'absorption spectrum' in photosynthesis.

Ans: 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.

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 ($400\ \eta m\ to\ 470\ \eta m$) and orange-red ($630\ \eta m\ to\ 660\ \eta m$) regions of the visible spectrum. On the other hand carotenoids show more absorption at $430\ \eta m\ to\ 500\ \eta m$.



Absorption spectra of different pigments

7. What is photosystem? Explain.

Ans: Photosystem:

Light is absorbed in the form of photons by the **photosystem** (a cluster of photosynthetic pigments). The absorption of photons causes photoelectric effect i.e., excitation of electrons in the atoms of photosystem and ultimately these excited electrons leave the photosystem. These excited electrons after leaving the photosystem begin to flow through an electron transport chain and their energy is utilized in formation of ATP and $NADPH_2$ by chemiosmosis mechanism.

8. What is the role of carbon dioxide in photosynthesis?

Ans: 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.

9. How it was confirmed that 'plants split water as a source of hydrogen releasing hydrogen as a byproduct'?

Ans: 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. Actually, during light reaction, chlorophyll-a (P680) in the reaction centre of photosystem-II loses electrons due to the absorption of light energy. This event makes the chlorophyll as strong oxidizing agent. When water reacts with chlorophyll in this state, the water molecule is broken down into $2H^+$ ions, $2e^-$ and $\frac{1}{2}O_2$. This splitting of water in the presence of sunlight is called **photolysis of water.**

The electrons released from water are used to reduce the oxidized chlorophyll-a so that it can absorb light energy again, whereas, $2H^+$ ions are taken up the $NADP^+$ to form NADPH. On the other hand, the oxygen which is produced by photolysis of water is released in atmosphere.

Hypothesis of Van Niel:

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.

$$6CO_2 + 12H_2O^{18} \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6H_2O + 6O_2^{18}$$

Carbon dioxide — Water — Chlorophyll — Glucose — Water — Oxygen

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Carbon dioxide — Water — Chlorophyll — Glucose — Water — Oxygen

10. What is light dependent phase of photosynthesis?

Ans: Light Dependent Phase (light reaction):

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.

11. What is light independent phase of photosynthesis?

Ans: Light Independent Phase (dark reaction):

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 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.

12. Explain lactic acid fermentation.

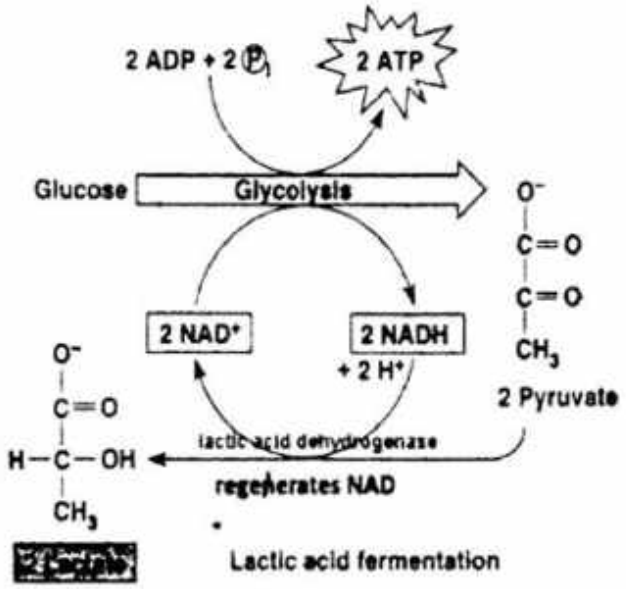
Ans: Lactic acid fermentation:

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.



Lactic acid fermentation

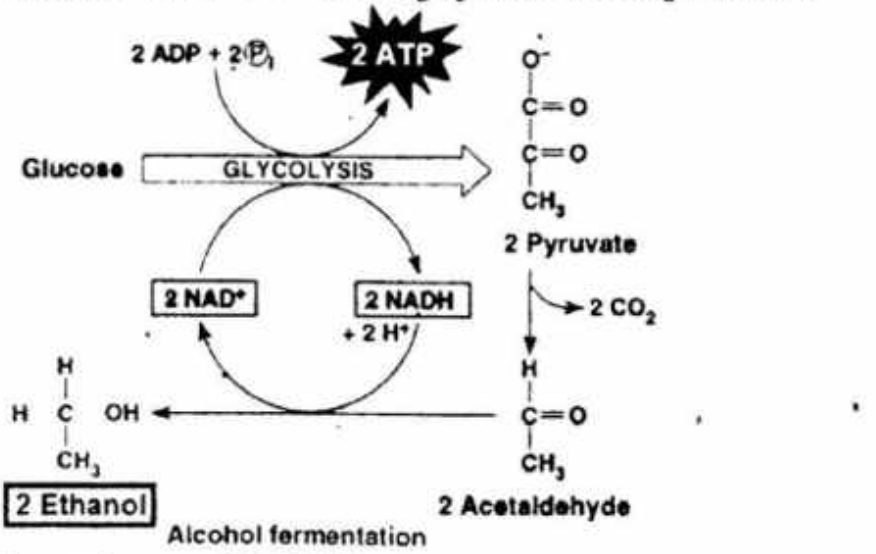
13. Explain alcoholic fermentation.

Ans: 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:

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

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



Alcohol fermentation

14. What is the importance of PGAL?

Ans: Importance of PGAL (G3P):

Phosphoglyceraldehyde (PGAL) or Glyceraldehydes 3-phosphate (G3P) is an important intermediate of respiration and photosynthesis.

i. In respiration, PGAL appears during glycolysis pathway where its oxidation produces 1,3-bisphosphoglycerate (PGAP) and 2NADH molecules, which leads to the formation of pyruvate.

ii. In the Calvin cycle of photosynthesis, PGAL molecules are converted into glucose phosphate within the chloroplast. Glucose phosphate is then

converted to starch. After photosynthesis the fixed carbons leave the chloroplast in the form of dihydroxyacetone phosphate. It is also formed from PGAL.

iii. In cytoplasm, dihydroxyacetone phosphate can be used to make the six-carbon sugars, glucose and fructose, which are then joined to form sucrose. It is transported to other parts of the plants.

15. What is the effect of temperature on the activities of RuBisCO?

Ans: 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.

16. What are the disadvantages of photorespiration?

Ans: Disadvantages of Photorespiration:

i. 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.

ii. Photorespiration is not essential for plant. It is also observed that if photorespiration is inhibited chemically, the plant can, still grow.

iii. Furthermore, some plants are naturally resistant to photorespiration.

17. What is C4 photosynthesis?

Ans: C4 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 C4 pathway in which phosphoenol pyruvate (PEP) carboxylase is used instead of RuBisCO to fix CO_2 to phosphoenol pyruvate (a C3 molecule), and the result is oxaloacetate, a C4 molecule. It takes place in cytoplasm of mesophyll cells.

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

As the first product of CO_2 fixation is a 4-carbon compound oxaloacetate, so that plants are called C4 plants e.g., maize, sugarcane, sorghum, etc.

Role of Oxaloacetate:

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 (C3) 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, RuBP carboxylase participates in Calvin cycle and not in photorespiration. Sugar formed in Calvin cycle is transported into the phloem. Pyruvic acid (pyruvate) generated in the bundle sheath cells re-enters mesophyll cells and regenerates phosphoenol pyruvic acid (PEP) by consuming one ATP. (Kranz anatomy: see glossary)

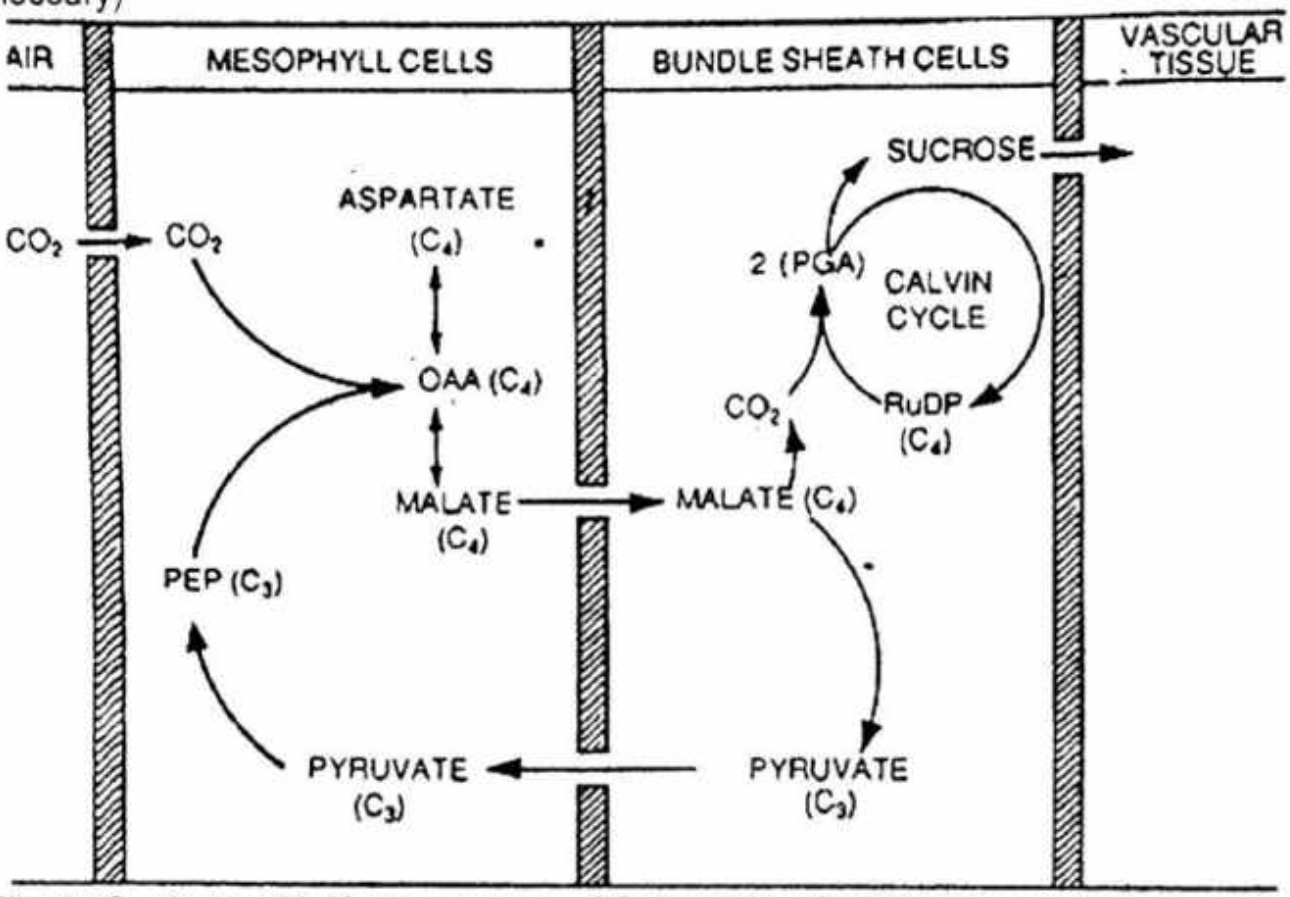


Fig: In C_4 plants with Kranz anatomy, CO_2 is initially fixed in mesophyll cells by the enzyme PEP-carboxylase, 4-carbon compound, malic acid (malate), transfers CO_2 to bundle sheath cells where it is further transferred to the Calvin cycle. Bundle sheath cells transfer the sugar they make to phloem tube transported through the body.

18. How photorespiration evolved?

Ans: Evolution of Photorespiration:

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.

19. Define/Describe/Explain briefly:

(a)	**bioenergetics**	**(b)**	**photosynthesis**
(c)	**photosystem**	**(d)**	**absorption spectrum**
(e)	**photophosphorylation**	**(f)**	**chemiosmosis**
(g)	**ATP synthase**	**(h)**	**cytochrome**
(i)	**plastoquinone**	**(j)**	**plastocyanin**

(k) Z-scheme **(l) C4 pathway**
(m) glycolysis **(n) RuBisCO**
(o) Krebs cycle **(p) electron transport chain**
(q) ubiquinone **(r) stalked particle**
(s) Photorespiration **(t) substrate level phosphorylation**

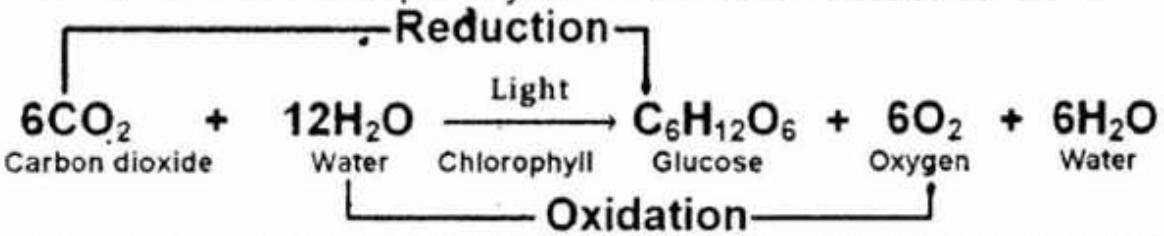
Ans: (a) Bioenergetics:

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**.

(b) 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:



The above mentioned main concept of photosynthesis indicates that this process involves the interaction of sunlight, pigments, water and carbon dioxide.

(c) Photosystem:

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.**

(d) 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.

(e) Photophosphorylation:

In non-cyclic electron flow, the excited electrons after leaving a 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 involved in this photophosphorylation is called **chemiosmosis.**

OR

In the process of photosynthesis, the phosphorylation of ADP to form ATP

using the energy of sunlight is called **photophosphorylation**. Only two sources of energy are available to living organisms: sunlight and reduction-oxidation (redox) reactions.

(f) Chemiosmosis:

Chemiosmosis is the movement of ions across a semipermeable membrane, down their electrochemical gradient. An example of this would be the generation of adenosine triphosphate (ATP) by the movement of hydrogen ions across a membrane during cellular respiration or photosynthesis.

(g) ATP Synthase:

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 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).

OR

ATP synthase is an enzyme that creates the energy storage molecule adenosine triphosphate. ATP is the most commonly used "energy currency" of cells for most organisms. It is formed from adenosine diphosphate and inorganic phosphate.

(h) Cytochrome:

Cytochrome is a protein that can transfer electrons with a chemical group called a heme group.

(i) Plastoquinone:

The primary electron acceptor is an iron containing protein, the **plastoquinone (PQ)**. From PQ the electrons flow through a cluster/complex of another iron containing proteins, the **cytochromes (Cyt)** which consist of **Cyt-b_6** and **Cyt-f**.

(j) Plastocyanin:

Plastocyanin is a copper-containing protein involved in electron-transfer. The protein is a monomer, with a molecular weight around 10,500 Daltons, and 99 amino acids in most vascular plants. It is a member of the **plastocyanin** family of copper-binding proteins.

(k) Z-scheme:

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

(l) C4 pathway:

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 **Hatch-Slack cycle** or **C4 pathway.**

(m) Glycolysis:

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.**

(n) 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.

(o) Krebs cycle:

Complete oxidation of acetyl coenzyme A into CO_2 and H_2O takes place in Krebs cycle. It begins with the binding of Acetyl CoA to 4C compound, the **oxaloacetate.** The resulting 6C compound is called **citrate** which passes through a series of electron yielding oxidation reactions in which NADH and $FADH_2$ are produced that release ATP upon further oxidation in respiratory chain. In addition, ATP is also produced directly by substrate level phosphorylation. Two CO_2 molecules are split off regenerating the 4C compound, the oxaloacetate which is free to bind another acetyl group. In this way the process become cyclic. In each turn of the cycle a new acetyl group comes into, to replace the two CO_2 molecules, that are lost and more electrons are extracted.

Discovery of Krebs Cycle:

This cycle was discovered by British scientist **Sir Hans Kreb,** 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.

(p) Electron Transport Chain:

Inner mitochondrial membrane contains groups of electron and proton transporting enzymes. In each group the enzymes are arranged in a specific series called electron transport chain (ETC) or mitochondrial respiratory chain or electron transport system (ETS). An electron transport chain or system is a series of electron carriers and some of them also work as proton pumps. They take part in the passage of electrons from NADH or $FADH_2$ to its ultimate acceptor i.e., molecular oxygen.

(q) Ubiquinone:

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.

(r) Stalked Particle:

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 which is also called **oxysome** or **stalked particles.**

(s) 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.

(t) Substrate Level Phosphorylation:

We 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

20. 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) phosphorylation and photophosphorylation
(i) Cyclic photophosphorylation and non-cyclic photophosphorylation
(j) C4 carbon fixation and C3 carbon fixation
(k) lactic acid fermentation and alcoholic fermentation
(l) Calvin cycle and Krebs cycle
(m) oxidative phosphorylation and substrate level phosphorylation
(n) photolysis and photorespiration

Ans: (a) chlorophyll a and chlorophyll b:

chlorophyll a	**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.
Molecular formula of chlorophyll a:	**Molecular formula of chlorophyll b:**
$C_{55}H_{72}O_5N_4Mg$	$C_{55}H_{70}O_6N_4Mg$

OR (Second Answer)

Chlorophyll a (Chl-a)	**Chlorophyll b (Chl-b)**
1. It is the principal photosynthetic pigment.	**1.** It is the accessory photosynthetic pigment.
2. It is present in all phototrophs other than bacteria.	**2.** It is present in all phototrophs other than diatoms, cyanobacteria, red and brown algae.
3. Blue green in pure state.	**3.** Olive green in pure state.
4. Empirical formula is. $C_{55}H_{72}O_5N_4Mg$	**4.** Empirical formula is. $C_{55}H_{70}O_6N_4Mg$
5. The 3rd carbon of the side group is methyl group ($-CH_3$)	**5.** Side group at the 3rd carbon is aldehyde group (-CHO)
6. Molecular weight is 873	**6.** Molecular weight is 907

(b) carotene and xanthophylls:

Xanthophyll	**Carotene**
Xanthophylls are yellow in colour and are also composed of isoprenoid units	The **carotenes** are orange red pigments, composed of isoprenoid

Lutein is widely distributed xanthophylls which is responsible for yellow colour of foliage in autumn.	units and are found in all photosynthetic eukaryotes. The most widespread and important carotene is β (beta) carotene.

(c) action spectrum and absorption spectrum

Absorption Spectrum	Action Spectrum
Absorption Spectrum is the graphic representation of the different wavelengths of light absorbed by the different pigments in a leaf during photosynthesis	Action Spectrum is the graphic representation of the effectiveness of different wavelengths of light in photosynthesis
Plot showing intensity of light absorbed relative to its wavelength	Plot showing relative efficiency of photosynthesis produced by light of different waveienqths
Explains the relationship between quality of light and absorbing capacity of pigments	Explains the relationship between photosynthetic activity in relation to different waveienqths of light
Chlorophyll absorb blue and red light Carotenoids absorb violet and blue light	The maximum photosynthesis occurs in blue and red light
Absorption of different wavelengths of light by pigments can be measured using spectrophotometer.	In action spectrum, the rate of photosynthesis is measured as amount of carbon dioxide fixation, oxygen production, NAOP+ reduction etc.

OR (Second Answer)

An action spectrum is a graph showing the effectiveness of different wavelengths of light in stimulating the process being investigated. An absorption spectrum is a graph of the relative amounts of light absorbed at different wavelengths by a pigment.

(d) absorption spectrum of chlorophyll a and b:

Photosynthesis uses two types of chlorophyll, chlorophyll a and b, to produce energy.

Chlorophyll a:

Chlorophyll a absorbs energy from wavelengths of blue-violet and orange-red light at 675 nm. It reflects green light which gives chlorophyll its green appearance. It is very important in the energy phase of photosynthesis because chlorophyll a molecules are needed before photosynthesis can proceed. It is the primary photosynthetic pigment. It is the reaction center of the antenna array which is made up of core proteins that bind chlorophyll a with the carotenoids. Organisms, specifically oxygenic photosynthetic ones use chlorophyll a and it uses various enzymes for biosynthesis.

Chlorophyll b:

Chlorophyll b absorbs energy from wavelengths of green light at 640 nm. It is the accessory pigment that collects energy and passes it on to chlorophyll a. It also regulates the size of antenna and is more absorbable than chlorophyll a. Chlorophyll b complements chlorophyll a. Its addition to chlorophyll a increases the

absorption spectrum by increasing the range of wavelengths and broadening the spectrum of light that is absorbed.

When there is little light available, plants produce more chlorophyll b than chlorophyll a to increase its photosynthetic ability. This is necessary because chlorophyll a molecules capture a limited wavelength so accessory pigments like chlorophyll b are needed to aid in the capture of a wider range of light. It then transfers the captured light from one pigment to another until they reach the chlorophyll a in the reaction center. Chlorophyll a cannot function well without the help of chlorophyll b and chlorophyll b cannot effectively produce enough energy on its own.

These two types of chlorophylls are therefore both very essential in the process of photosynthesis. They work best together.

(e) antenna complex and reaction centre

Antenna complex	Reaction centre
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.

(f) photosystem I and photosystem II:

Photosystem I (PS I)	Photosystem II (PS II)
PS I is located at the outer surface of the grana thylakoid membrane (non appressed granai regions and stroma lamella).	PS II is located at the inner surface of the grana thylakoid membrane (appressed granai region).
The photocentre or reaction centre is P700.	The photocentre is P680.
PS I has an iron-sulphur (FeS) type reaction centre (or type 1)	PS II has a quinone type reaction centre {also known as Q-Type or type II)
The core complex of PSI is composed by a smaller number of proteins (~15 subunits) than PS II.	The core of PSII is a multi-subunit complex composed of about ~25~30 subunits.
Pigments absorb longer wavelengths of light (>680nm).	Pigments absorb shorter wavelengths of light (<680nm).
Rich in chlorophyll a than chlorophyll-b	Rich in chlorophyll b than chlorophyll-a.
Participates in cyclic as well as *non cyclic photophospnorylation.*	Participates only in non-cyclic photo phosphorylation.
It is not associated with photolysis of water.	It is associated with photolysis of water.
PS I generates a strong reducing agent (reducing $NADP^+$ to NADPH) and a weak oxidant	PS II is the strong oxidant (capable of oxidizing H_2O) and a weak reductant.

Main function is ATP synthesis in cyclic photophosphophorylation and NADPH synthesis in non-cyclic photosynthesis..	Main functions are ATP synthesis and hydrolysis of water.

OR (Second Answer)

	Photosystem I	Photosystem II
Light	Photosystem I absorbs light of 700nm wavelengths.	Photosystem II absorbs light of 680nm wavelengths.
Active Center	Photosystem I has active center P700.	Photosystem II has active center P680.
Photophosphorylation	Photosystem I is involved in cyclic and non-cyclic photophosphorylation.	Photosystem II is involved only in non-cyclic photophosphorylation.
Main Function	The main function of photosystem I is the synthesis of ATP.	The main function of photosystem II is a synthesis of ATP and photolysis of water.
Located at	Photosystem I is located at the outer surface of grana of thylakoid.	Photosystem II is located in at the inner surface of grana of thylakoid.
Binding Proteins	Photosystem I has larger binding proteins.	Photosystem II has smaller binding proteins.

(g) light dependent reaction and light independent reaction of photosynthesis:

Basis of Distinction	Light Reaction in Photosynthesis	Dark Reaction in Photosynthesis
Location	Always takes place in the grana of the chloroplasts	Always take place in the stroma of the chloroplasts.
Process	Use light energy to make two molecules needed for the next stage of photosynthesis: the energy storage molecule ATP and the reduced electron carrier NADPH.	Make use of these organic energy molecules ATP and NADPH and this response cycle is also called Calvin Benison Cycle.
Requirement	Requires the processes such as photosystem 1 and photosystem 2..	Do not require any light, they do not have the requirement of photosystems.

Product	The photolysis of water occurs and hence, oxygen gets released.	The process of photolysis does not take place and carbon dioxide gets absorbed

(h) phosphorylation and photophosphorylation

Phosphorylation	Photophosphorylation
1. It takes place during aerobic respiration (a catabolic process) on cristae in mitochondria	**1.** It takes place during photosynthesis (an anabolic process) in thylakoids (of grana) in chloroplast.
2. It occurs during terminal oxidation of reduced coenzymes generated in glycolysis and Krebs' cycle with molecular oxygen.	**2.** It occurs during cyclic and non-cyclic electron transport in light reaction of photosynthesis. Molecular oxygen is not required.
3. It is independent of light.	**3.** It is dependent on light.
4. It is associated with mitochondrial electron transport system and is of only one type.	**4.** It is associated with two pigment systems and electron transport in chloroplasts and is of two types- cyclic and non-cyclic photophosphorylation.
5. Ultimate source of energy for oxidative phosphorylation is respiratory substrate.	**5.** Ultimate source of energy for photophosphorylation is light.
6. It is inhibited by 2, 4—dinitro phenol	**6.** Non-cyclic photophosphorylation is inhibited by CMU (Chlorophenyl, dimethylurea) and DCMU (dichlorophenyl, dimethyl urea).
7. Energy rich ATP molecules produced by this process are used for driving various metabolical process of the cells.	**7.** Energy rich ATP molecules produced by this process are mainly utilised in dark reaction of photo-synthesis for the synthesis of carbohydrates. These may also be used for other synthetic processes within the chloroplasts.

(i) Cyclic photophosphorylation and non-cyclic photophosphorylation:

- In cyclic phosphorylation lone photosystem 1 is concerned while both photosystem 1 and 2 are used in Non-cyclic Photophosphorylation.
- The active reaction center of cyclic Photophosphorylation is P700 while the active reaction center of Non-cyclic Photophosphorylation is 680.
- In cyclic Photophosphorylation the electron travels in a cyclic manner while in non-cyclic Photophosphorylation it does not complete the circuit.
- In cyclic Photophosphorylation electron travels back to PS1 while in non cyclic Photophosphorylation NADP takes away the electron.
- ATP is produced in cyclic Photophosphorylation while NADPH and ATP both are produced in non cyclic Photophosphorylation.
- Cyclic Photophosphorylation takes place in isolated chloroplast and bacterial photosynthesis while in Noncyclic green plants are involved

- Photolysis or water splitting is absent in cyclic Photophosphorylation while it is present in non cyclic Photophosphorylation.
- In cyclic Photophosphorylation oxygen is not evolved while in non cyclic Photophosphorylation oxygen is produced.
- Cyclic Photophosphorylation is predominantly seen in bacteria while non-cyclic Photophosphorylation is predominantly seen in green plants.
- There is no effect of DCMU on cyclic Photophosphorylation while DCMU inhibits the non cyclic Photophosphorylation.

OR (Second Answer)

Difference between Cyclic and Non-cyclic Photophosphorylation:

Cyclic photophosphorylation	**Non-cyclic photophosphorylation**
Cyclic photophosphorylation refers to the process which produces ATP during the cyclic electron transport chain of light dependent photosynthesis	Non-cyclic photophosphorylation refers to the process which produces ATP from noncyclic electron transport chain in light reactions of photosynthesis
Photosystem:	
Only one photosystem (PS I) is involved in cyclic photophosphorylation.	Photosystem I and II are involved in noncyclic photophosphorylation
Nature of the Electron Transport Chain:	
Electrons travel in a cyclic electron transport chain and return to the PS I	Electrons travel in noncyclic chains.
Products:	
Only ATP is produced in this process	ATP, O_2, and NADPH are produced in this process.
Water:	
Water is not split during this process.	Water splits or photolyses.
Generation of Oxygen:	
Oxygen is not generated during cyclic photophosphorylation	Molecular oxygen is generated in noncyclic photophosphorylation.
First Electron Donor:	
The first electron donor is PS I.	Water is the first electron donor.
First Electron Acceptor:	
The final electron acceptor is PS I.	The final electron acceptor is NADP+
Organisms:	
Cyclic photophosphorylation is shown by certain bacteria.	Non-cyclic photophosphorylation is common in green plants, algae, and cyanobacteria.

OR (Second Answer)

Difference between cyclic and noncyclic photophosphorylation			
	Cyclic photophosphorylation		**Non-cyclic photophosphorylation**
1.	Only the PS I is engaged	**1.**	Both the PS I and PS II are engaged
2.	ATP molecules are formed	**2.**	ATP and $NADPH_2$ are formed.

3.	It takes place in stroma lamella and grana lamella.	**3.**	It takes place only in grana lamella.
4.	Photolysis of water does not occur so oxygen is not released.	**4.**	Photolysis of water occurs and oxygen is released.
5.	The wave length of light required is P 700	**5.**	The wave length of light required is P 680
6.	The photophosphorylation takes place at two stages of the cycle.	**6.**	The photophosphorylation takes place at only one stage of the cycle.

(j) C4 carbon fixation and C3 carbon fixation:

No.	C3 Cycle (Calvin Cycle)	C4 Cycle (Hatch & Slack Pathway)
1	C3 cycle is commonly known as Calvin Cycle (Melvin Calvin described it first).	C4 cycle is commonly known as Hatch and Slack pathway (in honor of Marshall Davidson Hatch and C. R. Slack who elucidated this pathway).
2	Examples of C3 plants. Wheat, Rye, Oats, Rice, Cotton, Sunflower, Chlorella.	Examples of C4 plants Maize, Sugarcane, Sorghum, Amaranthus.
3	Leaves of C3 plants do not have Kranz anatomy.	Leaves of C4 plants possess Kranz anatomy.
4	C3 plants are cool season plants, commonly seen in cool and wet areas (temperate areas).	C4 plants are warm season plants, commonly seen in dry areas (tropical areas).
5	The C3 cycle is present in all plants	The C4 cycle is present only in C4 plants
6	First stable product in C3 cycle is a 3 carbon (3C, hence the name) compound -Phosphoglyceric Acid (PGA).	First stable product in C4 cycle is a 4 carbon (4C, hence the name) compound - Oxaloacetic Acid (OAA).
7	The CO_2 acceptor in the C3 cycle is RuBP (Ribulose-1,5-bisphosphate), RuBp is a 5 carbon compound.	The first CO_2 acceptor in the C4 cycle is PEP(Phosphoenolpyruvate). PEP is a 3 carbon compound.
8	The first enzyme in C3 cycle is RUBISCO (Ribulose-i,5-bisphosphate carboxylase/oxygen ase).	The first enzyme in C4 cycle is PEP carboxylase.
9	The first enzyme RUBISCO has high affinity towards oxygen.	First enzyme PEP carboxylase does not have any affinity for oxygen.
10	Increased oxygen concentration has an inhibitory effect on C3 cycle	Concentration of oxygen does not have any inhibitory role in C4 cycle.

11	C3 cycle requires 18 ATP molecules to synthesize one molecule of glucose.	C4 cycle requires 30 ATP molecules to synthesize one molecule of glucose.
12	The complete steps of C3 cycle are executed in the mesophyll cells only.	The mesophyll cells will only do the initial steps of C4 cycle, the rest are completed in the bundle sheath cells.
13	In C3 cycle, the carbon dioxide fixation takes place only at one place.	In C4 cycle, the carbon dioxide fixation takes places twice (first in mesophyll cells, second in bundle sheath cells).
14	Only a single type of chloroplasts is involved in C3 cycle. All chloroplasts are granal.	Two types of chloroplasts are involved in C4 cycle. Granal in mesophyll cells and agranal in bundle sheath cells
15	RuBP is the only CO2 acceptor in C3 cycle	There are two CO_2 acceptors in C4 cycle. Phosphoenolpyrdate (PE) is the primary CO_2 acceptor in C4 cycle.
16	There is no secondary CO_2 acceptor in C3 cycle.	In C4 plants, there is a secondary CO_2 acceptor. RuBP is the secondary CO_2 acceptor in C4 plants.
17	In C3 plants, the bundle sheath cells do not contain chloroplasts.	In C4 plants, the bundle sheath cells contain chloroplasts.
18	In C3 plants, the light and dark reactions of photosynthesis occur in a single location	In C4 plants, the light and dark reactions of the photosynthesis are physically separated and completed in two different locations.
19	C3 plants can perform photosynthesis only when the stomata are open.	C4 plants can do photosynthesis even in the closed condition of stomata:
20	The optimum temperature for photosynthesis in C3 plants is very low.	The optimum temperature for photosynthesis in C4 plants is high.
21	The rate of photorespiration is very high in C3 plants.	The photorespiration is altogether absent in C4 plants(if present very little).
22	C3 cycle is less efficient in Photosynthetic energy fixation due to the presence of photorespiration.	C4 cycle is more efficient than C3 cycle in photosynthesis due to the absence of photorespiration.
23	The carbon dioxide compensation point is high in C3 cycle (about 50 ppm).	The carbon dioxide compensation point is low in C4 cycle (2 to 5 or even 0 ppm).
24	In high light intensity, the rate of CO_2 evolution is high in C3 plants.	In the high light intensity, the rate of CO_2 evolution is very low in C4 plants.
25	The water loss per g of biomass produced with C3 cycle is high (450 to 950).	The water loss per g of biomass produced with C4 cycle is low (250-350).

OR (Second Answer)

	C3 Pathway	C4 Pathway
Definition	Such plants whose first product after the carbon assimilation from sunlight is 3-carbon molecule or 3-phosphoglyceric acid for the production of energy is called C3 plants, and the pathway is called as the C3 pathway. It is most commonly used by plants	Plants in the tropical area, convert the sunlight energy into C4 carbon molecule or oxaloacetice acid, which takes place before the C3 cycle and then it further convert into the energy, is called C4 plants and pathway is called as the C4 pathway. This is more efficient than the C3 pathway.
Cells involved	Mesophyll cells	Mesophyll cell, bundle sheath cells.
Example	Sunflower, Spinach, Beans, Rice, Cotton	Sugarcane, Sorghum and Maize.
Can be seen in	All photosynthetic plants.	In tropical plants
Types of plants using this cycle	Mesophytic, hydrophytic, xerophytic.	Mesophytic.
Photorespiration	Present in high rate.	Not easily detectable.
For the production of glucose	12 NADPH and 18 ATPs are required.	12 NADPH and 30 ATPs are required.
First stable product	3-phosphoglycerate (3-PGA).	Oxaloacetate (OAA).
Calvin cycle operative	Alone.	Along with the Hatch and Slack cycle.
Optimum temperature for photosynthesis	15-25 °C	30-40 °C
Carboxylating Enzyme	RuBP carboxylase.	In mesophyll: PEP carboxylase. In bundle sheath: RuBP carboxylase.
CO_2: ATP: NADPH2 ratio	1:3:2	1:5:2
Initial CO_2 acceptor	Ribulose-1,5-biphophate(RuBP).	Phosphoenolpyruvate (PEP).
Kranz Anatomy	Absent.	Present.
CO_2 compensation point (ppm)	30-70.	6-10.

(k) lactic acid fermentation and alcoholic fermentation:

Lactic acid fermentation	Alcoholic fermentation
Definition:	
Lactic acid fermentation refers to a metabolic process by which glucose is converted into the metabolite: lactate and cellular energy.	Alcoholic fermentation refers to a metabolic process by which glucose is converted into ethanol and carbon dioxide.
Occurrence:	
Lactic acid fermentation occurs in *Lactobacillus spps*, yeast, and muscle cells.	Alcoholic fermentation occurs in yeast and other microorganisms.
Products:	
Lactic acid fermentation produces lactic acid molecules from the pyruvate.	Alcoholic fermentation produces ethanol and carbon dioxide from the pyruvate molecule.
Enzymes:	
Lactate dehydrogenase and pyruvate decarboxylase are the two enzymes involved in the lactic acid fermentation.	Pyruvate decarboxylase and alcohol dehydrogenase are the two enzymes involved in the alcoholic fermentation.
In the Food Industry:	
Lactic acid fermentation is used in the production of yogurt and cheese.	Alcoholic fermentation is used in the production of bread, beer, wine, and vinegar.
Conclusion: Lactic acid and alcoholic fermentation are two mechanisms involved in the respiration in the absence of oxygen. Both types of fermentation occur in the cytosol. Glycolysis is the first step of both lactic acid and alcoholic fermentation, which produced pyruvate. Lactic acid fermentation produces lactic acid molecules from pyruvate while alcoholic fermentation produces ethanol and carbon dioxide from pyruvate. The main difference between lactic acid and alcohol fermentation is the products of each fermentation.	

(l) Calvin cycle and Krebs cycle:

Krebs Cycle	Calvin Cycle
Part of the aerobic respiration process	Part of the dark reaction of photosynthesis
Takes place in the matrix of the mitochondria	Takes place in the stroma of chloroplast
Leads to synthesize ATP	ATP is spent for the process
Takes place in all the organisms with aerobic respiration	Takes place only in the photosynthetic plants
Carbon dioxide is produced	Carbon dioxide is used
The process does not take place without oxygen	The process does not demand the presence of oxygen

(m) Oxidative phosphorylation and substrate level phosphorylation:

Substrate level phosphorylation	Oxidative phosphorylation
Substrate level phosphorylation directly transfers a phosphate group from the substrate (phosphorylated compound) to ADP to produce ATP.	Oxidative phosphorylation is a process by which energy released by chemical oxidation of nutrients is used for the synthesis of ATP.
Energy Used:	
Energy is generated from a coupled reaction for this process.	Energy generated from the reaction of electron transport chain is used for this process.
Redox Potential:	
A small difference of redox potential is generated in substrate level phosphorylation.	A large difference in redox potential is generated to power this phosphorylation.
Conditions:	
This occurs under both aerobic and anaerobic conditions.	This occurs under aerobic conditions.
Oxidization of Compounds:	
Substrates are partially oxidized.	Electron donors are completely oxidized.
Locations:	
Substrate level phosphorylation occurs in the cytosol and mitochondria.	Oxidative phosphorylation occurs in the mitochondria.
Occurrence:	
This can be seen in glycolysis and Krebs cycle	This occurs only during the electron transport chain.
Association with Electron Transport Chain and ATP Synthase:	
Substrate level phosphorylation is not associated with electron transport chain or ATP synthase.	This is associated with electron transport chain and ATP synthase.
Involvement of O_2 and NADH:	
This does not use O_2 or NADH for the formation of ATP.	This uses O_2 and NADH to produce ATP.

OR (Second Answer)

Substrate level phosphorylation	Oxidative phosphorylation
Substrate level phosphorylation refers to a type of phosphorylation in which a phosphate group is transferred from a substrate to ADP.	Oxidative phosphorylation refers to a type of phosphorylation which uses the energy released from the electron transport chain to generate ATP.
Occurs in the cytoplasm and itochondria matrix	Occurs on the inner membrane of mitochondria
A phosphate group is directly removed from a substrate by a coupled reaction and transferred into ADP.	Phosphate groups are added from the energy released in the electron transport chain.
Direct phosphorylation.	Indlrect phosphorylation.

Occurs in the glycolysis and Krebs cycle	Occurs in the electron transport chain.
NAD and FAD are reduced.	NADH+ and FADH+ are oxidized.
Four ATPs are produced.	Thirty four ATPs are produced.
The change of the redox potential of the substrate is less.	The change of the redox potential of the substrate is more
Partial oxidation of the substrate occurs.	Complete oxidation of the electron donors occurs.

(n) photolysis and photorespiration:

Photolysis	Photorespiration
Photolysis a process whereby molecules of water may have their hydrogen split from the oxygen, because of light energy present on chlorophyll. This part of photosynthesis occurs in the granum of a chloroplast where light is absorbed by chlorophyll. **For example,** the photolysis of water molecule in photosynthesis occurred under the influence of light. When photons are absorbed, it causes the hydrogen to bind to an acceptor, subsequently releasing the oxygen.	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.

21. Explain the effect of temperature on the oxidative activity of RuBP carboxylase.

Ans: 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.

22. Analyse the impact of photorespiration on the agricultural yield in the tropic climates.

Ans: 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.

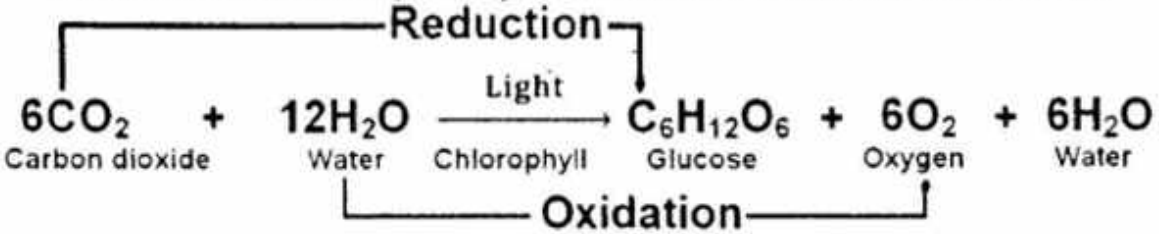
EXTENSIVE QUESTIONS

23. What is photosynthesis? Explain the role of light in photosynthesis.

Ans: 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:

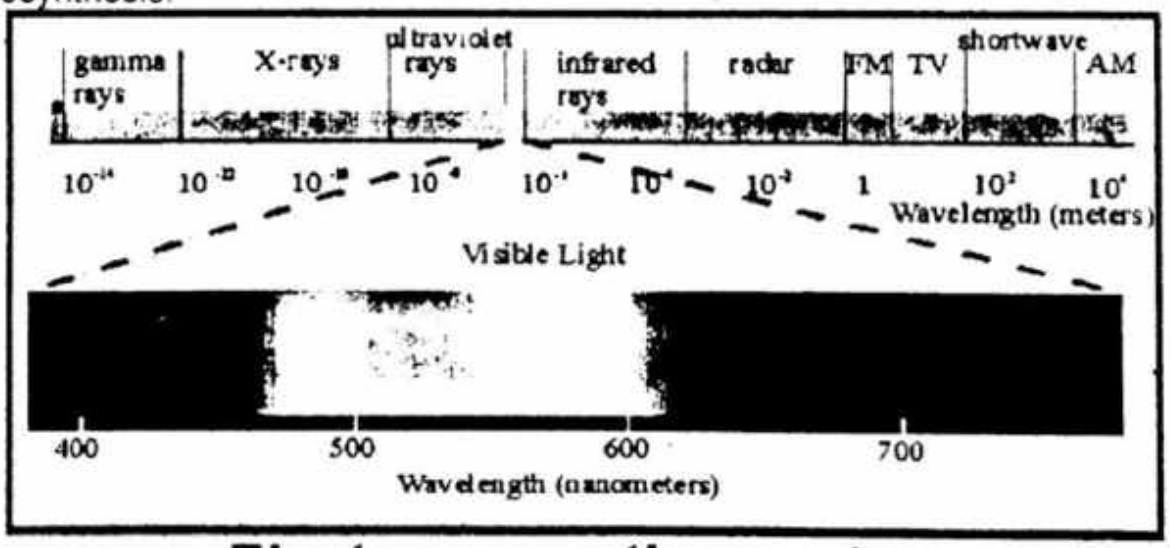


The above mentioned main concept of photosynthesis indicates that this process involves the interaction of sunlight, pigments, water and carbon dioxide.

Role of Light:

Sunlight is an electromagnetic or radiant 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 380 ηm to 750 ηm which is not only seen by naked eye but is also effective for the process of photosynthesis.



Electromagnetic spectrum

Effectiveness of Wavelength of Light:

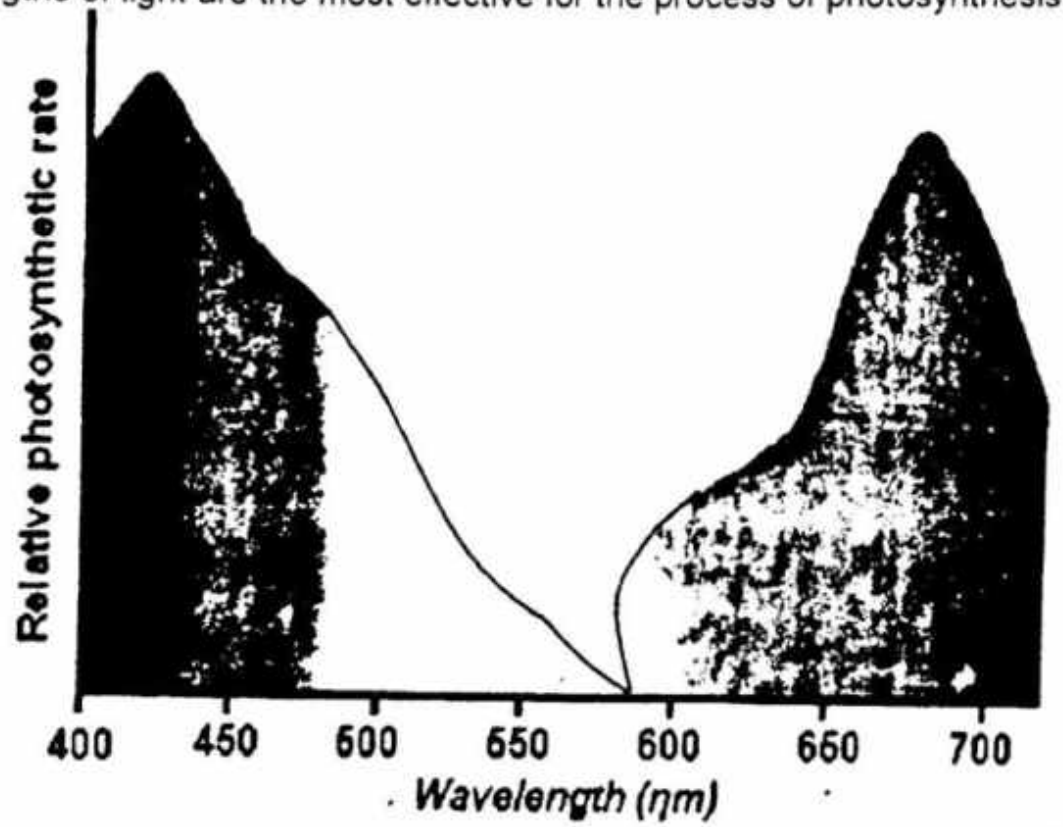
The effectiveness of a particular wavelength of light for the process of photosynthesis primarily depends upon its absorption in plant body. As different wavelengths (colours) of visible light are differently absorbed by various

photosynthetic pigments, therefore, each wavelength has its own effectiveness for the process of photosynthesis.

Action Spectrum:

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 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 (430 ηm) and red (670 ηm) wavelengths of light are the most effective for the process of photosynthesis.



Action spectrum of photosynthesis

Photosystem:

Light is absorbed in the form of photons by the **photosystem** (a cluster of photosynthetic pigments). The absorption of photons causes photoelectric effect i.e., excitation of electrons in the atoms of photosystem and ultimately these excited electrons leave the photosystem. These excited electrons after leaving the photosystem begin to flow through an electron transport chain and their energy is utilized in formation of ATP and $NADPH_2$ by chemiosmosis mechanism.

24. Describe the structure of chlorophyll.

Ans: Chlorophyll:

Chlorophylls absorb mainly violet, blue, orange and red wavelengths. Green and yellow are least absorbed and are transmitted or reflected.

Types of Chlorophyll:

Two major types of chlorophyll are Chlorophyll-a and Chlorophyll-b.

i. Chlorophyll-a:

Chlorophyll-a is a bluish green pigment which is found in all photosynthetic organisms except photosynthetic bacteria.

ii. Chlorophyll-b:

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 = $C_{55}H_{72}O_5N_4Mg$

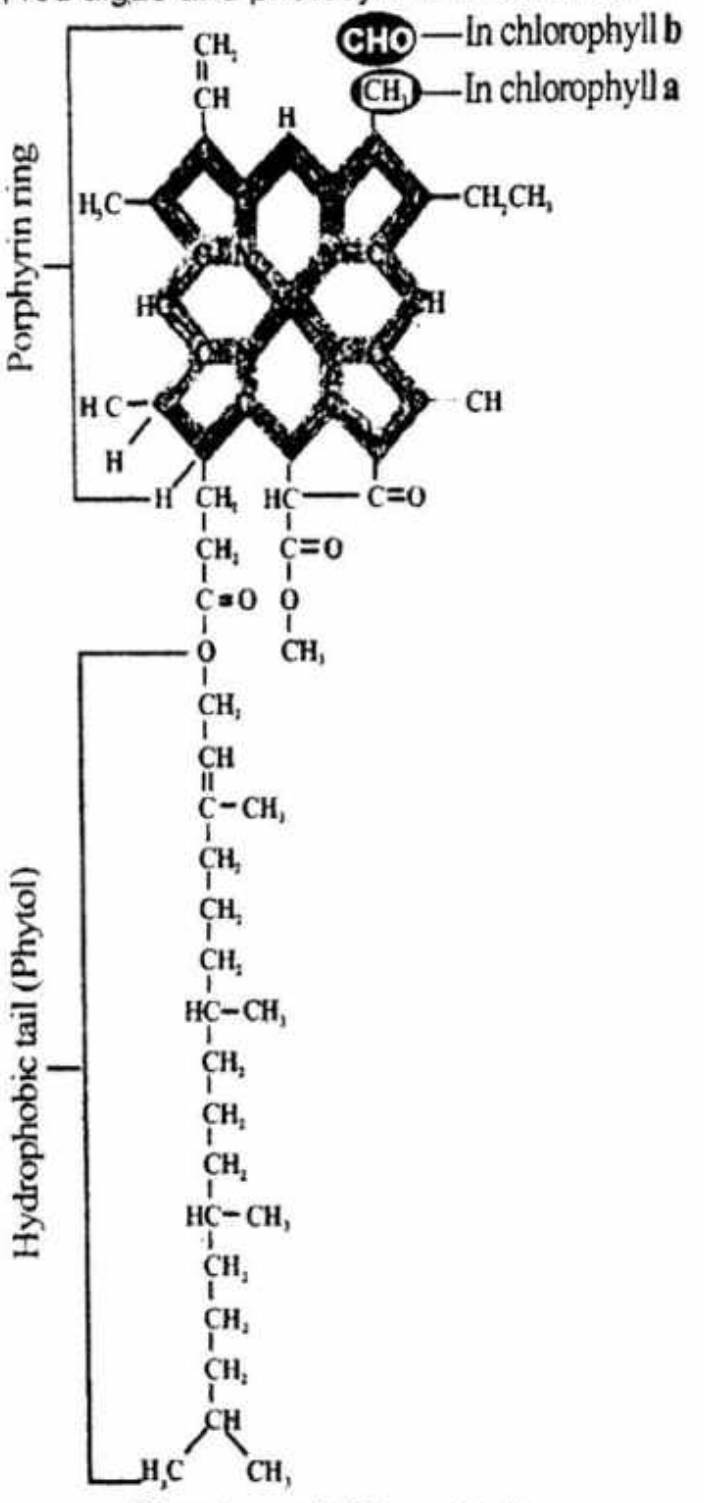
Chlorophyll b = $C_{55}H_{70}O_6N_4Mg$

Structure of Chlorophyll:

A molecule of chlorophyll consists of a head and two tails.

Head:

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.



Structure of Chlorophyll

Tails:

The two side chains in the chlorophyll molecule are called tails. One side chain consists of a long chain terpenoid alcohol phytol ($C_{20}H_{39}$) esterified with propionic acid. This chain is linked with 4th pyrrole ring of the head. The other side chain consists of methyl (CH_3) ester which is linked to head between 3rd and 4th pyrrole rings of porphyrin. The chlorophyll tails are hydrophobic in nature. They are embedded into the thylakoid membranes and serve to anchor the chlorophyll molecule in the membrane.

25. Write a note on the photosynthetic pigment carotene.

Ans: 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.

Carotenoids:

Carotenoids are terpenoid lipids, which are yellow, orange, red or brown pigments.

Spectrum of Carotenoids:

They absorb light strongly in the blue-violet range. They are seen in leaves before leaf fall, present in some flowers and fruits.

Role of Carotenoids:

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.

Types of Carotenoids:

There are two types of carotenoids: carotenes and xanthophylls.

i. Carotenes:

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.

ii. Xanthophylls:

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.

26. Explain the arrangement of photosystems.

Ans: 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.**

Structure of Photosystem:

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 660 ηm.

Types of Photosystem:

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).

Photosystem-I (PS-I):

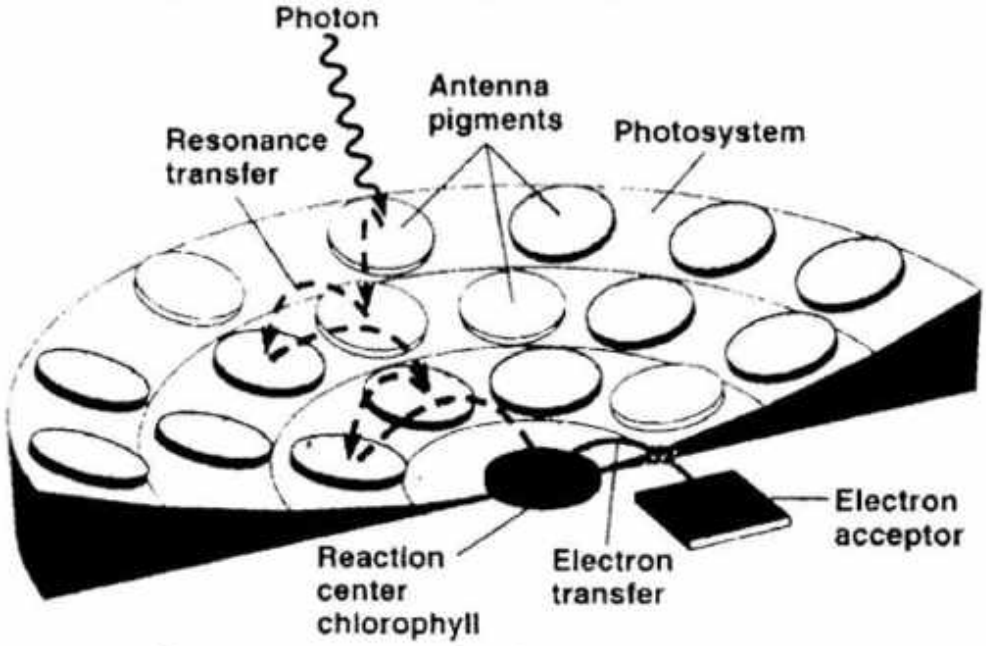
The chlorophyll-a in the reaction centre of PS-I can absorb maximum 700 ηm wavelength of light, hence called P700.

Photosystem-II (PS-II):

Similarly, the chlorophyll-a in the reaction centre of PS-II can absorb maximum $680\ \eta m$ 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.

Electron Transport:

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.



Structure of photosystem

$$\underset{\text{(Reduced form)}}{\text{Chlorophyll}} \xrightarrow{\text{Light Energy}} \underset{\text{(Oxidized form)}}{\text{Chlorophyll}} + \underset{\text{Electron}}{e^-}$$

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

27. Describe the role of water in photosynthesis.

Ans: 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. Actually, during light reaction, chlorophyll-a (P680) in the reaction centre of photosystem-II loses electrons due to the absorption of light energy. This event makes the chlorophyll as strong oxidizing agent. When water reacts with chlorophyll in this state, the water molecule is broken down into $2H^+$ ions, $2e^-$ and $\frac{1}{2}O_2$.

Photolysis of Water:

This splitting of water in the presence of sunlight is called **photolysis of water.** The electrons released from water are used to reduce the oxidized chlorophyll-a so that it can absorb light energy again, whereas, $2H^+$ ions are taken

up the $NADP^+$ to form NADPH. On the other hand, the oxygen which is produced by photolysis of water is released in atmosphere.

Hypothesis of Van Niel:

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.

$$6CO_2 + 12H_2O^{18} \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6H_2O + 6O_2^{18}$$

Carbon dioxide — Water — Chlorophyll — Glucose — Water — Oxygen

$$6CO_2{}^{18} + 12H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6{}^{18} + 6H_2O + 6O_2$$

Carbon dioxide — Water — Chlorophyll — Glucose — Water — Oxygen

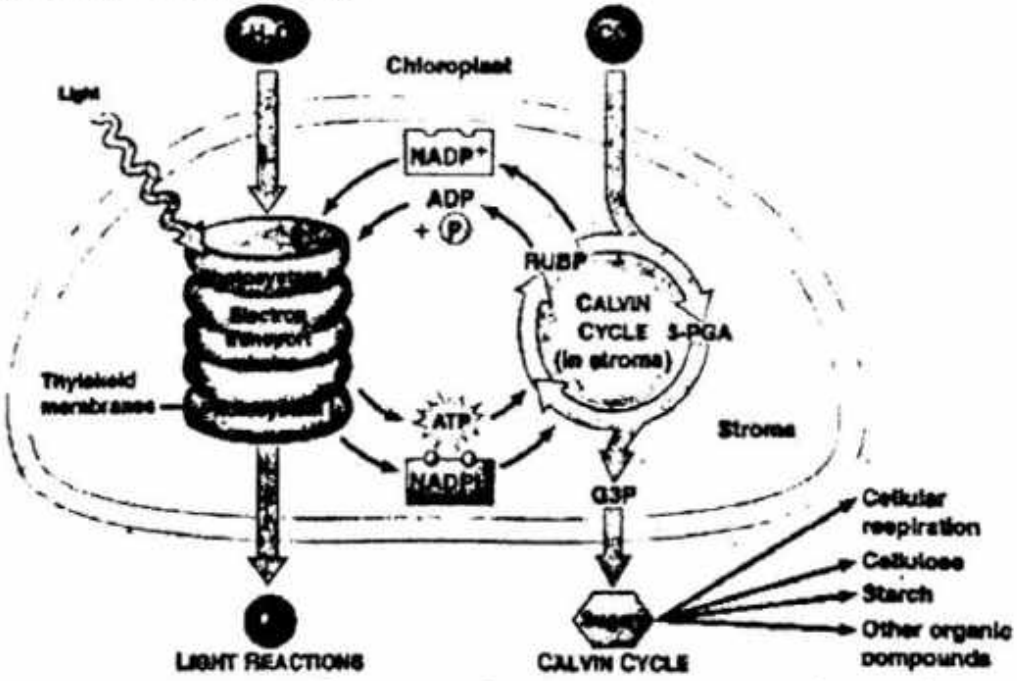
28. Describe the mechanism of photosynthesis.

Ans: Mechanism of photosynthesis:

The process of photosynthesis has been divided into two phases

Light Dependent Phase (light reaction):

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.



An overview of photosynthesis

Light Independent Phase (dark reaction):

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 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.

29. Explain in detail the light dependent phase of photosynthesis?

Ans: 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.

$$ADP + Pi \longrightarrow ATP$$

In non-cyclic electron flow, the excited electrons after leaving a 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 involved in this photophosphorylation is called **chemiosmosis.**

The process of photophosphorylation during non-cyclic electron flow is called noncyclic photophosphorylation and during cyclic electron flow is called cyclic 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" (electron deficiency) in the photosystem behind.

Photolysis of water:

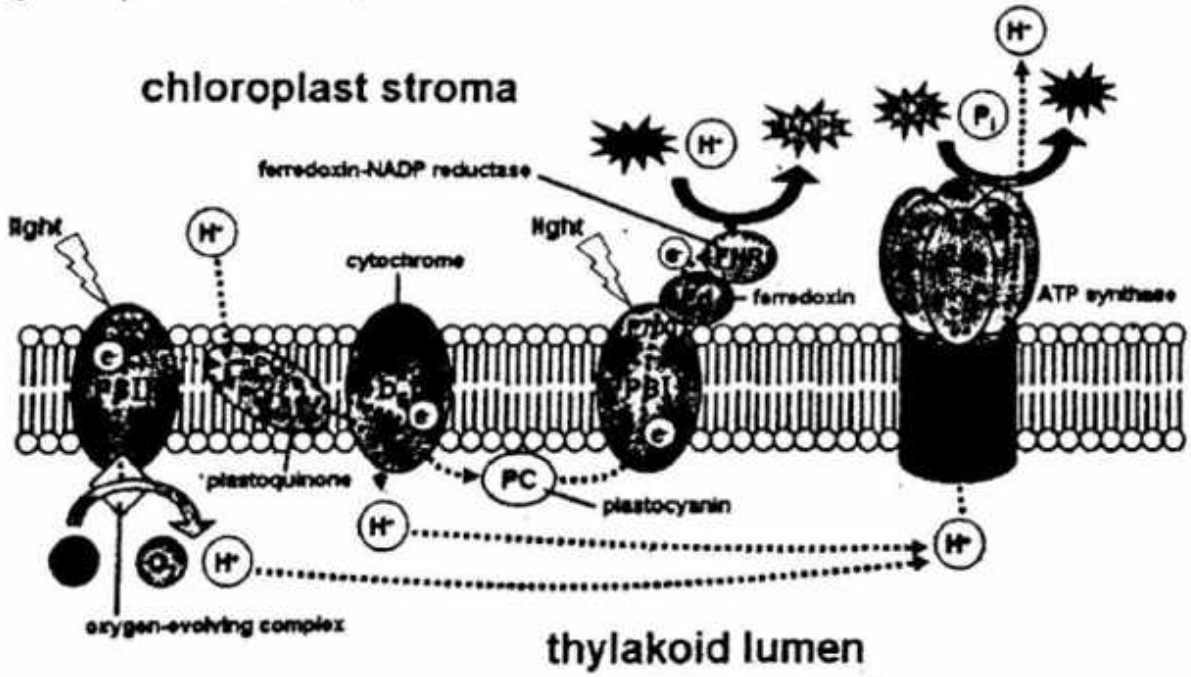
The electron holes of photosystem must be filled so that in the presence of water splitting enzyme reactions can proceed. When water reacts with oxidized state of chlorophyll in photosystem, it breaks up into $2H^+$ ions $2e^-$ and $\frac{1}{2}O_2$. Since

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.

$$H_2O \xrightarrow{\text{Photolysis of water}} 2H^+ + 2e^- + \tfrac{1}{2}O_2$$

Electron flow from PS-II to PS-I:

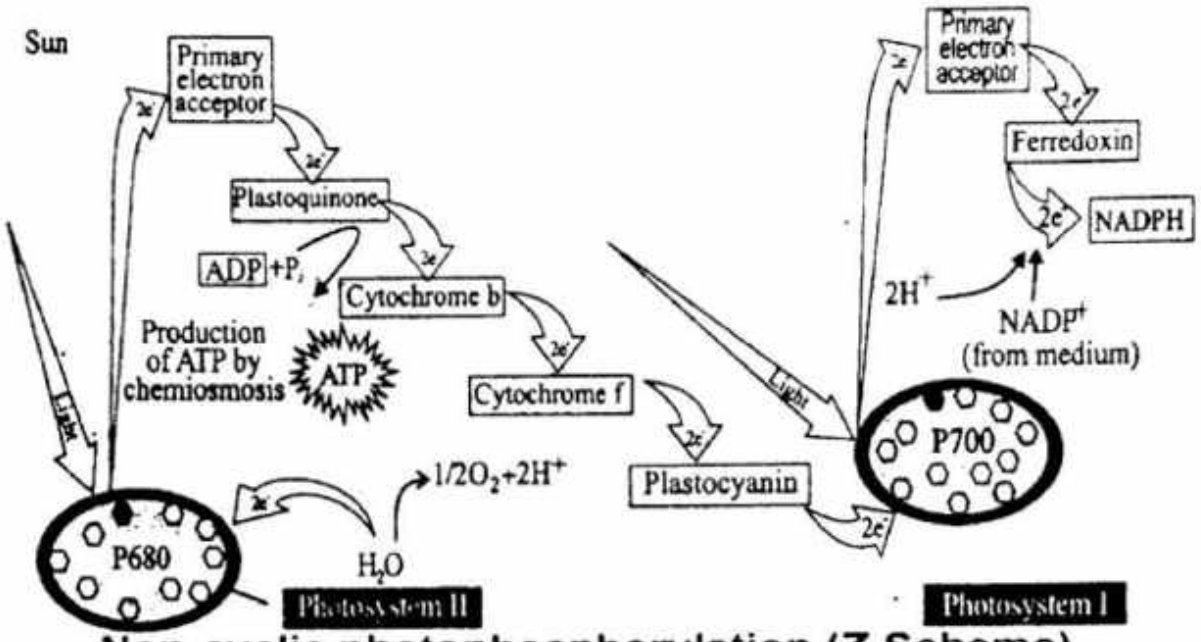
The excited/energized electrons which have been released from PS-II and captured by primary electron acceptor now begin to flow to PS-I through an electron transport chain. The primary electron acceptor is an iron containing protein, the **plastoquinone (PQ).** From PQ the electrons flow through a cluster/complex of another iron containing proteins, the **cytochromes (Cyt)** which consist of **Cyt-b_6** and **Cyt-f.** 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 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 a copper containing protein, the **plastocyanin (PC)** and finally incorporated into the PS-I.



Chemiosmotic synthesis of ATP during light reaction

Absorption of light by PS-I and excitation of its electron:

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 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.



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** (fiavoprotein 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.

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

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

30. Explain in detail the light independent phase of photosynthesis?

Ans: 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. However, this phase can occur at night but generally it takes place in day time because the products of light reaction are available in day time.

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) also called **phosphoglyceraldehyde** (PGAL) 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 **Hatch-Slack cycle** or **C4 pathway.** The plants in which only Calvin cycle occurs during dark reaction are called **C3 plants.** Whereas, the plants in which both Calvin cycle and Hatch-Slack cycle occur are called C4 plants.

31. Describe cyclic photophosphorylation.

Ans: 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. It is also a predominant pathway of light reaction during bacterial (except cyanobacteria) photosynthesis.

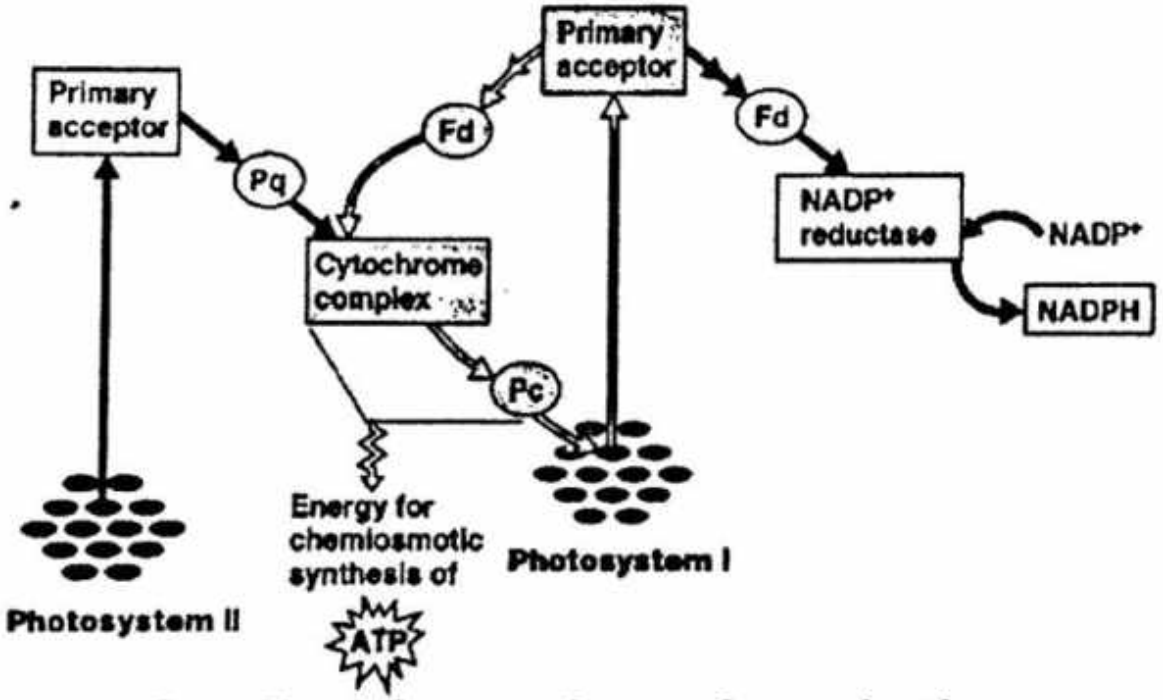
i. In this mechanism only PS-I is utilized. It absorbs energy in the form of photons.

ii. 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 D6-f complex and plastocyanin.

iii. When electrons are passed from cytochrome b6-f complex an ATP is generated by chemiosmosis.

iv. Finally, the electrons after losing the energy return back to P700 chlorophyll in PS-I reaction centre.

v. There is no production of NADPH, no occurrence of photolysis of water and therefore, no release of oxygen.

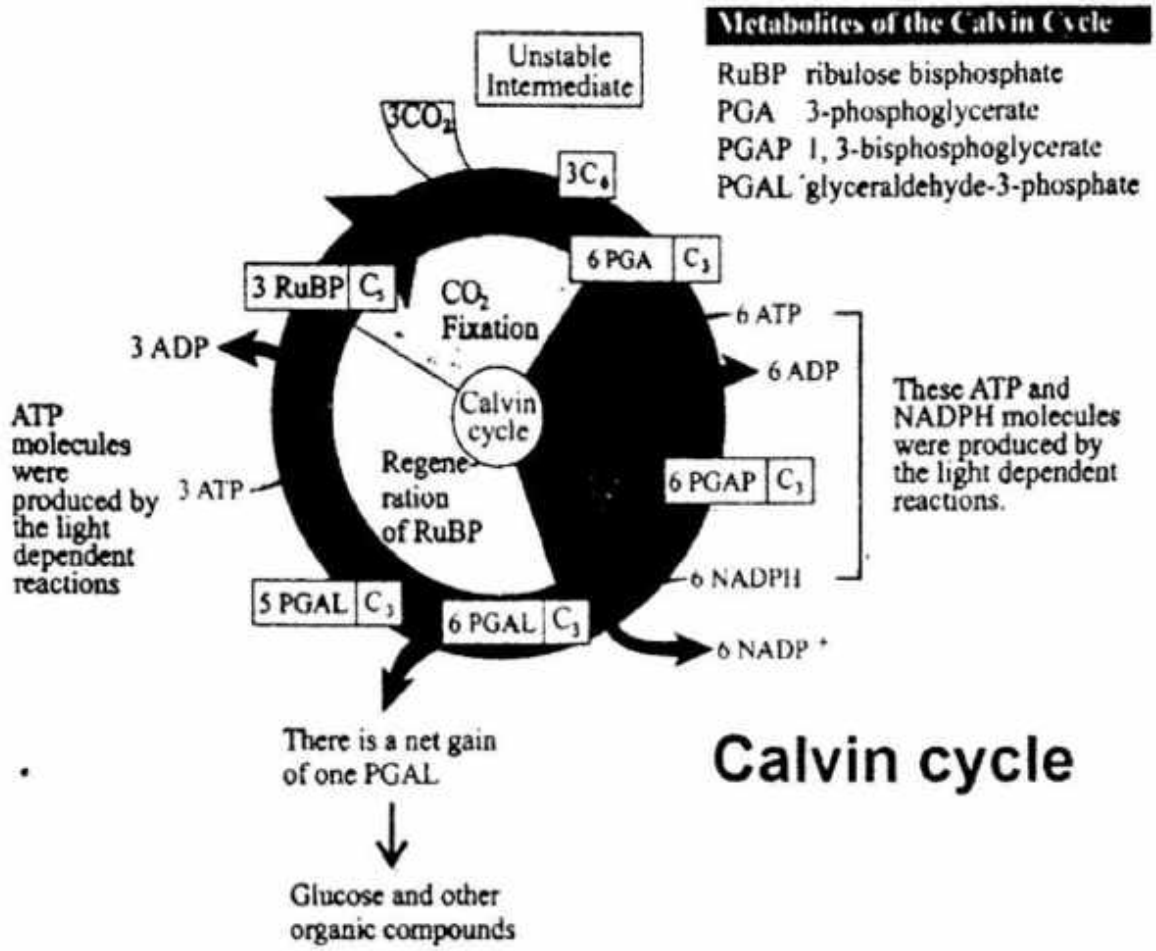


Cyclic photophosphorylation

32. Describe Calvin cycle.

Ans: 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 coworkers 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.



Calvin cycle

Carbon fixation:

Ribulose Bisphosphate (RuBP):

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**.

Carbon Fixation:

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-phosphoglyceric acid or 3-PGA), a phosphorous containing compound with three carbon atoms. Since, the carbon of inorganic compound (CO2) becomes the part of organic compound (RuBP) during this phase, hence, it is called **carbon fixation.**

C3 Pathway:

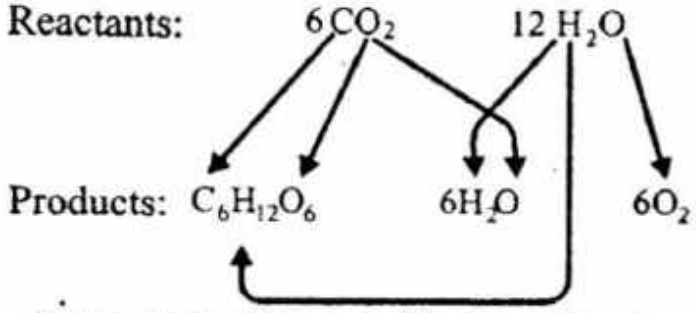
As the first stable compound in the Calvin cycle is a three carbon compound (3-PGA) that is why Calvin cycle is also known as **C3 pathway**.

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 (1,3-BisPGA or PGAP).

These molecules are then reduced by the hydrogen of NADPH and finally glyceraldehyde 3 phosphate (G3P or PGAL) molecules are produced.

During this reduction process a phosphate group from each 1,3-BisPGA molecule is also given off. There are total six molecules of G3P or PGAL 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.



Fate of the Atoms in Photosynthesis

Regeneration of CO_2 acceptor:

Five molecules of G3P or PGAL 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 (not given in the diagram) 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 (CO_2 acceptor) 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 or PGAL form the cycle. However, in order to produce a glucose molecule, two molecules of G3P or PGAL are required. The overall process of Calvin cycle can be represented as:

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

33. Describe the kinds of cellular respiration.

Ans: 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.

Kinds of Cellular Respiration:

There are two kinds of respirations:

i. Aerobic Respiration **ii.** Anaerobic Respiration

i. Aerobic Respiration:

Aerobic respiration takes place in the presence of abundant atmospheric oxygen.

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.

ii. Anaerobic Respiration:

Anaerobic respiration occurs in the absence of oxygen.

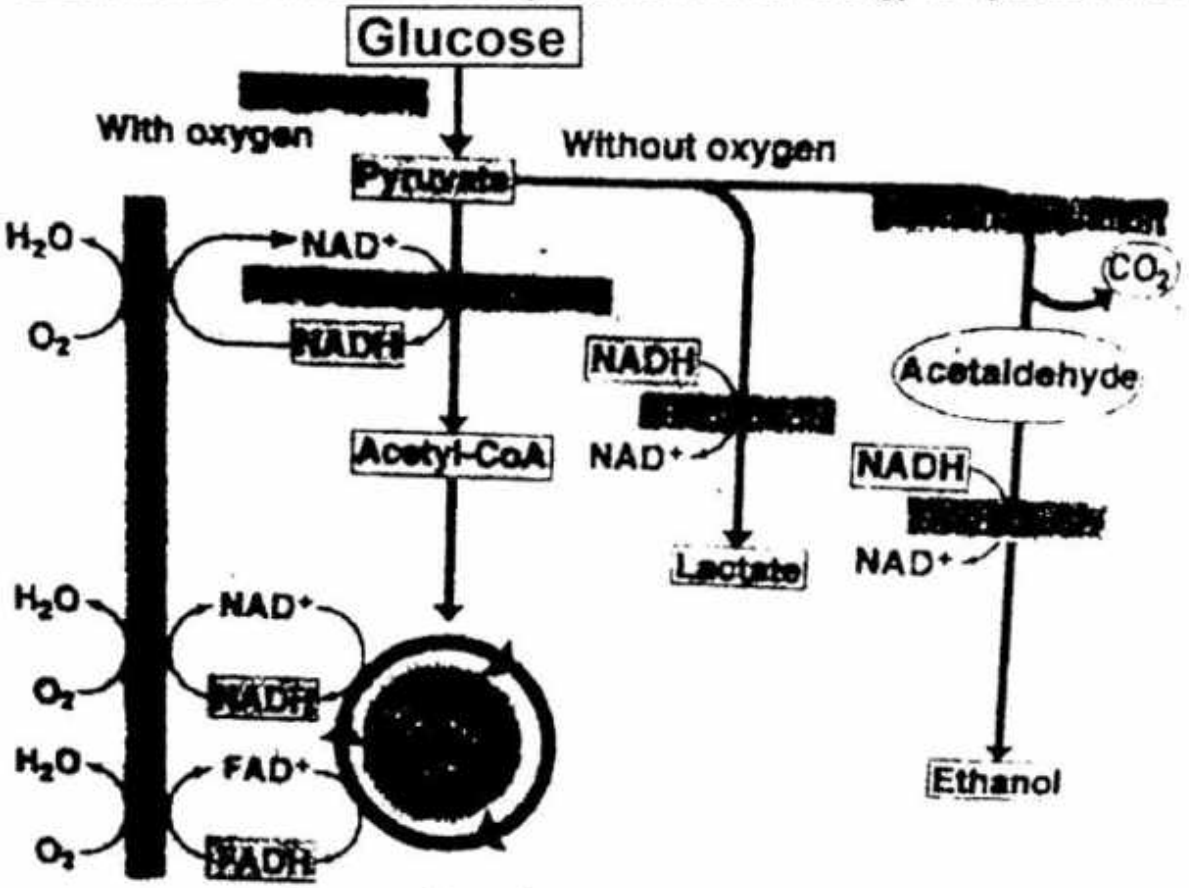
Mechanism of Anaerobic Respiration:

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.

Common Steps of Aerobic Respiration and Anaerobic Respiration:

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.



An overview of respiratory pathways

34. Give an account of 'Glycolysis'.

Ans: Glycolysis:

EMP pathway:

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

Phases of Glycolysis

It is completed in two phases i.e., preparatory phase and oxidative phase.

a. Preparatory phase

Preparatory phase is an investment phase in which two ATPs are consumed. Its end products are two molecules of G3P or PGAL.

b. Oxidative Phase:

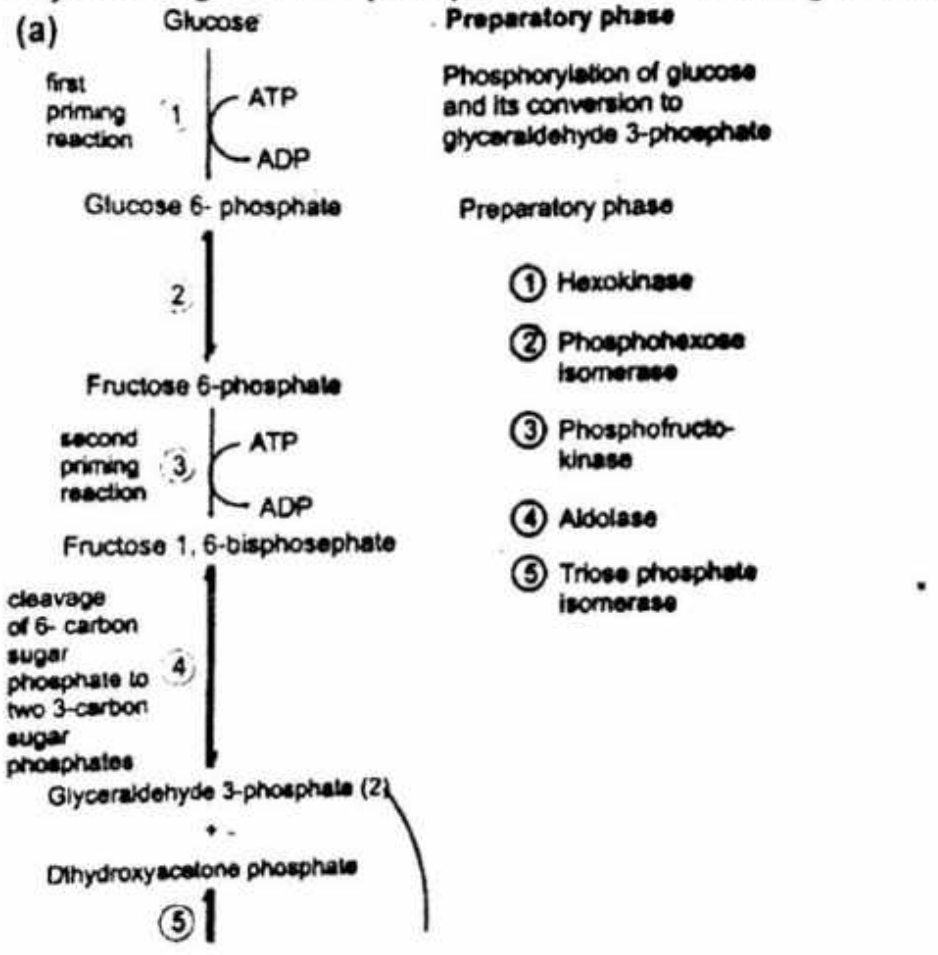
On the other hand **oxidative phase** is **pay off phase** in which not only ATPs are produced through substrate level phosphorylation but it also produces NADH which upon further oxidation in respiratory electron transport chain yields more ATPs.

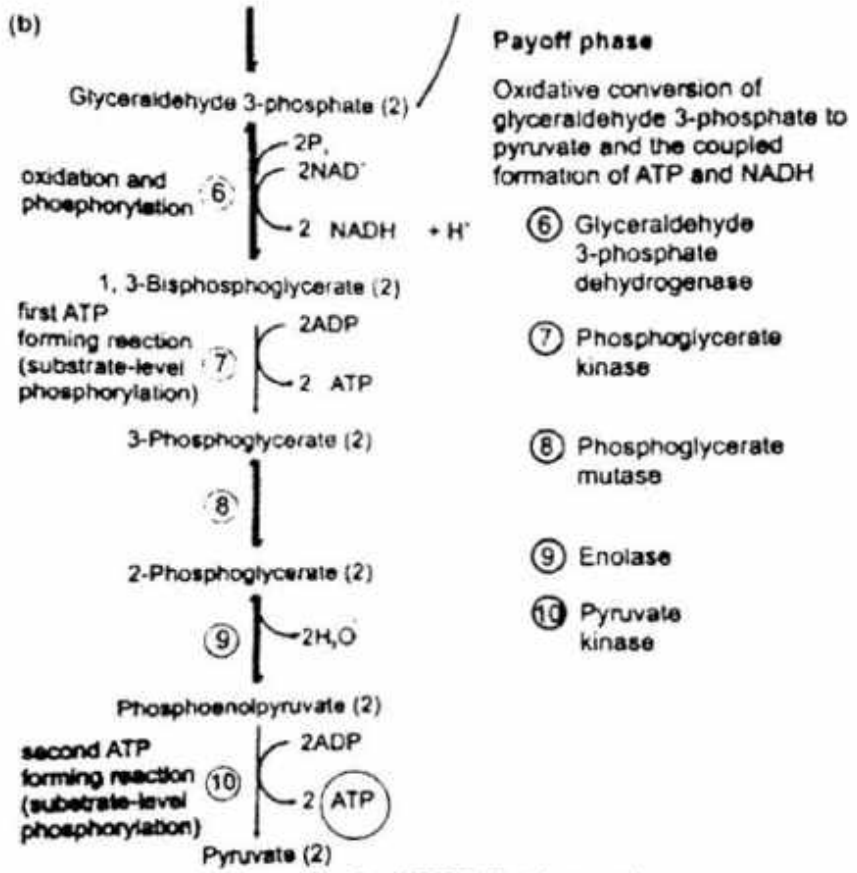
Sub Steps of Glycolysis Pathway:

The whole glycolysis pathway takes place in the following sub steps.

1. Phosphorylation:

When glucose reacts with ATP in the presence of enzyme **hexokinase** or glucokinase, a phosphate group from ATP is transferred to glucose. In this way glucose is phosphorylated to **glucose-6-phosphate** and ATP is changed into ADP.





Glycolysis (EMP Pathway)

2. Isomerization:

Glucoses-phosphate is changed to its isomer **fructose-6-phosphate** with the help of enzyme **phosphohexose isomerase.** Fructose-6-phosphate can also be produced directly by phosphorylation of fructose with the help of enzyme fructokinase.

3. Phosphorylation:

When fructose-6-phosphate reacts with ATP in the presence of enzyme **phosphofructo -kinase,** a phosphate group from ATP is again transferred to fructose-6-phosphate. In this way fructose-6-phosphate is phosphorylated to **Fructose-1, 6-bisphosphate** and ATP is changed into ADP.

4. Splitting:

Now fructose-1, 6-bisphosphate splits up by an enzyme aldolase to form one molecule each of 3- carbon compounds, **glyceraldehyde 3-phosphate** (G3P) also known as 3-phosphoglyceraldehyde (PGAL) and **dihydroxyacetone** 3-phosphate (DHAP).

5. Isomerization:

The dihydroxyacetone 3-phosphate (DHAP) is ultimately changed into its isomer, the **glyceraldehyde 3-phosphate** (Q3P) by enzyme **triose phosphate isomerase** (phosphotriose isomerase). In this way preparatory phase is completed. Next phase of glycolysis is proceeded by two molecules of G3P or PGAL, therefore, the remaining reactions occur twice.

6. Dehydrogenation and Phosphorylation (Oxidative phosphorylation):

In the presence of enzyme **glyceraldehyde 3-phosphate dehydrogenase,** G3P donates hydrogen to NAD to form 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 by substrate level phosphorylation when an enzyme, **phosphoglycerate kinase** removes a phosphate group from 1, 3-bisphosphoglycerate which is taken up by the ADP to form ATP. In this way, 1, 3-bisphosphoglycerate is changed into 3-phosphoglycerate after dephosphorylation.

8. Isomerization:

In this step position of phosphate group is changed from C3 to C2 of phosphoglycerate. In this way, 3-phosphoglycerate is changed into its isomer, the 2-phosphoglycerate by an enzyme, the **phosphoglycerate mutase** (also known as phosphoglyceromutase.)

9. Dehydration:

In this step, 2-phosphoglycerate undergoes dehydration (removal of water molecule) in the presence of an enzyme **enolase.** In this way 2-phosphoglycerate is converted into **phosphoenol pyruvate (PEP).**

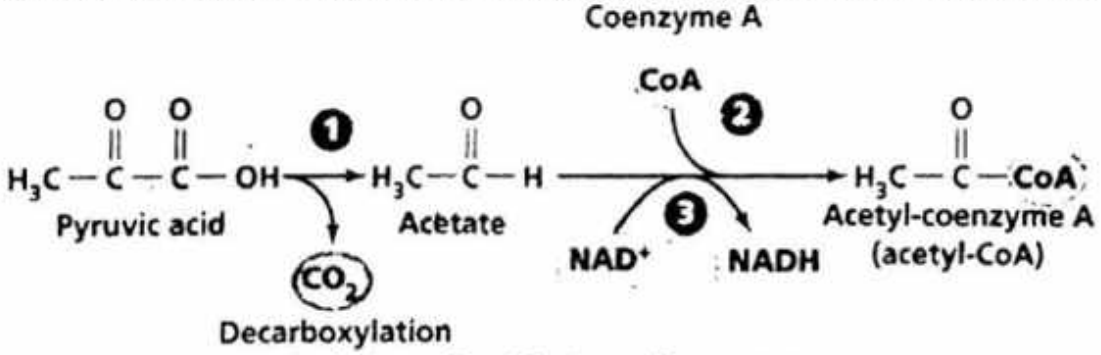
10. Formation of ATP:

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 after dephosphorylation is finally converted into **pyruvate.**

35. Explain oxidation of pyruvate.

Ans: 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 **pyruvate transloçase.** On entering the mitochondria, pyruvates do not directly participate in Krebs cycle but they 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.



Pathway of oxidation of pyruvate

Steps in Oxidation of Pyruvate:

The oxidation of pyruvate takes place in three steps.

i. First, it undergoes **decarboxylation** in which a molecule of CO_2 is removed from pyruvate to form **acetate.**

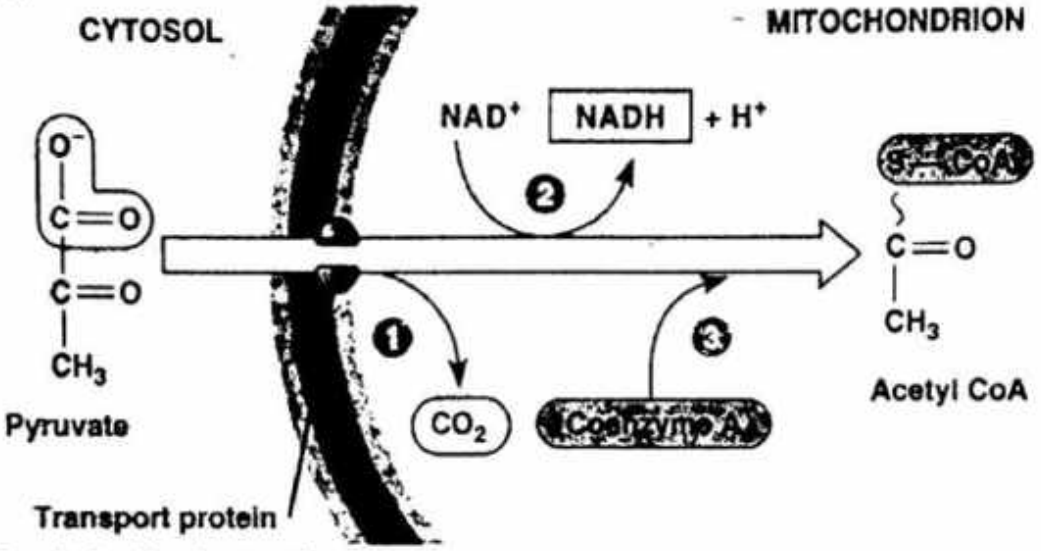
ii. Then NAD^+ removes hydrogen from acetate. As a result of this oxidation/ dehydrogenation a 2C fragment acetyl and NADH are produced.

iii. Finally, acetyl group is combined with coenzyme-Atoform acetyl **CoA.** The whole oxidative decarboxylation and addition of coenzyme A is catalyzed by

a cluster of three enzymes and five factors called pyruvate dehydrogenase complex.

Site of oxidation of pyruvate:

Conversion of pyruvate to acetyl CoA, the junction between glycolysis and the citric acid cycle.



36. Explain Krebs cycle.

Ans: Krebs Cycle:

Complete oxidation of acetyl coenzyme A into CO_2 and H_2O takes place in Krebs cycle. It begins with the binding of Acetyl CoA to 4C compound, the **oxaloacetate.** The resulting 6C compound is called **citrate** which passes through a series of electron yielding oxidation reactions in which NADH and $FADH_2$ are produced that release ATP upon further oxidation in respiratory chain. In addition, ATP is also produced directly by substrate level phosphorylation. Two CO_2 molecules are split off regenerating the 4C compound, the oxaloacetate which is free to bind another acetyl group. In this way the process become cyclic. In each turn of the cycle a new acetyl group comes into, to replace the two CO_2 molecules, that are lost and more electrons are extracted.

Discovery of Krebs Cycle:

This cycle was discovered by British scientist **Sir Hans Kreb,** 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.

Steps of Krebs Cycle:

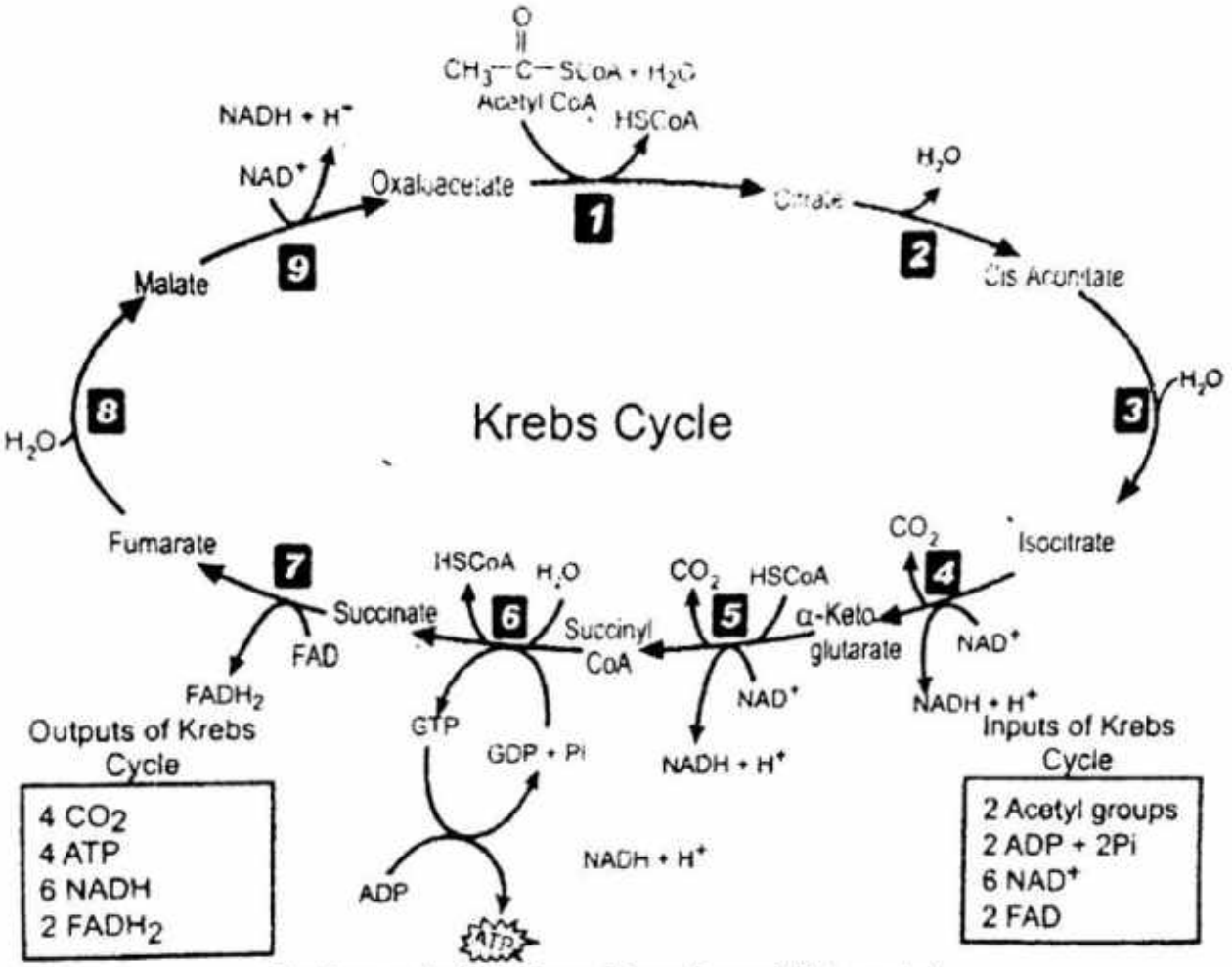
The Krebs cycle comprises following nine steps.

1. Synthesis:

Acetyl CoA (2-carbon compound) and a water molecule combine with oxaloacetate (4-carbon compound) in the presence of **citrate synthetase** enzyme to form a tricarboxylic 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 (dehydration) in the presence of an enzyme aconitase. The resulting compound is **cis-aconitate.**



Krebs cycle (Citric acid cycle or TCA cycle)

3. Hydration:

Cis-aconitate is converted into **isocitrate** with the addition of water (hydration) in the presence of same enzyme aconitase. Actually, citrate and isocitrate are isomers of each other.

4. Oxidative decarboxylation:

This is a two-step process, which involves oxidation/dehydrogenation of isocitrate to oxalosuccinate, followed by the **decarboxylation** of oxalosuccinate to **alpha-ketoglutarate.** Both these steps are catalyzed by enzyme complex isocitrate dehydrogenases. 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 to form **succinate** in the presence of an enzyme **complex α-ketoglutarate dehydrogenase.** 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, succinate combines with coenzyme A to form succinyl **CoA** in the presence of the same enzyme.

6. Formation of ATP by substrate level phosphorylation:

Succinyl CoA is acted upon by enzyme **succinyl thiokinase** to remove coenzyme A, hence succinate is formed. 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.

7. Dehydrogenation/oxidation:

Succinate undergoes dehydrogenation/oxidation to form fumarate with the help of **succinate dehydrogenase** enzyme which uses FAD as oxidizing agent. 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 (hydration) to fumarate to form **malate** in the presence of an enzyme **fumarase.**

9. Dehydrogenation/oxidation:

Malate undergoes dehydrogenation or oxidation in the presence of an enzyme **malate dehydrogenase** 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 (activated acetate) to repeat the cycle.

37. Explain electron transport chain.

Ans: Electron Transport Chain:

Inner mitochondrial membrane contains groups of electron and proton transporting enzymes. In each group the enzymes are arranged in a specific series called electron transport chain (ETC) or mitochondrial respiratory chain or electron transport system (ETS). An electron transport chain or system is a series of electron carriers and some of them also work as proton pumps. They take part in the passage of electrons from NADH or $FADH_2$ to its ultimate acceptor i.e., molecular oxygen.

Components of electron transport chain:

The components of electron transport chain include:

(1) NADH-Q reductase or NADH-dehydrogenase complex (flavin mononucleotide i.e., FMN and iron sulphur (Fe-S) complex).

(2) FADH-dehydrogenase or coenzyme Q or Ubiquinone (UQ).

(3) Cytochrome (Cyt) reductase complex (Cyt-b and Cyt-C_1).

(4) Cytochrome-c, (5) Cytochrome oxidase complex (Cyt-a and Cyt-a3).

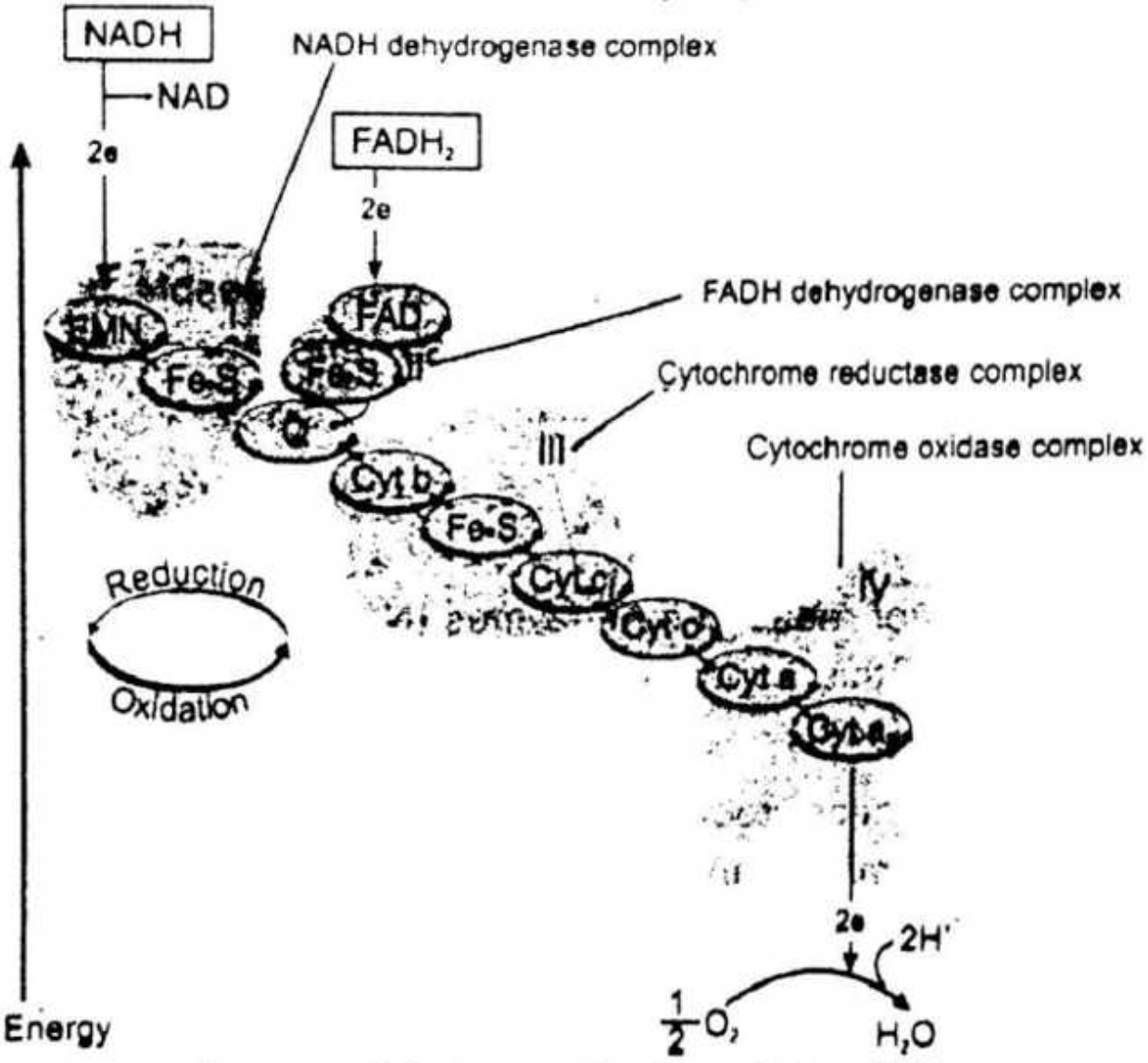
The passage of electrons from one carrier to the next is a downhill journey with a loss of energy at each step because the energy of flowing electrons is utilized by some carriers to pump protons (H^+) from matrix (inner chamber) to inter-membrane space (outer chamber). The accumulation of protons (H^+) in inter-membrane space is termed as proton gradient which activates the ATP synthetase to catalyze oxidative phosphorylation (synthesis of ATP in the presence of oxygen).

Passage of electron flow:

i. Electrons removed from NAD^+ during glycolysis and Krebs cycle form NADH. NADH is oxidized when it reacts with **NADH- dehydrogenase complex (I).** It has two prosthetic groups, flavin mononucleotide (FMN) and iron sulphur (Fe-S) complex. Both electrons and protons pass from NADH to FMN. The 3FMN now moves the electron to the Fe-S complex and pumps the protons to inter-membrane space.

ii. Electron now moves from Fe-S complex to a mobile electron carrier, the **co-enzyme Q,** also called **ubiquinone (UQ).** If $FADH_2$ is to be oxidized through

ETC, it also hands over its electrons and protons to coenzyme Q, therefore, this enzyme is also known as **FADH dehydrogenase complex (II).**



Sequence of electron carriers in respiratory ETC

iii. The flowing electrons from coenzyme Q are now transferred to **cytochrome** reductase complex **(III)** which has three components i.e., cytochrome b, Fe-S complex and cytochrome C_1. This enzyme complex not only forwards the electrons to the next electron carrier but it also pumps protons into the inter-membrane space.

iv. Cytochrome **c1** hands over its electron to **cytochrome c.** Like co-enzyme **Q**, cytochrome **c** is also mobile carrier of electrons.

v. Cytochrome **c** delivers the electrons to **cytochrome oxidase complex (IV)** which comprises cytochrome-a and cytochrome-a_3. Cytochrome-a_3 also possesses copper. This enzyme complex also works as an electron carrier as well as proton pump.

vi. Finally, the electrons from Cyt-a_3 are transferred to oxygen. The oxygen is the ultimate acceptor of electrons. It becomes reactive. Each oxygen atom also picks up pair of hydrogen ions from the aqueous solution forming water.

vii. Energy released during passage of electrons from one carrier to the next is made available to specific transmembrane complexes, which pump protons

(H^+) from the matrix side of the inner mitochondrial membrane to the outer chamber. There are three such sites, corresponding to three enzymes present in the electron transport chain (NADH-dehydrogenase complex, cytochrome reductase and cytochrome oxidase (see figure). If the energy were released in one step, most of it would be lost as non-useable heat.

FMN —— CoQ, Cyt b —— Cyt c1, Cyt a —— Cyt a_3

viii. 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.

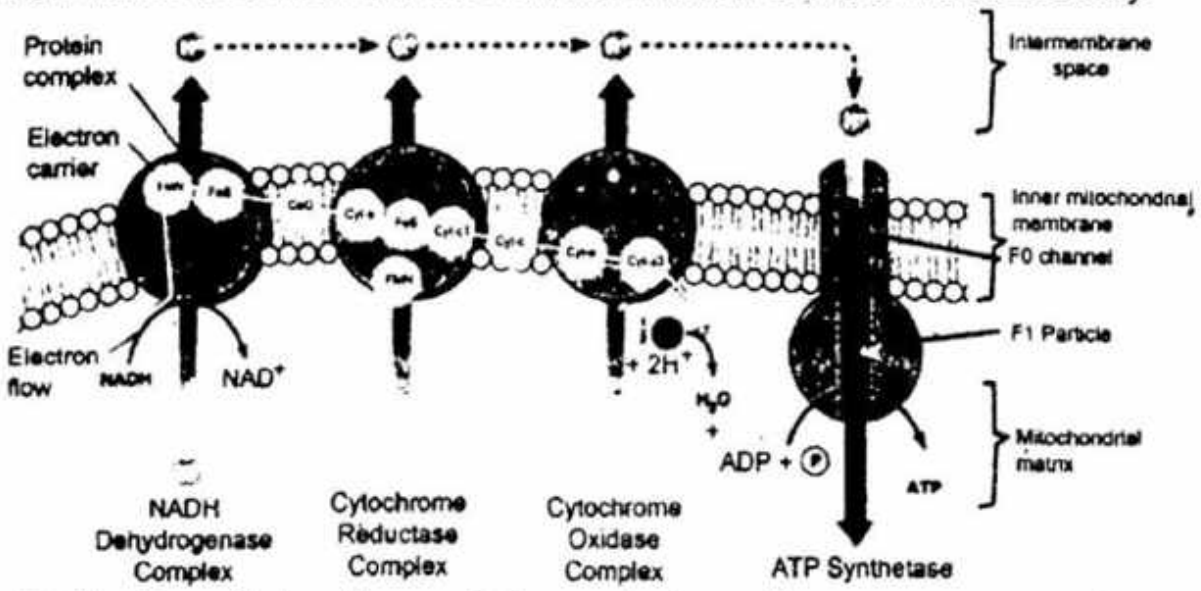
38. Explain chemiosmosis and oxidative phosphorylation.

Ans: 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 which is also called **oxysome** or **stalked particles.**

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 radicle 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 because this mechanism specifically involves the diffusion of protons (H^+) across the membranes as osmosis involves similar diffusion of water molecules only.



Mechanism of chemiosmosis in respiratory electron transport chain

Peter Mitchell, received a Nobel Prize in 1978 for his chemiosmosis theory of ATP production in mitochondria and chloroplast.

39. Describe substrate level phosphorylation.

Ans: 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.

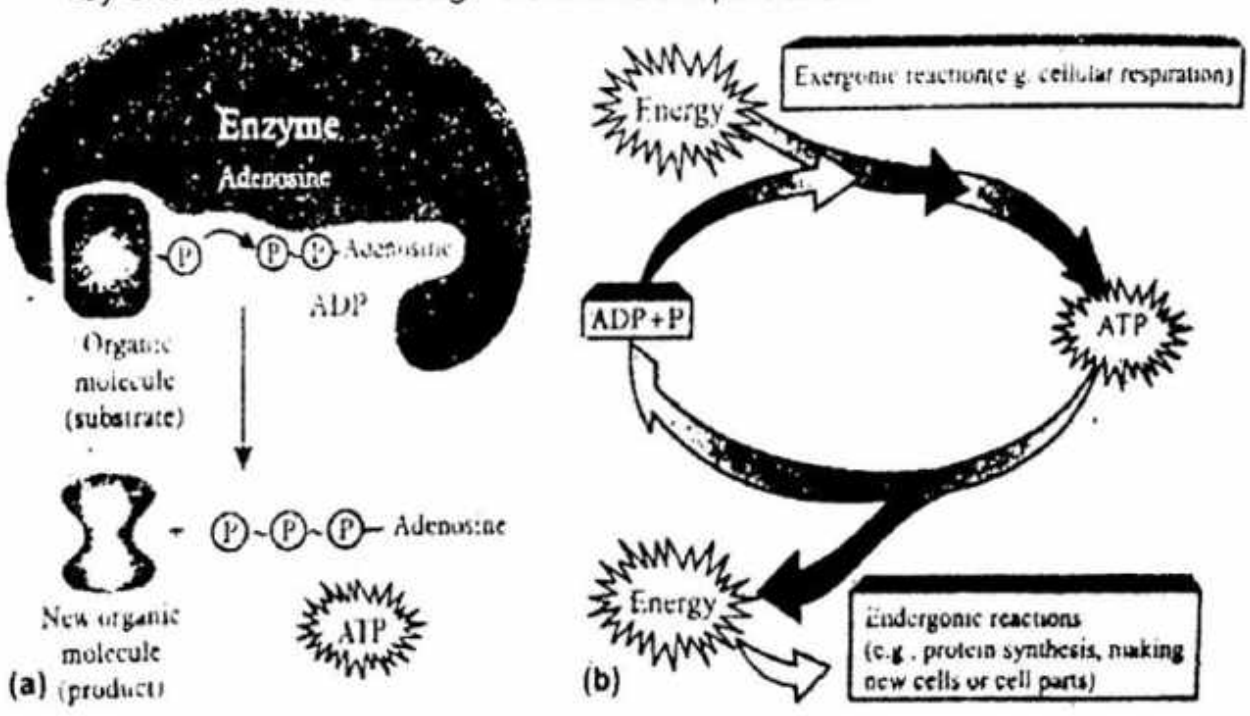
As far as substrate level phosphorylation is concerned, you are already familiar that the addition of inorganic phosphate to any organic molecule is called phosphorylation but, when phosphate is enzymatically transferred from an organic substrates molecule it is called **substrate level phosphorylation**.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

It occurs at three occasions during aerobic respiration.

i. 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 are 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.

ii. In Krebs cycle, substrate level phosphorylation occurs when succinyl CoA is converted into succinate. There are two molecules of ATP are 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.

iii. 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.



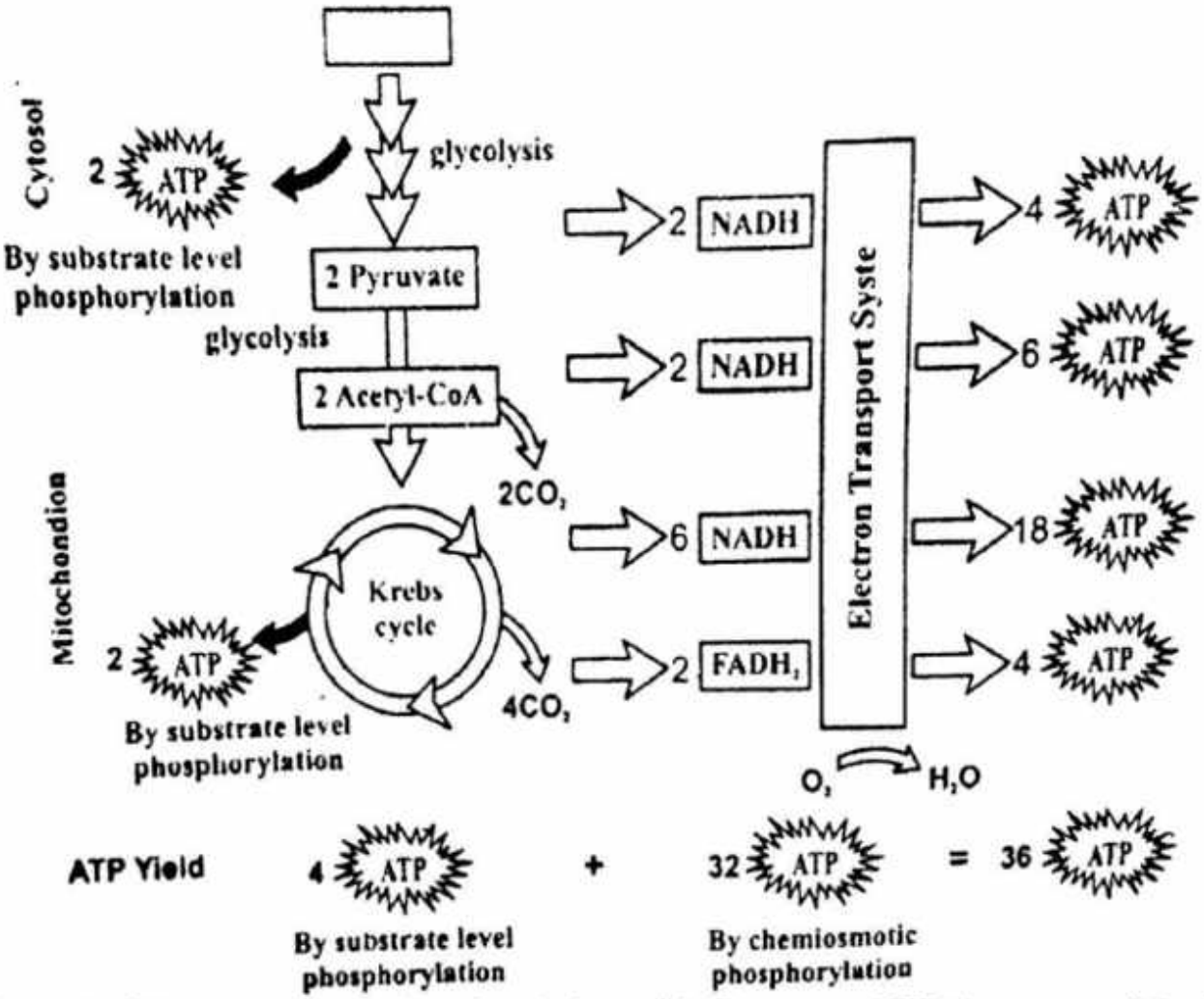


Fig: (a) Substrate level phosphorylation, (b) Because ATP is responsible for coupling many endergonic and exergonic reactions it is an important link between anabolism and catabolism in living cells, (c) ATP Budget in aerobic respirations.

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 FADH2. Hence, four ATP molecules are produced instead of six. So, eukaryotes yield two less number of ATP than prokaryotes.

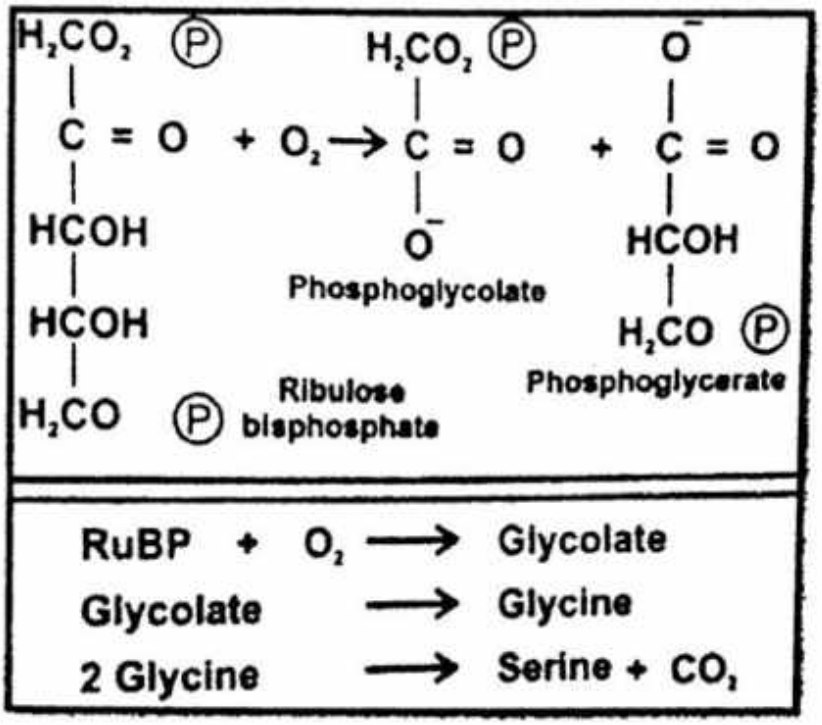
40. Give an account of photorespiration in plants.

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 produce CO_2 and H_2O like aerobic respiration. However ATP is not produced during photorespiration.

Mechanism of Photorespiration:

i. 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.



ii. The net result of this is that instead of producing two 3C molecules of phosphoglycerate (PGA), only one molecule of PGA is produced and a toxic 2C molecule called **phosphoglycolate** is produced.

iii. The plant must get rid of the phosphoglycolate. First it immediately gets rid of the phosphate group, converting the molecule to **glycolic acid** (glycolate).

iv. The glycolic acid 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.

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:

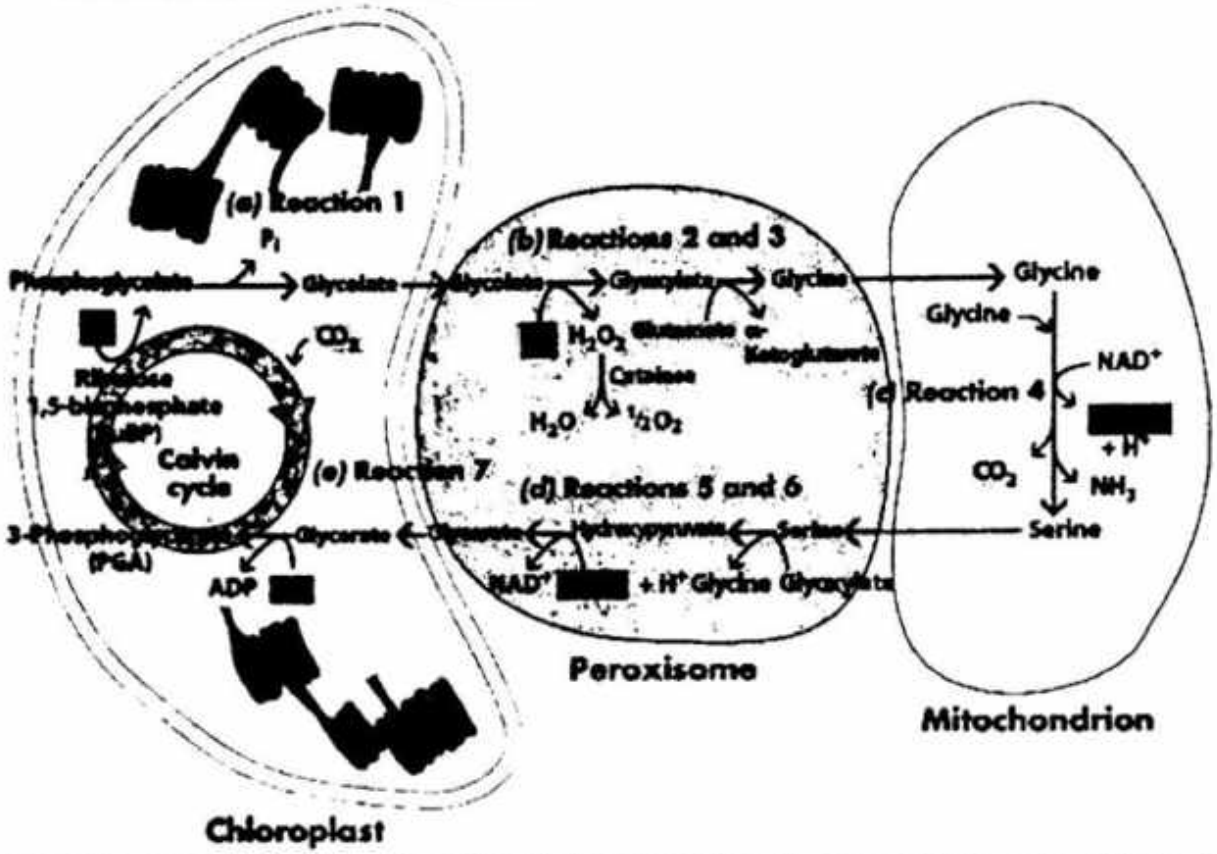
i. Photorespiration costs the plant energy and results in the net loss of CO_2 fixation from the plant. Thus, it reduces the rate of photosynthetic process. In most plants, photorespiration reduces the amount of carbon fixed into carbohydrate during photosynthesis by 25 percent.

ii. Photorespiration is not essential for plant. It is also observed that if photorespiration is inhibited chemically, the plant can, still grow.

iii. 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.



Schematic representation of pathway involved in photorespiration in chloroplast, peroxisomes and mitochondria"

41. Explain that C4 photosynthesis is an adaptation to the problem in photorespiration.

Ans: C4 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 C4 pathway in which phosphoenol pyruvate (PEP) carboxylase is used instead of RuBisCO to fix CO_2 to phosphoenol pyruvate (a C3 molecule), and the result is oxaloacetate, a C4 molecule. It takes place in cytoplasm of mesophyll cells.

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

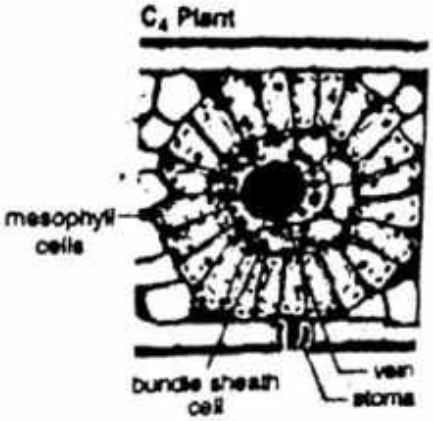
As the first product of CO_2 fixation is a 4-carbon compound oxaloacetate, so that plants are called C4 plants e.g., maize, sugarcane, sorghum, etc.

Role of Oxaloacetate:

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 (C3) 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, RuBP carboxylase participates in Calvin cycle and not in photorespiration. Sugar formed in Calvin cycle is transported into the phloem. Pyruvic acid (pyruvate) generated in the bundle sheath cells re-enters mesophyll cells and regenerates phosphoenol pyruvic acid (PEP) by consuming one ATP.

Kranz anatomy: the special structure of leaves in C4plants (e.g. maize) where the tissue equivalent to the spongy mesophyll cells is clustered in a ring around the leaf veins, outside the bundle-sheath cells. (The term **'Kranz' means** wreath or ring in German).



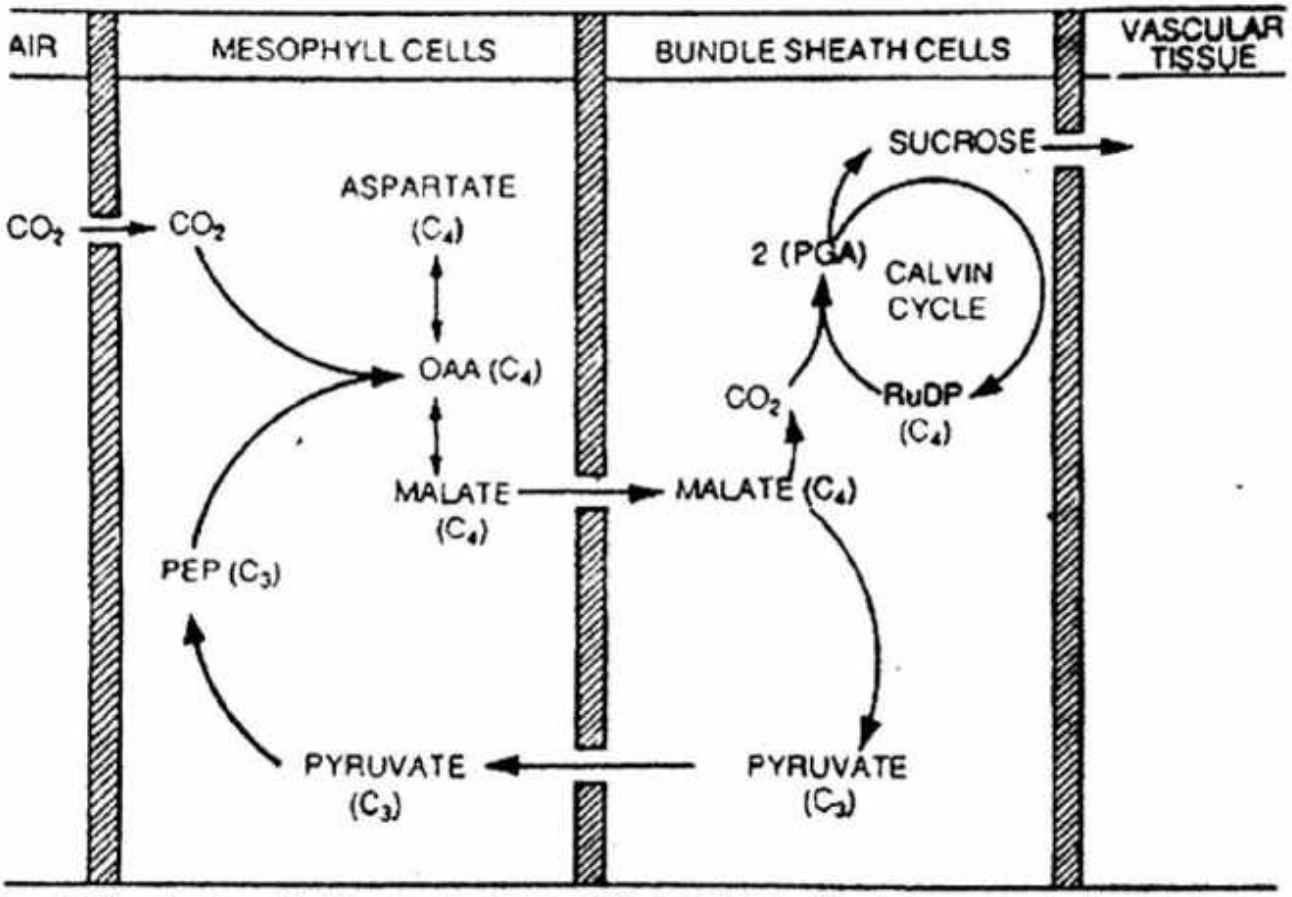


Fig: In C_4 plants with Kranz anatomy, CO_2 is initially fixed in mesophyll cells by the enzyme PEP-carboxylase, 4-carbon compound, malic acid (malate), transfers CO_2 to bundle sheath cells where it is further transferred to the Calvin cycle. Bundle sheath cells transfer the sugar they make to phloem tube transported through the body