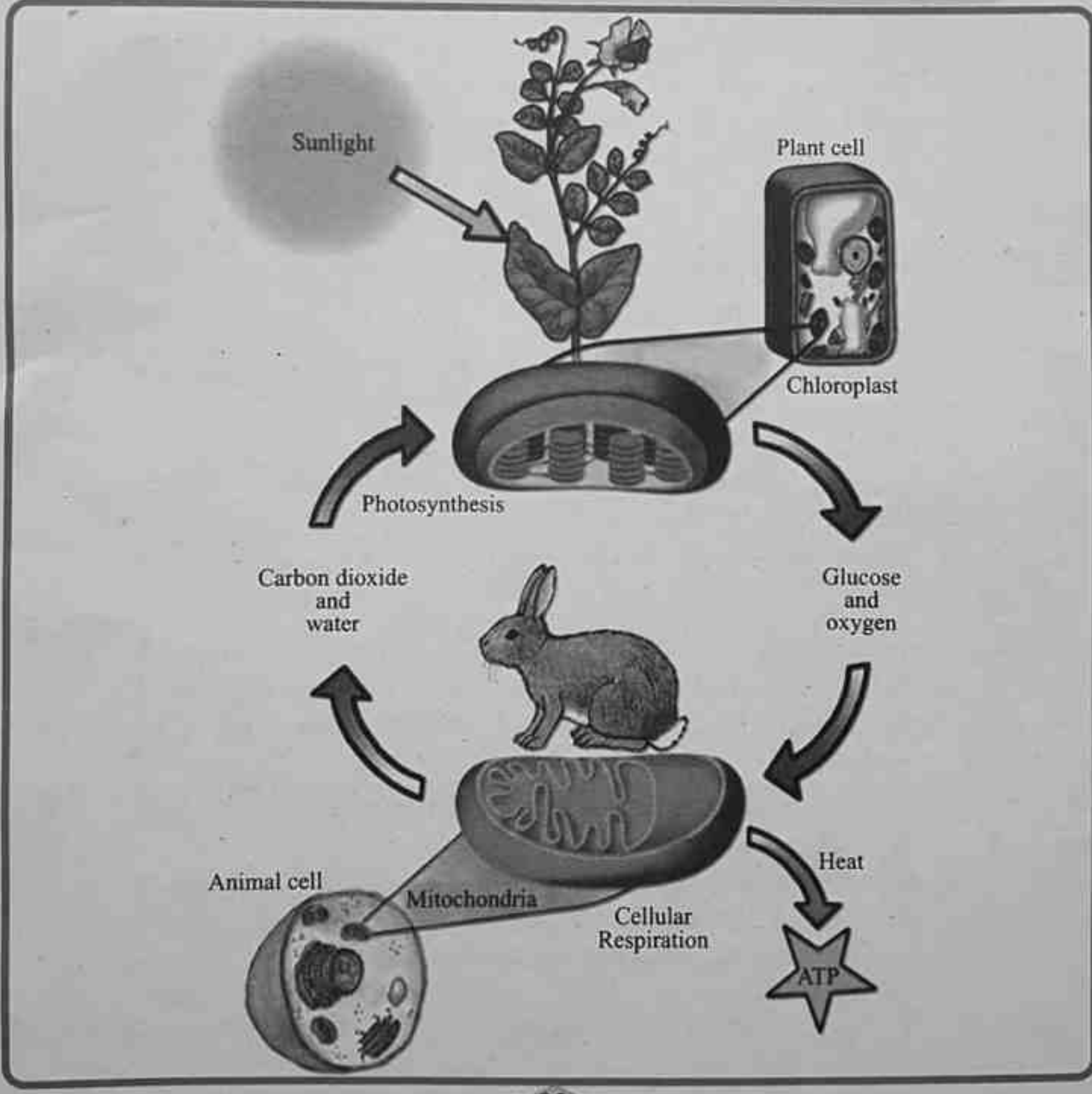
UNIT 4

BIOENERGETICS

Major Concepts

4.1 Photosynthesis
4.2 Cellular Respiration
4.3 Photorespiration



Students Learning Outcomes

On completion of this unit students will be able to:

- Explain the role of light in photosynthesis.
- Identify the two general types of photosynthetic pigments (carotenoids and Chlorophylls).
- The role of photosynthetic pigments in the absorption and conversion of light energy into chemical energy.
- Differentiate between the absorption spectra of chlorophyll a and b.
- Describe the arrangement of photosynthetic pigments in the form of photosystem I and II.
- State the role of CO_2 as one of the raw materials of photosynthesis.
- Explain the role of water in photosynthesis.
- Describe the events of non-cyclic photophosphorylation and outline the cyclic photophosphorylation.
- Explain the Calvin cycle.
- Explain the process of anaerobic respiration in terms of glycolysis and conversion of pyruvate into lactic acid or ethanol.
- Outline the events of glycolysis.
- Describe the conversion of pyruvate to acetyl-CoA.
- Outline the steps of Krebs cycle.
- Explain the passage of electrons through electron transport chain.
- Describe chemiosmosis and relate it with electron transport chain.
- Explain the substrate-level Phosphorylation during which exergonic reactions are coupled with the synthesis of ATP.
- Comprehend the importance of PGAL in photosynthesis and respiration.
- Outline the cellular respiration of proteins and fats and correlate these with that of glucose.
- Define photorespiration and outline the events occurring through it.
- Rationalize how the disadvantageous process of photorespiration evolved.
- Explain the effect of temperature on the oxidative activity of RuBP carboxylase.
- Outline the process of C4 photosynthesis as an adaptation evolved in some plants to deal with the problem of photorespiration.

Bioenergetics

Bioenergetics is the field of biochemistry and cell biology which deals with the study of the processes by which cells use, store and release energy. The quantitative study of energy relationships in biological system is called **bioenergetics**.

A central component of bioenergetics is energy transformation, the conversion of energy from one form to another. The biological energy transformations obey the laws of thermodynamics. Energy is necessary for growth and reproduction. We cannot exhibit any of characteristics of life without a ready supply of energy. In this chapter we will discuss the most fundamental metabolic processes which are photosynthesis and respiration.

> **Tit bits**
> *An exergonic reaction is a spontaneous chemical reaction that releases energy. It is catabolic reaction. An endergonic reaction is an anabolic chemical reaction that consumes energy.*

4.1 Photosynthesis

Photosynthesis is the biological process that captures light (solar) energy and converts it into chemical energy (i.e. organic molecules, e.g., glucose). It takes place in plants, algae, cyanobacteria and many bacteria.

Photosynthesis is a "redox" process which links non-living world to the living world. It involves the reduction of carbon dioxide into sugars and the oxidation of water into molecular oxygen. The overall reactions of photosynthesis can be summarized as follows:

$$\overbrace{6CO_2 + 12H_2O \xrightarrow[\text{Chlorophyll}]{\text{Sunlight}} C_6H_{12}O_6}^{\text{Reduction}} + 6H_2O + 6O_2$$

$$\underbrace{12H_2O \longrightarrow 6O_2}_{\text{Oxidation}}$$

4.1.1 Role of Light in Photosynthesis

Light is a form of energy called **Electromagnetic energy or radiation**. Solar radiation is consist of photons. Photons (Gk. "*Phos*"=Light) are separate and distinct packets of energy which come from solar radiation. Photons travel in waves, these waves contain energy. Short waves contain more energy than long wave.

The full range of electromagnetic radiation in the universe is called **electromagnetic spectrum** while visible light (380-750 nm) is only a small part of the spectrum.

Visible light:

Visible light is the part of the spectrum that the human eye can see which is white light. Photons of visible light have just the right amount of energy to promote electrons to higher electron shell in atoms. Leaves absorb only 1% of total light, which falls on them, rest is reflected or transmitted. The synthesis of ATP from ADP or AMP is called phosphorylation which is endergonic process.

$$\mathbf{ADP + Pi + energy \rightleftharpoons ATP}$$

In photosynthetic organisms the energy comes from light thus the process of formation of ATP during photosynthesis is referred to as **photophosphorylation.** Light falls on green tissues thereby water molecules are broken down (photolysis) into $\mathbf{H^+}$ ions, $\mathbf{OH^-}$ radicals and electrons. The $\mathbf{OH^-}$ radicals are collected and reassembled as water and molecular oxygen, both are released into

> **Do you know?**
> *Some carotenoids may protect chlorophyll and human eye from intense light by absorbing and dissipating excessive light energy.*

atmosphere. The Hydrogen ions (protons) are pumped across the thylakoid membrane into the lumen. H^+ ions are used to convert NADP to $NADPH_2$ in photosystem I.

4.1.2 Role of Photosynthetic Pigments

A photosynthetic pigment is a pigment that is present in chloroplasts or photosynthetic bacteria and captures the light energy necessary for photosynthesis. Different pigments absorb light of different wavelengths. The light appear in different colours when passed through a prism.

Carotenoids:

These are a group of yellow, orange, red or brown pigments that absorb blue, violet and green light. They are associated with the chlorophyll inside the chloroplast or occur alone inside the chloroplast. Carotenoids absorb different wavelengths than chlorophyll, so broaden the spectrum of light that provides energy for photosynthesis. The chlorophyll *b* and carotenoids together are called accessory pigments because they absorb light and transfer the energy to chlorophyll *a* which then starts the light reaction.

Tit bits

Carotenoids in flowers and fruits attract insects, birds and other animals for pollination and seed dispersal respectively. They also protect chlorophyll from oxidation by oxygen produced in photosynthesis.

Carotenoids $\longrightarrow$ Chlorophyll *b* $\longrightarrow$ Chlorophyll *a*

Chlorophylls:

Chlorophylls are green and main photosynthetic pigments which absorb violet, blue, orange and red wavelengths, while green and yellow are least absorbed and are reflected (therefore, leaves look green). There are six types of chlorophylls (*a, b, c, d, e,* and *f*) out of these only two types occur in chloroplasts of higher plants, i.e. chlorophyll *a* and *b*. Chlorophyll *c* and *d* are found only in algae while chlorophyll *e* and *f* are found only in bacteria.

Do you know?

There are two types of carotenoids, i.e. Carotenes and Xanthophylls.

Carotenes (Red to Orange):

Carotenes are hydrocarbons with a general formula of $C_{40}H_{56}$. Red colour of tomato and chilli are due to carotenes. The most common carotene is beta-carotene which is converted to vitamin A by animals and human beings.

Xanthophylls (Yellow to Orange):

Xanthophylls are yellow pigments that are oxygen containing derivatives of carotenes. Lutein and zeaxanthin ($C_{40}H_{56}O_2$) are the two primary xanthophylls found in green leafy vegetables and other foods like eggs. Yellow colour of leaves in autumn is due to lutein.

The xanthophylls of brown algae is called fucoxanthin ($C_{40}H_{56}O_6$). Both carotenes and xanthophylls are lipid compounds, soluble in organic solvents like other lipids.

Chlorophyll *a*:

It occurs in all photosynthetic organisms except pigmented bacteria thus termed as universal photosynthetic pigment. It is also known as primary photosynthetic pigment because it involves in primary reaction during photosynthesis, i.e. convert light energy into chemical energy. Molecular formula of chlorophyll *a* is ($C_{55}H_{72}O_5N_4Mg$).

Chlorophyll *b*:

Chlorophyll *b* occurs in all photosynthetic organisms except brown, red and blue green algae. Molecular formula of chlorophyll *b* is ($C_{55}H_{70}O_6N_4Mg$).

Do you know?

Porphyrin is derivative of porphin, consists of four pyrrole like rings linked by four CH groups in an alternate double and single bonds. If Mg++ or Fe++ are added to porphin then known as Mg++ porphyrin in chlorophyll or Fe++ porphyrin in Heme and cytochrome.

Structure of Chlorophyll:

Each chlorophyll molecule has two main parts, one flat square part which absorbs light and hydrophilic head. The other part is long anchoring hydrophobic carbon tail.

The head of chlorophyll is composed of four pyrrole rings (pyrrole is five sided unsaturated nitrogen containing compound) having Mg^{++} in the center, thus it is Mg^{++} **porphyrin** with two side chains.

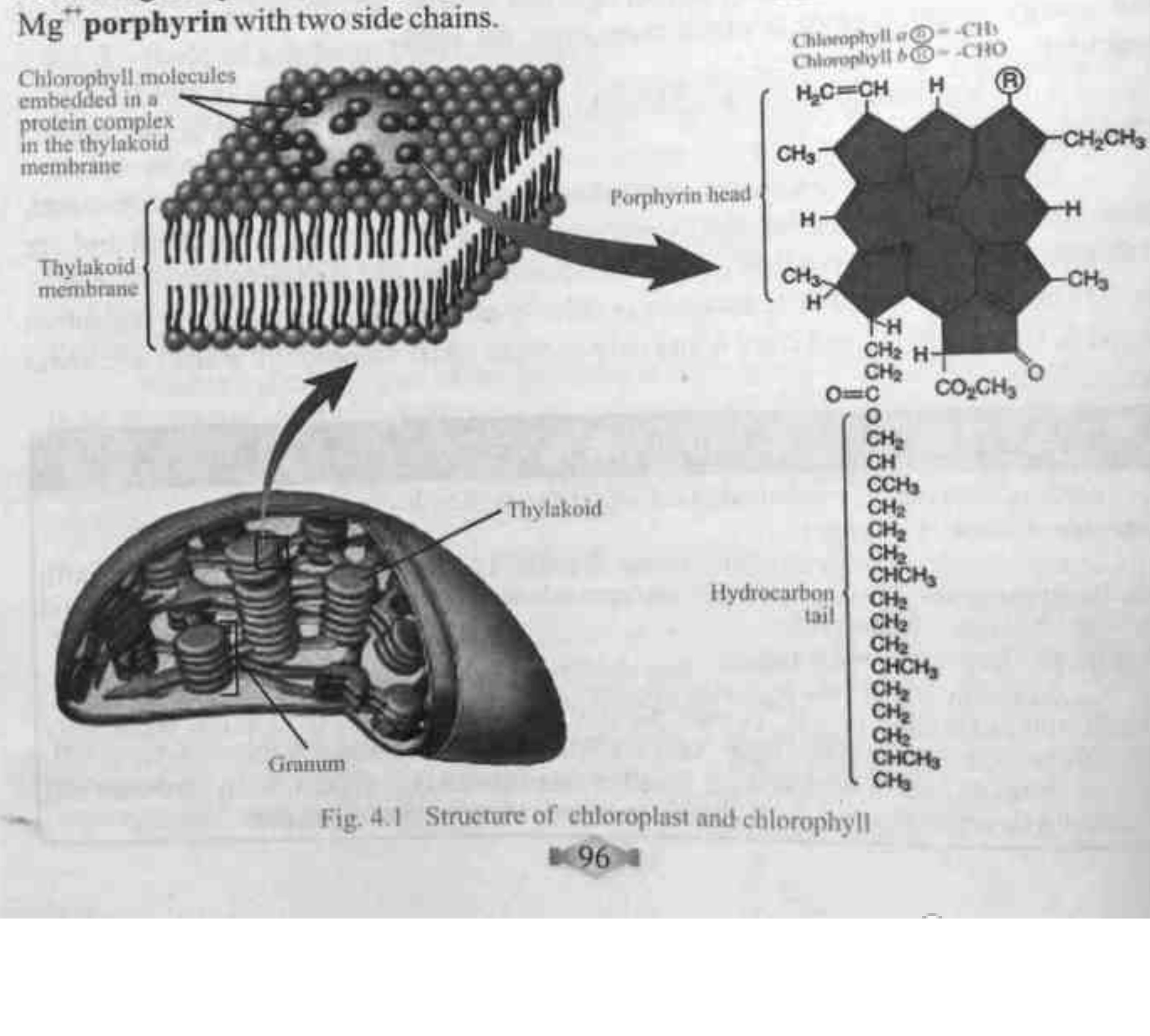


Fig. 4.1 Structure of chloroplast and chlorophyll

a. **Acid chain:** It is a methyl (CH_3) ester ($H_3C–O–C=O$).

b. **Hydrocarbon chain:** It is a long hydrocarbon tail which is attached to one of the pyrrole rings and is an alcohol phytol ($C_{20}H_{39}$) (it is an ester linkage with propionic acid) (CH_3-CH_2-COOH).

Phytol consists of four isoprene units. It is insoluble and serves to anchor the molecule in the membrane of the granum (molecular formula of isoprene is ($CH_2=C-CH_3-CH=CH_2$) (C_5H_8).

Differences Between Chlorophyll *a* And *b*:

There is only one difference between chlorophyll *a* and *b* that is one of functional group bonded to the porphyrin. In chlorophyll *a* methyl group (CH_3) while in chlorophyll *b* aldehyde group (-CHO) is present.

Role of Pigments in Photosynthesis

The clusters of photosynthetic pigments are called photosystem. Each pigment complex is composed of chlorophyll *a* and *b* molecules with accessory pigments. When these pigments absorb light they are said to be excited. The light energy is used to boost electrons to a higher energy level which is transferred into chemical energy. The excited state is unstable and molecules will tend to return to its unexcited state.

The energy which is released during this process can be passed from one chlorophyll molecule to another chlorophyll molecule. The instrument which is used to measure relative abilities of different pigments to absorb different wavelength of light is called **Spectrophotometer**.

4.1.3 Absorption Spectrum

It is a measure which exhibits the absorbed amount of the light of different wavelengths (different colours) from the visible spectrum of light. The main photoreceptors are chlorophyll *a* and chlorophyll *b* which absorb violet blue (430 nm) and red light (670 nm). The green light (550 nm) is least absorbed. The carotenoids absorb light between 430-470 nm of light spectrum and transfer it to chlorophyll *b* then to chlorophyll *a*. The chlorophyll *a* and *b* show different absorption spectra as shown figure 4.2 (a). Chlorophyll *a* shows absorption peaks at about 680 and 700 nm while chlorophyll *b* absorption peaks range between 450-475 nm.

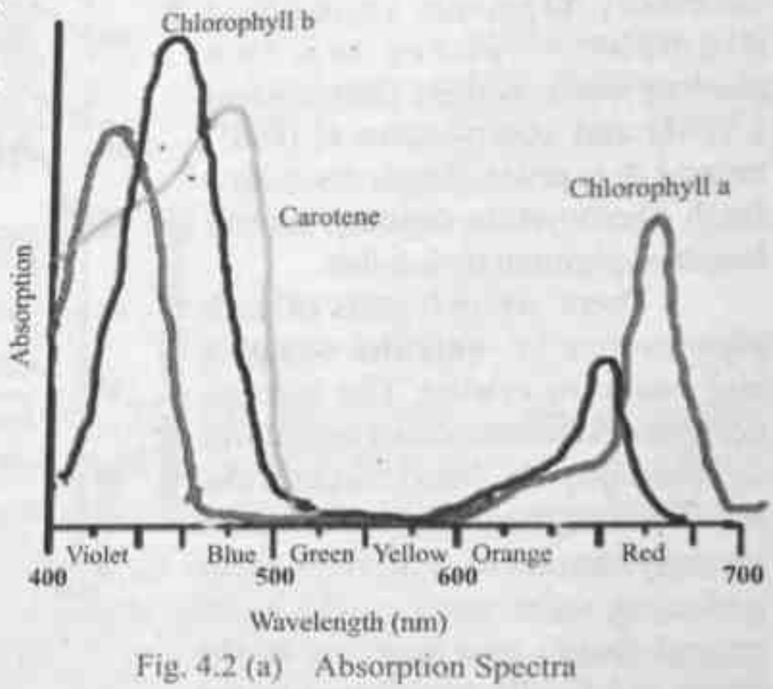


Fig. 4.2 (a) Absorption Spectra

4.1.4 Action Spectrum

A graph showing the measure of effectiveness of light of various wavelengths in driving photosynthesis is called action spectrum. Some of absorbed light is released as heat and rest of light is stored in organic compound as chemical energy. Action spectrum of a particular pigment can be calculated by measuring the rate of photosynthesis at each type of wavelength of light. A plant is illuminated with light of different wavelengths. During photosynthesis plant gives off oxygen. As photosynthesis produces oxygen and consumes CO_2, the rate of production of oxygen or consumption of CO_2 can be used as a measure of the rate of photosynthesis.

Do you know?

Accessory pigments are photosynthetic pigments that trap light energy and channel it to chlorophyll "a" the primary pigment which initiates the reaction of photosynthesis. Accessory pigmants are carotenoids, phycobilin, some proteins and chlorophyll b, c and d.

4.1.5 Arrangement of Photosynthetic Pigments in the form of Photosystem I and II

Light reaction takes place in the grana of chloroplast. It is initiated when photosynthetic pigments capture light energy. The clusters of photosynthetic pigment complex are composed of chlorophyll *a* and *b* molecules and accessory pigments (carotenoid pigments). There are two photosystems, namely photosystem I (PSI) and photosystem II (PSII) named so in order of their discovery. Each photosystem contains several hundred pigment molecules.

There are two parts of each photosystem i.e. **antenna complex** and **reaction center**. The antenna complex possesses many molecules of chlorophyll *a*, *b* and carotenoids. All these pigment molecules in the photosystem serve as an antenna for gathering solar energy, which is passed from one pigment to the other and finally transferred to the

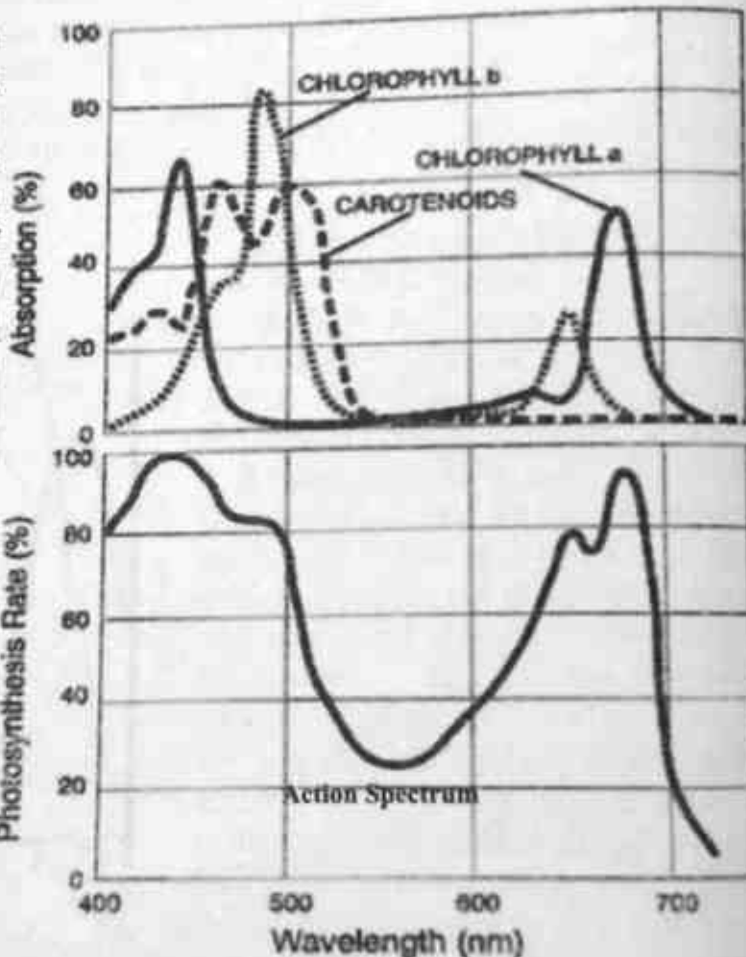


Fig. 4.2 (b) Absorption and Action spectra of different pigments

reaction center. **Reaction center** contains one more molecule of chlorophyll *a* alongwith primary electron acceptor and electron carriers of electron transport system. Electron transport system plays a role in the generation of ATP by **chemiosmosis.** The PSI absorbs light of 700 nm and is called P700 while the PSII absorbs light of P680 nm and is called P680. The **primary electron acceptor** traps the electrons from the reaction center and then passes them on to the series of electron carriers. Electrons have two pathways in the light reaction of photosynthesis; The non-cyclic electron pathway (flow) and cyclic electron pathway. The cyclic is less common and generates only ATP while non-cyclic is predominant and generates both ATP and $NADPH_2$.

Do you know?

The action spectrum is somewhat different from absorption spectrum of chlorophyll. It is more in some wavelengths, such as in 500-600 nm is more than the absorption of green light by chlorophyll. This is because the carotenoids absorb light in this region and pass on some of this absorbed light to chlorophyll, which converts light energy into chemical energy. Similarly when equal intensities of light are given, there is more photosynthesis in red than in blue part of the spectrum.

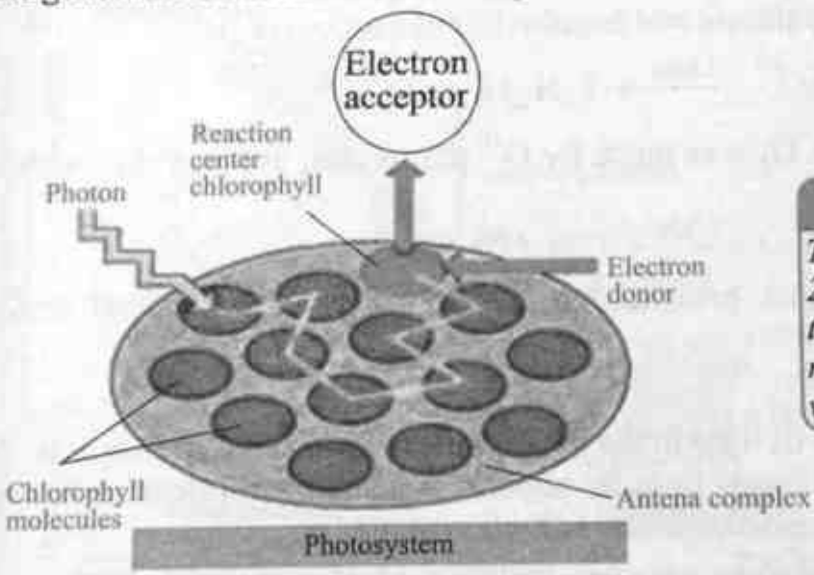


Fig. 4.3 Structure of Photosystem

Thinking Question

The stomata cover only 1 to 2% of the leaf surface but they allow proportionally much more gas to diffuse, why?

4.1.6 Role of CO_2 in Photosynthesis

Air contains about 0.03 to 0.04 % of CO_2. This CO_2 is used by terrestrial plants for photosynthesis while aquatic plants use dissolved CO_2 and carbonates present in water as source of carbon. The chloroplasts of guard cells of stomata absorb CO_2, some of which react with water to form carbonic acid.

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

In the presence of solar energy carbonic acid in the guard cells is decomposed again into water and CO_2.

$$H_2CO_3 \longrightarrow H_2O + CO_2$$

Water and carbondioxide are rapidly used in photosynthesis to synthesize organic substances. The entry of CO_2 into the leaves depends upon the opening of stomata.

4.1.7 Role of Water in Photosynthesis

Water is one of the raw materials used in photosynthesis. A film of water present around mesophyll cells of leaf helps to absorb CO_2. The water molecule is broken down into hydrogen and oxygen by the P_{680} during **photolysis**. The hydrogen combines with CO_2 to form organic food and molecular oxygen is released into atmosphere during photolysis of H_2O. Earlier it was thought that the oxygen released in the process of photosynthesis comes from CO_2. Van Neil 1903, was first who observed that water splits during photosynthesis, hydrogen released from water is used to synthesize glucose while O_2 is removed as byproduct. The idea of Van Neil was also supported by another scientist named Hill. In first experiment water was made of O^{18} and algae were grown in it. The oxygen evolved during photosynthesis was found to be radioactive (O^{18}).

> **Tit bits**
>
> *Photolysis is the splitting of a chemical compound by means of light energy i.e., photons e.g., photolysis of water in photosynthesis produces H^+ and O_2.*

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

In second experiment CO_2 was made by O^{18} the oxygen evolved was without isotope.

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

Thus above experiments proved that source of oxygen evolved during photosynthesis was water.

4.1.8 Light Reaction

It occurs in the presence of light in the thyllakoids of granum of chloroplast. The light reaction involves absorption of light by photosystems, flow of electron through electron transport chain i.e. chemiosmosis and reduction of NADP.

Photophosphorylation: In light reaction addition of phosphate to ADP in the presence of light is called photophosphorylation. There are two pathways:

(i) Cyclic photophosphorylation (ii) Non Cyclic photophosphorylation

Cyclic Photophosphorylation: The cyclic photophosphorylation is less common and generates only ATP while non-cyclic photophosphorylation is predominant and generates both ATP and $NADPH_2$.

Non-Cyclic Photophosphorylation: During non-cyclic photophosphorylation electrons move from water through PS-II to PS-I then to NADP.

Photosystem II:

When light strikes the chlorophyll molecules in PSII (p680) its energy causes the chlorophyll molecule to be activated. The activated chlorophyll loses its two electrons and the positively charged chlorophyll molecule is left in the photosystem with a gap of two electrons. The high energy electrons instead of falling back into the photosystem are captured by primary electrons acceptor of first electron transport chain. The **primary electron acceptor is pheophytin** which then passes the electrons to a plastoquinone (PQ). Now from primary electrons acceptor, the electrons pass along a series of electron acceptor molecules from one to another in oxidation process. These electron acceptors are two **cytochromes** (cytochrome *b* and *f*) and **plastocyanin** (PC) (a copper containing protein).

Production of ATP:

When electrons are passed through electron transport chain, they lose energy. Some of the energy lost by electrons between cytochrome *b* and cytochrome *f* is used to make ATP from ADP and Pi. This ATP, which is generated by PS-II will provide energy for Calvin cycle where CO_2 is fixed to synthesize sugar.

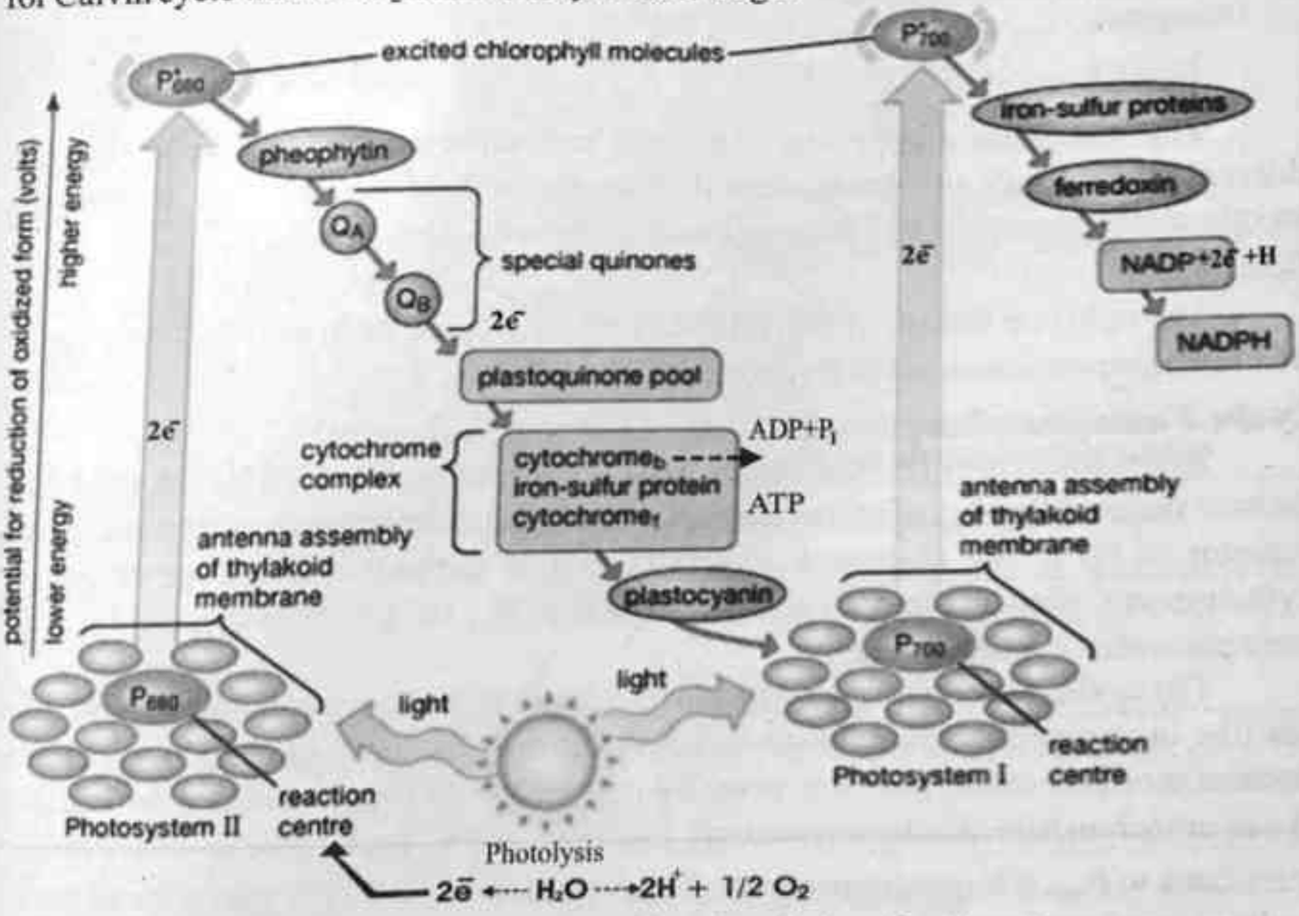


Fig. 4.4 Non- cyclic photophosphorylation (Z-scheme)

Activity

1. *Why do we consider the leaves in plants as food factories?*
2. *Trace out the environmental factors that affect the rate of photosynthesis?*

Photosystem I:

The electrons from PS II pass to PS I. The electrons from plastocyanin are received by another photosystem called photosystem I (P_{700}), where these electrons are boosted to high energy state by absorbing a photon of light.

The photoexcited electron of PS I enters in the second electron transport chain. Here electrons are accepted by ferredoxin (FD), which is also an iron containing protein. The enzyme NADP reductase (flavo protein enzyme) by a redox reaction transfers the electrons from ferredoxin to NADP. The NADP combines with electrons and hydrogen to form $NADPH_2$.

ATP and NADPH are used in Calvin cycle to produce sugar.

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

When photosystem II absorbs light water molecule splits into **OH⁻** and **H⁺**. The **OH⁻** ions react to form some water and release oxygen and electrons.

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

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

The electrons from water molecule are accepted by positively charged chlorophyll molecule of photosystem II, thus the emptied hole is filled by the two energized electrons while PS I receives electrons from PS II.

Z-Scheme:

The light reaction of the PS II and PS I follows zigzag path, therefore, non-cyclic electron transport is also called Z-scheme of light reaction.

Cyclic Photophosphorylation (Cyclic Electron Transport):

It consists of only PS I and occurs in rare condition i.e. when PS II is blocked. The electrons released by P_{700} of PS I in the presence of light are taken up by primary electron acceptor of PS I. The electron acceptors consist of ferredoxin (FD), cytochrome *b*, Cytochrome *f*, plstocyanin (PC) and finally back to P_{700} i.e. electrons come back to the same place after cyclic movement.

The **cyclic photophosphorylation** also result in the formation of ATP molecules just like in non-cyclic photophosphorylation. As the electrons move downhill in the electron transport chain, they lose potential energy and ATP molecules are formed (just like in mitochondrion during respiration). Electrons of PS I do not pass to NADP instead come back to P_{700}. It is important to note that oxygen and $NADPH_2$ are not formed during cyclic photophosphorylation.

Which conditions lead to cyclic electron pathway?

1. When production of ATP is low thus Calvin cycle does not begin.
2. Due to slow rate of Calvin cycle, $NADPH_2$ do not oxidize into NADP.

3. There are many other enzymatic reactions which use ATP in stroma, thus Calvin cycle becomes slow.
4. Limited supply of CO_2 also affects carbohydrate synthesis.

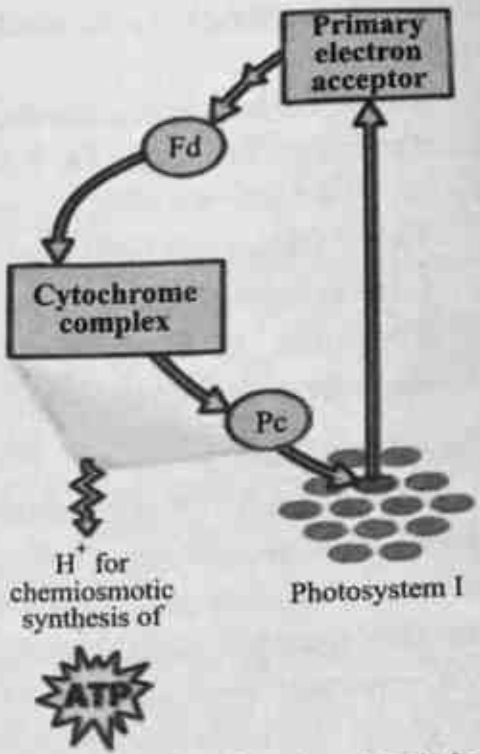


Fig. 4.5 Cyclic photophosphorylation

Summary of Light Reactions:

Requirements:

1. Light
2. Enzymes needed for different reactions in the chloroplast
3. H_2O
4. NADP
5. ADP and Pi (inorganic phosphate)

Products:

1. Oxygen
2. ATP
3. $NADPH_2$

Activity

1. Draw the Z-scheme for explaining the events of light dependent reactions.
2. Draw the labelled structure of chloroplast.

Table 4.1 Comparison between cyclic and non-cyclic photophosphorylation

Non-cyclic photophosphorylation	Cyclic photophosphorylation
Elections do not come back to the same molecule.	Electrons come back to the same molecule.
First electron donor is water.	First electron donor is P_{700} (PS I).
Involves both PS I and PS II.	Involves PS I only.
Last electron acceptor is NADP.	Last electron acceptor is (P_{700}).
The net products are ATP, $NADPH_2$ and O_2.	The Product is ATP only.

4.1.9 Light Independent Reaction or Dark Reaction

The light independent reaction was discovered by Melvin Calvin and coworkers (1950) at the University of California. He was awarded Noble prize in 1961 for his work. Therefore, this cycle is also called **Calvin cycle.** They used radioactive isotope of C^{14} in CO_2. Light independent reactions do not need direct energy of sunlight. It may occur during day time but it is called dark reaction, so as to differentiate it from the light reaction.

Calvin cycle occurs in the stroma of chloroplast by a series of reactions in which CO_2 is fixed into carbohydrate **$(CH_2O)n$** in the absence of light.

The **Calvin cycle** is completed in three stages:

i) Carbon fixation
ii) Reduction
iii) Regeneration of ribulose bi-phosphate.

> **Do you know?**
> *Rubisco is the most abundant protein on earth.*

> **Do you know?**
> *Oxidation is the loss of electron from an atom or molecule while reduction is the gain of electrons by an atom or molecules.*

> **Tit bits**
> *9 ATP and 6 $NADPH_2$ from light reaction are used in Calvin cycle to produce one PGAL, which can be used to form glucose, fructose etc.*

Carbon Fixation:

It is first step of dark reaction in which **CO_2** from air combines with pre-existing five carbon phosphorylating sugar known as ribulose biphosphate (RuBP). As a result an unstable 6-carbon intermediate compound is formed. The enzyme that speeds up this reaction is called RuBP carboxylase; also known as **Rubisco.**

The six carbon intermediate molecule exists for such a brief time that it cannot be isolated and thus named as an intermediate compound.

Formation of PGA:

The unstable intermediate compound splits into two molecules of three carbon containing phoshoglyceric acid (PGA). It is first identifiable product in dark reaction. Therefore, Calvin cycle is also called **C_3 Cycle**.

$$CO_2 + RuBP(C_5) \longrightarrow C_6\ \text{(intermediate compound)} \longrightarrow 2\ PGA(C_3)$$

The carbon that was part of CO_2 molecule is now a part of organic molecule. This is called CO_2 fixation.

Reduction (Formation of PGAL or G3P):

In this step the product of light reaction that is ATP and $NADPH_2$ are used. Each molecule of phosphoglyceric acid (PGA) receives energy from ATP and H^+ from $NADPH_2$ forming 3 carbon phosphoglyceraldehyde (PGAL). In this step water is also formed. In reduction process fixed carbon is reduced into a 3-carbon sugar molecule of PGAL.

$$PGA + ATP + NADPH_2 \longrightarrow PGAL + ADP + Pi + NADP + H_2O$$

ADP and Pi and NADP return back to light reaction where ADP is converted into ATP and NADP is reduced into $NADPH_2$.

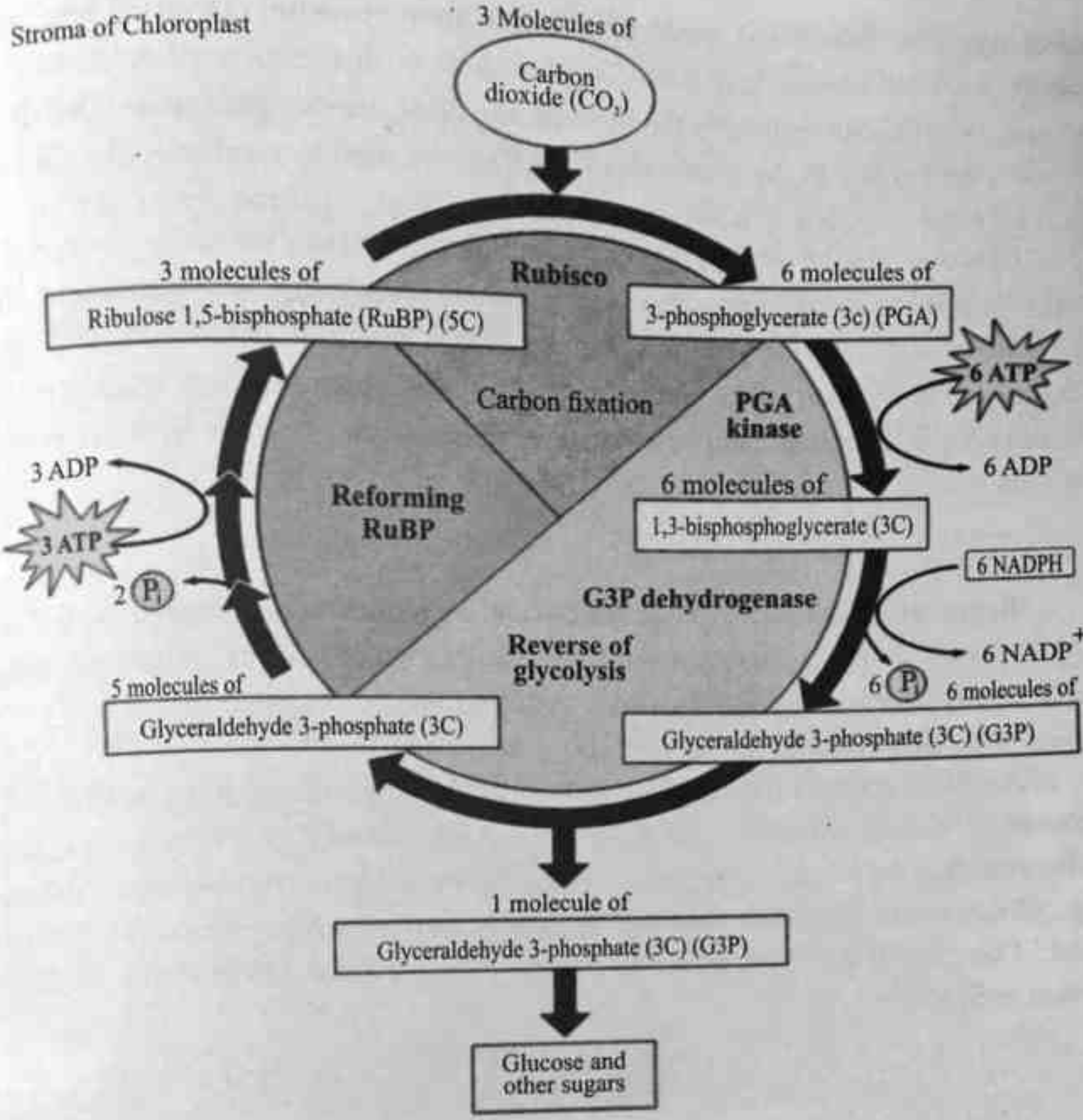


Fig. 4.6 Calvin cycle

Regeneration of RuBP (Formation of glucose and other organic compounds):

For every turn of Calvin cycle five molecules of PGAL are used to reform three molecules of RuBP, so that cycle can continue. It also uses ATP of light reaction.

$$5\ PGAL + ATP \longrightarrow ADP + Pi + 3\ RuBP$$

Thus out of every six molecules of PGAL formed in the reduction stage, only one molecule leaves the cycle, which is to be used by plant for making glucose and other organic compounds.

Use of PGAL

From PGAL 3C, 4C, 5C, 6C and 7C compounds are produced, all are interconvertible. Two PGAL molecules from Calvin cycle are converted into glucose phosphate within chloroplast. Glucose phosphate is then converted to starch. Fixed carbons leave the chloroplast in the form of dihydroxyacetone phosphate (DHAP). It is formed from PGAL. In the cytoplasm DHAP can be used to synthesize the six carbon sugars, glucose and fructose, which are then joined to form sucrose.

Glucose is also used to synthesize cellulose. Glucose is readily converted into amino acids (with the addition of nitrogen). Other compounds like organic acids that is fatty acids and glycerols appear quite rapidly in the cell during photosynthesis. Glucose accumulates more than other compounds, so it was observed more readily by early investigators in chemical analysis. Other compounds can be seen by more sensitive methods.

4.2 Cellular Respiration

Respiration is a series of complex oxidation reduction reactions in living things. In this process cells get energy through the break down of various organic substances. There are two types of respiration aerobic and anaerobic.

Aerobic Respiration: (Gk. "*Aeros*" air)

Aerobic respiration takes place in the presence of molecular oxygen. Glucose is a high energy molecule and its breakdown product is CO_2 and H_2O, which are low energy molecules thus the stored energy is released. The electrons are removed from substrate (e.g., glucose) and eventually received by oxygen atom which combines with H^+ to form water. The overall equation of aerobic respiration for breakdown of glucose can be written as follows:

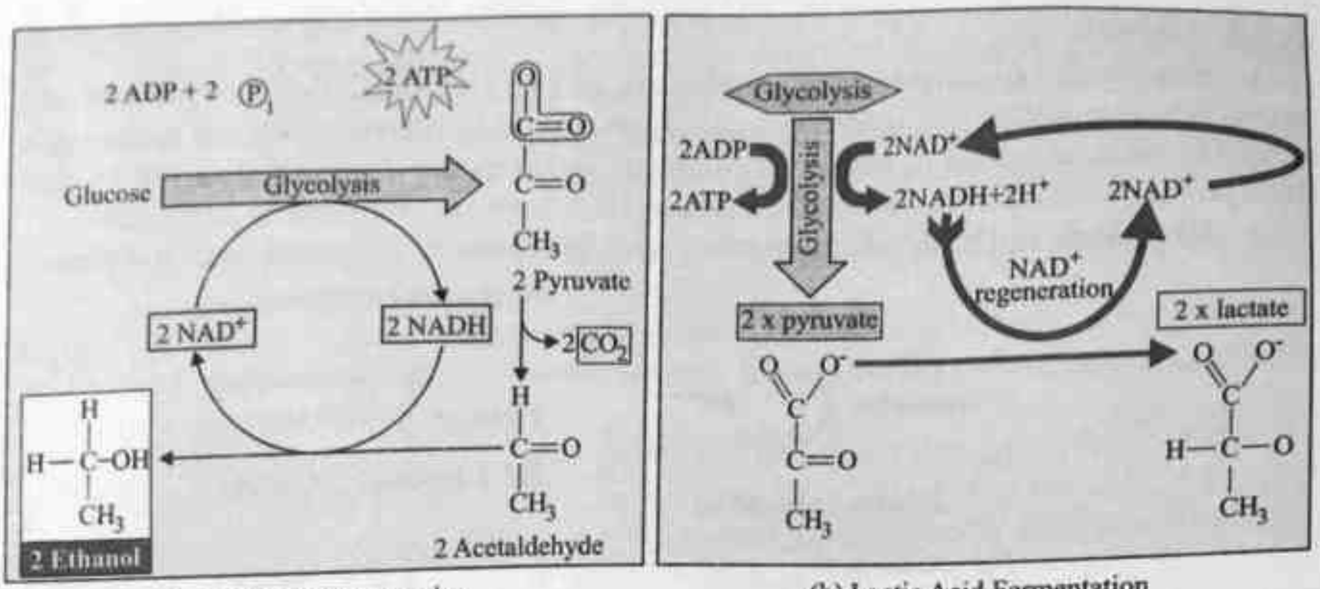
$$C_6H_{12}O_6 + 6O_2 + 36ADP + 36Pi \xrightarrow{\text{Enzymes}} 6CO_2 + 6H_2O + 36ATP$$

Anaerobic Respiration:

Anaerobic respiration takes place in the absence of molecular oxygen, it is also known as **fermentation**. It is incomplete oxidation reduction reaction. The energy released from the substrate (glucose) is a result of its molecular rearrangement and some of this energy is available to the cell. The NADH is oxidized to NAD, it is called fermentation because glycolysis is followed by the reduction of pyruvate by NADH to either alcohol and CO_2 or lactate.

Alcoholic Fermentation:

In primitive cells and cells of some eukaryotic organisms such as yeast and plants, pyruvate is further broken down by alcoholic fermentation into alcohol and CO_2.



(a) Alcohol Fermentation (b) Lactic Acid Fermentation

Fig. 4.7 Fermentation

Lactic Acid Fermentation:

It takes place in many bacteria, animals and muscles of human. Each pyruvate molecule is converted into lactic acid in the absence of molecular oxygen.

Process of cellular respiration:

It takes place in four steps.

1. Glycolysis
2. Oxidation of pyruvic acid
3. Krebs cycle
4. Electron transport chain

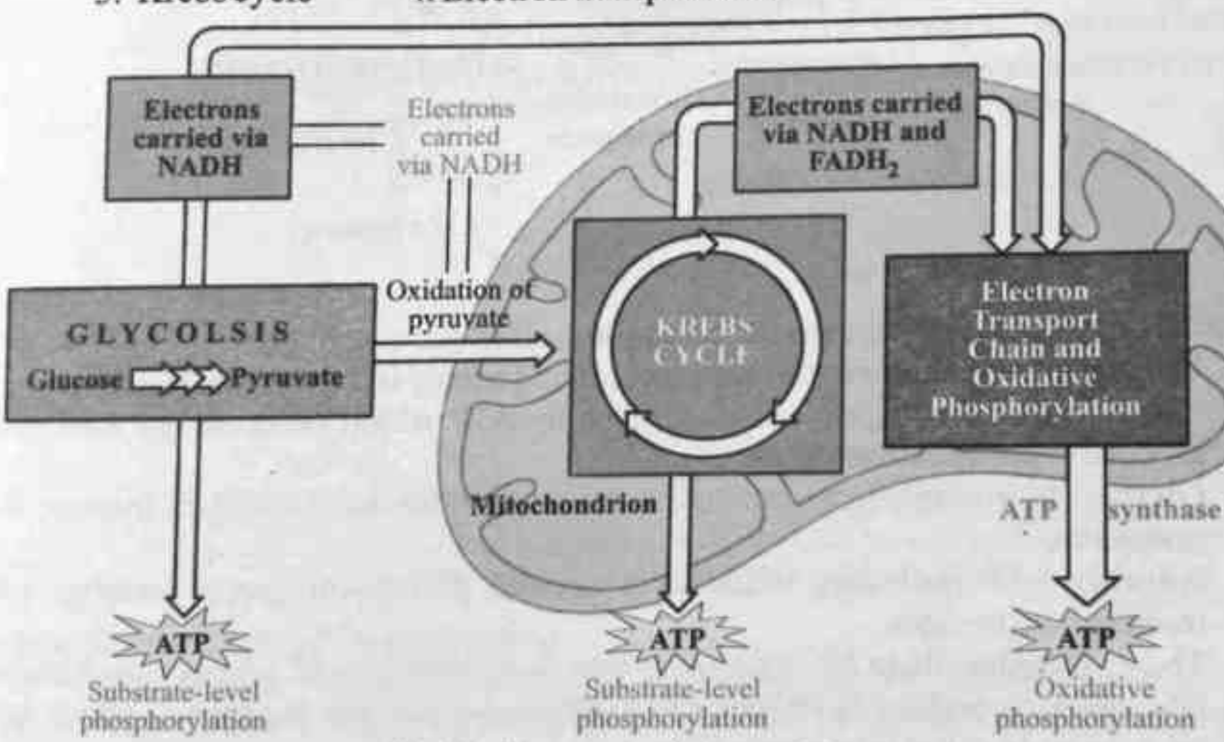


Fig. 4.8 Process of cellular respiration

4.2.2 Glycolysis

Glycolysis takes place in the cytoplasm and it is the break down of glucose into two pyruvate molecules. It is found in all organisms and evolved before the krebs cycle and ETC. This occurs in cytosol of cytoplasm and does not require molecular oxygen (thus probably first life was anaerobic bacteria). Each step is catalyzed by an enzyme.

Glycolysis can be divided into two stages, preparatory phase and oxidative phase.

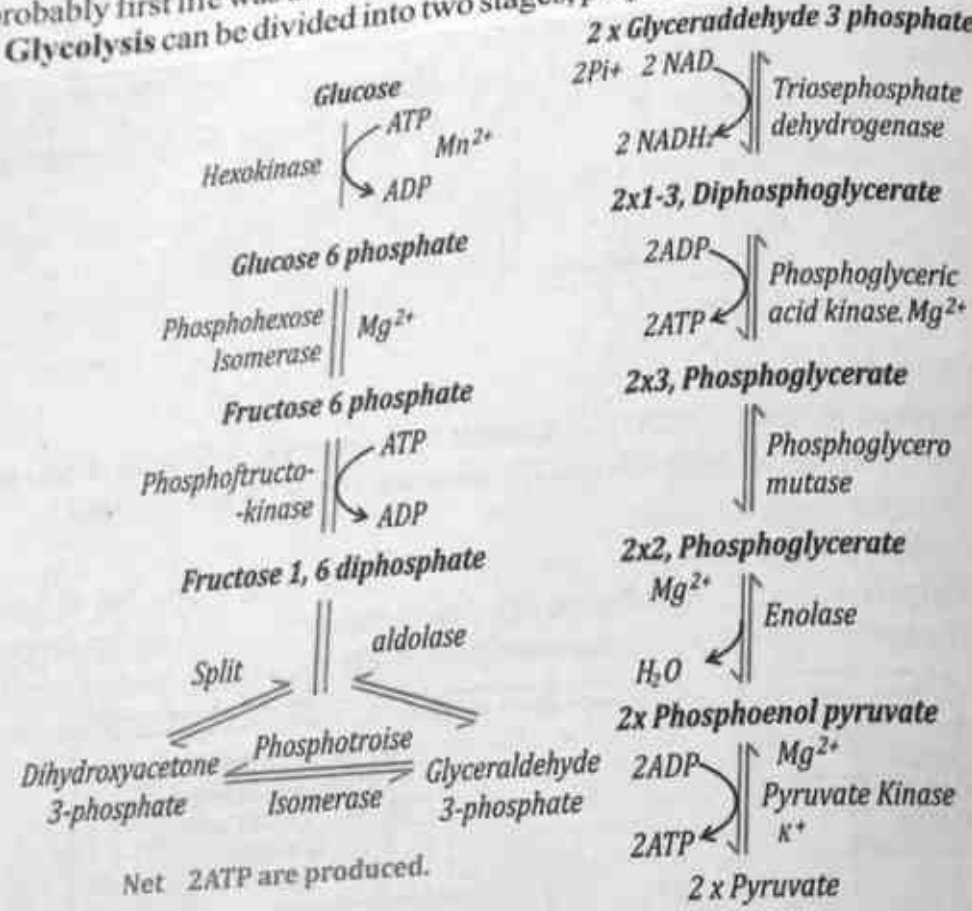


Fig. 4.9 Glycolysis

Preparatory Phase (energy investment phase):

In this phase breakdown of glucose occurs and energy is utilized, the steps are:

1. Phosphorylation of glucose takes place by ATP which produces an activated glucose 6- phosphate molecule.
2. Glucose 6- phosphate is converted by an enzyme to its isomer fructose 6- phosphate.
3. Another ATP molecule transfers a second phosphate group forming 1,6 biphosphate fructose.
4. The 1, 6 biphosphate fructose splits into two molecules of 3-carbon molecules (Phosphoglyceraldhyde (PGAL) and dihydrooxyacetone phosphate) which are isomers and readily interconvertible.

Oxidative Phase (Energy yielding phase):

1. Two electrons or two hydrogen atoms are removed from the molecule of PGAL which is oxidized and these electrons are transferred to a molecule of NAD which is reduced. Inorganic phosphate is present in the cell, from which a second phosphate is donated to the molecule forming 1,3 bi or diphosphoglycerate (BPG or DPG).
2. DPG is converted to 3 phosphoglycerate (3-PGA). Meanwhile a phosphate bond is transferred from DPG to ADP forming ATP.
3. 3 PGA is converted to 2 phosphoglycerate (2PGA).
4. From 2 PGA a molecule of water is removed and phosphoenol pyruvate (PEP) is formed.
5. PEP then gives up its high energy phosphate which converts ADP to ATP. The product is pyruvate or pyruvic acid ($C_3H_4O_3$). It is equivalent to half glucose molecule that has been oxidized to the extent of losing two electrons as hydrogen atoms.

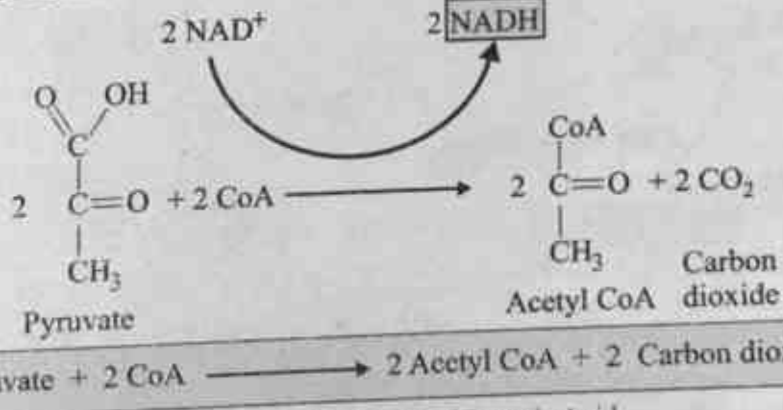
4.2.3 The Oxidation of Pyruvic Acid

It takes place into two stages.

1. Oxidation of pyruvic acid to form Acetyl Coenzyme A.
2. Oxidation of Acetyl Coenzyme A.

Oxidation of Pyruvic Acid:

It is a transition reaction during which CO_2 is released. The oxidation of pyruvic acid is called **transition reaction** because it connects glycolysis and krebs cycle. In this reaction pyruvate is converted to 2-carbon acetyl Co A by attaching coenzyme A. It gives off carbon dioxide. This is an oxidation reaction in which electrons are removed from pyruvate by dehydrogenase that uses NAD as a coenzyme. This reaction occurs twice for each original glucose molecule.



2 Pyruvate + 2 CoA ⟶ 2 Acetyl CoA + 2 Carbon dioxide

Fig. 4.10 Oxidation of Pyruvic Acid

Oxidation of Acetyl Co enzyme A:

It takes place through krebs cycle. As a first step 4-C compound oxaloacetate binds with 2-carbon acetyl CoA to become 6-carbon compound. This 6-carbon compound passes through a series of electron yielding oxidation reactions. Two carbon dioxide molecules are given off. Finally regenerating 4-carbon compound which is free to bind another acetyl Co A. This cycle is called citric acid cycle or krebs cycle.

> **Do you know?**
> *Krebs cycle is also called Tricarboxylic acid cycle because each of its first three reaction has three molecules of carboxylic acid.*

4.2.4 Citric Acid Cycle or Krebs Cycle

This is cyclic metabolic pathway located in the matrix of mitochondria. The krebs cycle was named after Sir Hans krebs a British scientist who discovered it in 1930.

Steps of the Krebs cycle:

1. At the start of this cycle the (2-C) acetyle group (produced by transition reaction) joins with a (4-C) oxaloacetate molecule, forming 6-carbon citrate molecule.
2. Citrate is converted to an isomer called isocitrate.

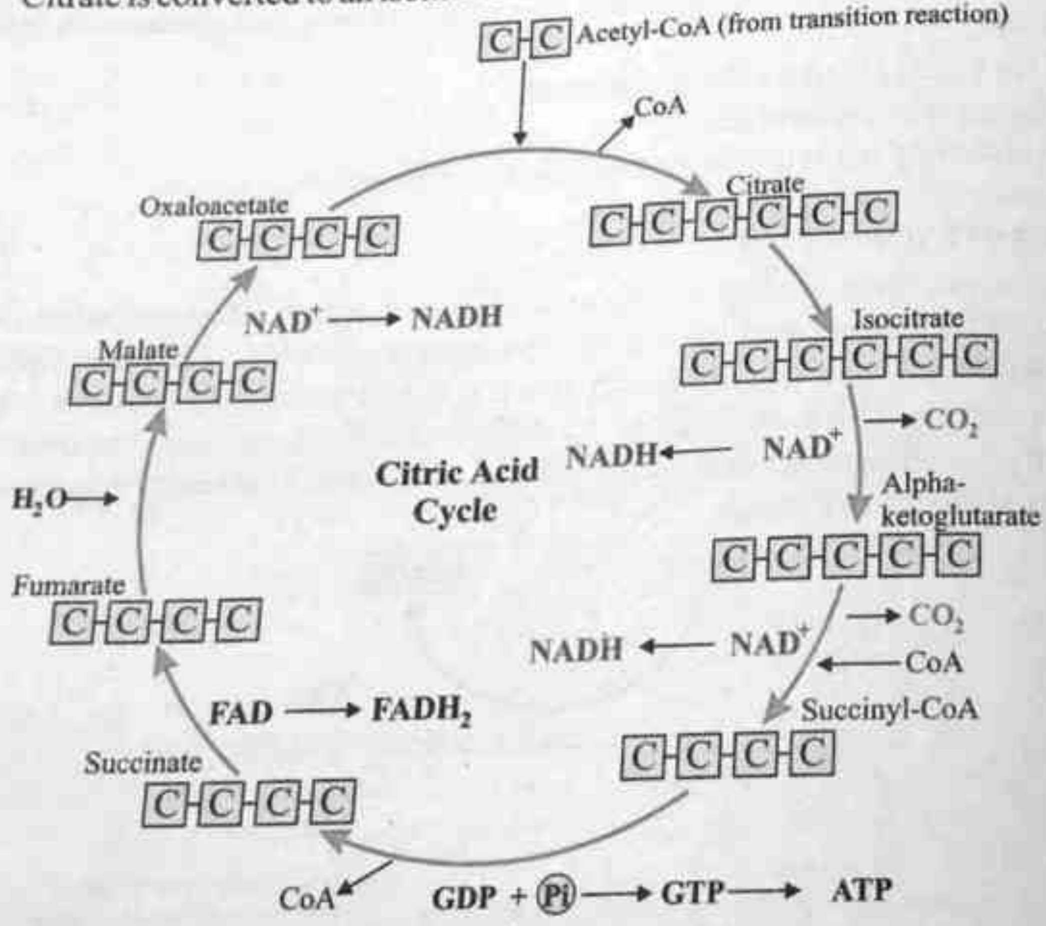


Fig. 4.11 Krebs cycle

Input	Output
2 acetyl groups	$4CO_2$
2ADP + 2Pi	2ATP
6NAD	6 $NADH_2$
2FAD	$2FADH_2$

3. Isocitrate is oxidized by NAD to 5-C alpha-ketoglutarate, NAD is reduced into $NADH_2$ and CO_2 is released.
4. Alpha-ketoglutarate is converted into 4-carbon succinyl CoA and NAD is reduced to $NADH_2$, another molecule of carbon dioxide is removed.
5. 4-carbon Succinyl CoA is oxidized to 4-C molecule, Succinate. GTP is formed which reacts with ADP to form ATP.
6. Now Succinate is converted to 4-carbon Fumarate and FAD is reduced into $FADH_2$.
7. Fumarate combines with water to produce 4 -carbon Malate.
8. Malate is oxidized by NAD to Oxaloacetate and $NADH_2$ is formed.
9. Oxaloacetate is again ready to combine with Acetyl CoA to start a new citric acid cycle.

4.2.5 Electron Transport Chain (ETC)

The ETC is located in cristae of mitochondria. It consists of series of carriers that pass electrons from one to the other. The electrons that enter the ETC are carried by NADH and $FADH_2$ formed during krebs cycle and glycolysis.

Whenever hydrogen is removed from a substrate there are seven intermediate hydrogen acceptors to catch the atom. They are NADH reductase complex (FMN and Fe-S), FADH reductase or co-enzyme Q or Ubiquinone (UQ) and four cytochromes that is b, c, a and a_3 (cytochromes become pink in color when they are reduced. They are protein plus pigment molecules containing iron. They have ability to gain or lose electron. While ubiquinone is not protein it is lipid soluble and water insoluble). Electrons are passed to ubiquinone, at this step an electron is split off the hydrogen atom. The proton becomes free and electron is passed successively from coenzyme Q to cytochrome b, c, a and a_3.

Do you know?

In krebs cycle the extracted electrons are temporarily housed within NADH and $FADH_2$ molecules. These enter in electron transport system where H^+ are removed, ATP and H_2O are formed.

Thinking Questions

Each NADH + H^+ gives 3 ATP in electron transport chain, while each $FADH_2$ gives 2ATP. Can you guess why?

Steps of Electron Transport Chain:

1. The substances in the chain event are alternately oxidized and reduced.
2. Oxidation is accomplished by the loss of hydrogen in case of NAD, FAD and the coenzyme while oxidation is accomplished by loss of electrons from cytochrome b, c, a and a_3.
3. Since two hydrogen atoms are released at a time and cytochrome b through a_3 can accept only one electron at a time so there are two cytochrome systems to capture

the electrons.

4. An electron and proton are brought together after the final transfer from cytochrome a_3. It produces hydrogen.

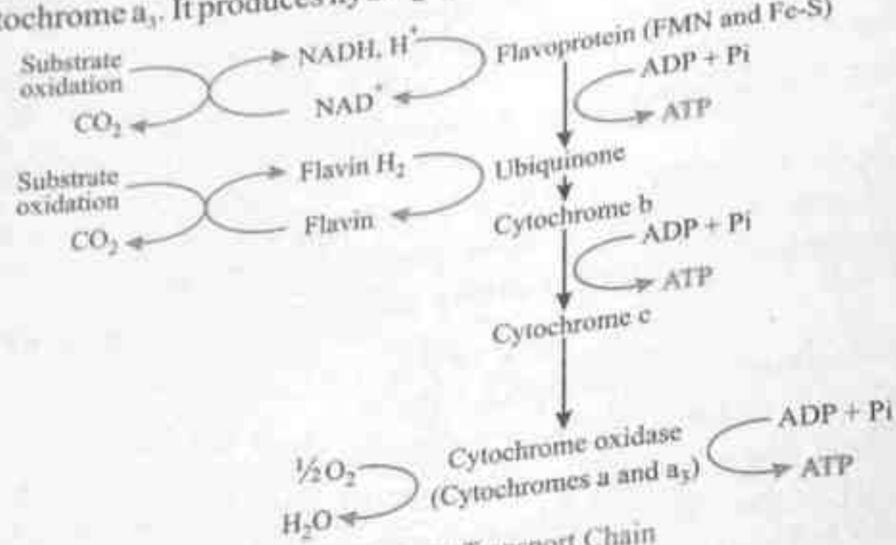


Fig. 4.12 Electron Transport Chain

5. Molecular oxygen is the hydrogen acceptor and water is the final product.

$$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$$

6. Energy is released at three steps, flavoprotein to ubiquinone cyt. b to c, a to a_3. The released energy is captured by ADP to form ATP.

7. Electron transport chain is the main producer of ATP.

4.2.6 Chemiosmosis

Chemiosmosis is the synthesis of ATP from ADP and Pi in the electron transport chain through the joint event of chemical and osmotic processes. The chemiosmotic theory was proposed by Peter Mitchell who got Nobel prize in 1978 for his chemiosmotic theory of ATP production in mitochondria and chloroplasts.

The chemiosmosis can also be defined as the coupling reaction in which synthesis of ATP molecule occurs during the movement of H^+ across a proton gradient. Chemiosmosis generates more ATP as compared to substrate level ATP phosphorylation.

> **Tit bits**
>
> *Chemiosmosis is the movement of ions across a semipermeable membrane, down their electrochemical gradient. For example, generation of ATP by the movement of H^+ across a membrane during cellular respiration or photosynthesis.*

Mechanism of Chemiosmsis:

1. The mitochordrial membranes have transmembrane channels. These channels can pump protons. The flow of electron induce a change in the shape of protein, thus

proton move out of the inner compartment of mitochondria. As a result the proton (H^+ conc.) in the outer compartment of the mitochondrion becomes greater than that of inner compartment.

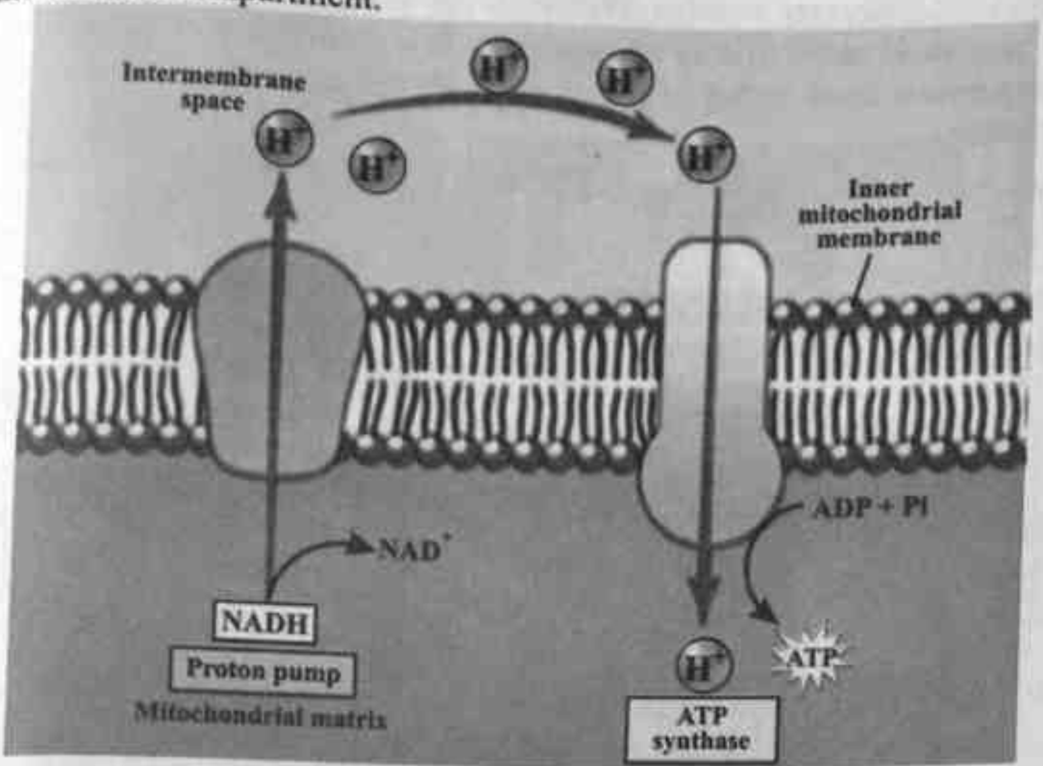


Fig. 4.13 Chemiosmosis

2. Electrical-chemical proton gradient is established between outer and inner membrane. This gradient drives the outer proton across the membrane. Thus the proton move down this gradient between the inner and outer mitochondrial compartments. Their movement induce the formation of ATP from ADP and inorganic phosphate. This process is controlled by an enzyme ATP synthase.
3. The electrons are obtained from the chemical bonds of food molecules in all organisms. This electron removing process needs free oxygen, so it is called aerobic respiration.

Activity

1. Make a list of differences between photosynthesis, respiration and photorespiration.
2. Draw different steps of ETC.

4.2.7 Substrate level phosphorylation

Substrate level phosphorylation occurs in the cytoplasm of the cell during glycolysis and in mitochondrion during the krebs cycle under both aerobic and anaerobic conditions.

ATP formation from ADP and Pi needs input of energy. The energy comes from breakdown of organic molecules in the cells. This type of reaction which releases energy is called **exergonic reaction.** An enzyme transfers a phosphate group to ADP from a substrate, so ATP molecule is formed. The energy from exergonic reaction is greater than the energy input necessary to drive ATP synthesis. The substrate level phosphorylation appeared very early in the history of organisms. It is recorded in all organisms because initially organisms used carbohydrate as an energy source. Moreover first organisms were anaerobic.

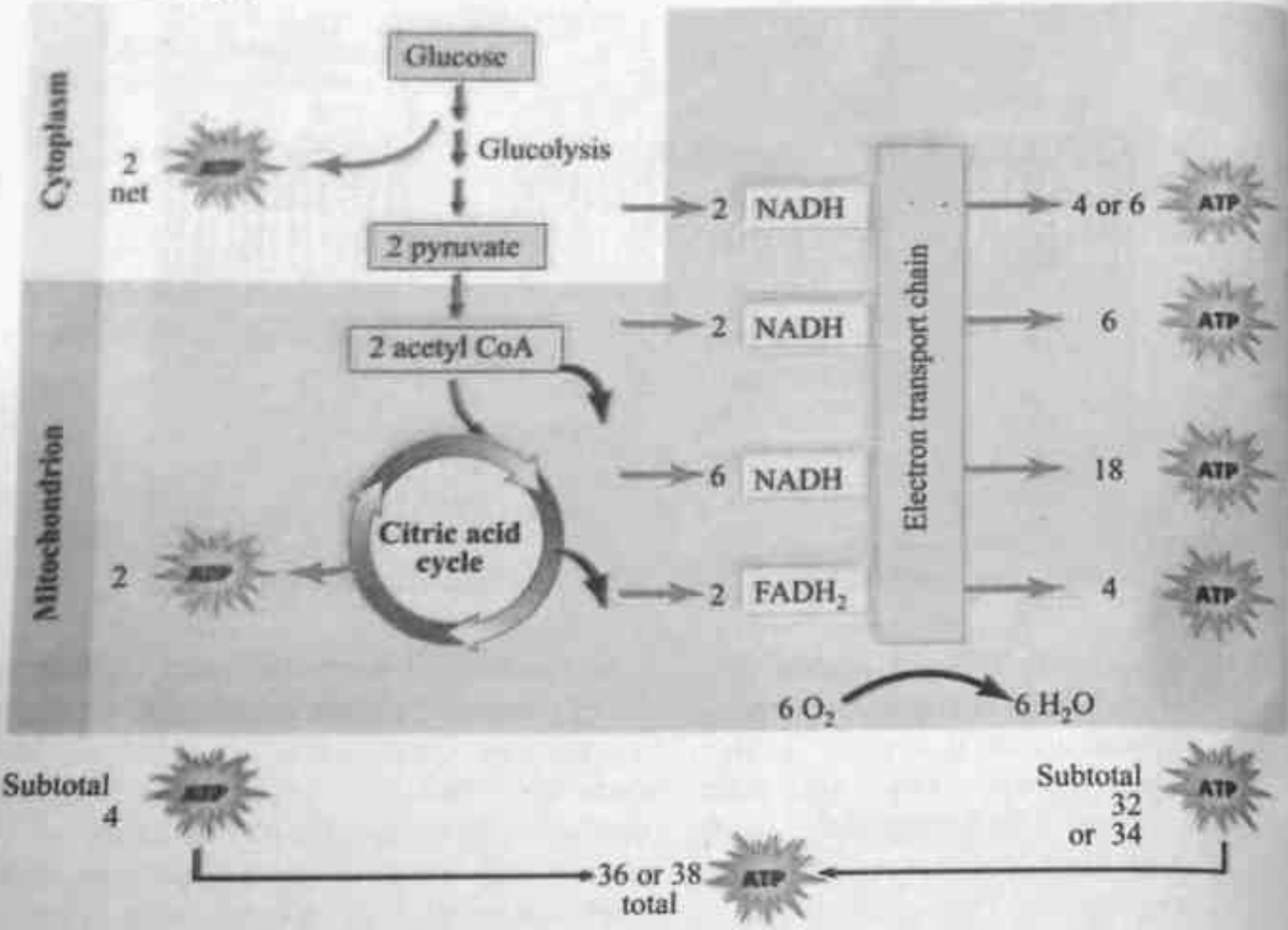


Fig. 4.14 Energy yield per glucose molecule

4.2.8 Importance of PGAL

The preparatory phase of glycolysis completes with the splitting of fructose bi-phosphate into PGAL and Dihydroxyacetone phosphate (DHAP) and both are inter-convertible.

The oxidation of glyceraldehydes 3-phosphate produces 1,3 biphosphoglycerate and 2 NADH molecules which lead to the formation of pyruvic acid.

PGAL is also formed during the Calvin cycle of photosynthesis, one PGAL molecule leaves Calvin cycle. It is converted into glucose phosphate within chloroplast which is converted into starch.

Fixed carbons leave the chloroplast in the form of dihydroxyacetone phosphate. It is formed from PGAL. The DHAP can be used to make the six carbon sugars, glucose and fructose which become a disaccharide, called sucrose. Now sucrose is transported to other parts of the plants.

4.2.9 Cellular Respiration of Proteins and Fats

Animals and humans besides glucose also consume fats and proteins to harvest energy. Fats are broken down into glycerol and three fatty acids. First the glycerol is phosphorylated then enters the glycolytic pathway at the level of glyceraldehyde 3-Phosphate (PGAL) while fatty acids $(2\text{-}C)_n$ enter in the mitochondrion where their carbons are removed. They form acetyl CoA (2-C) which is entry point for krebs cycle (an 18-carbon fatty acid results in nine acetyl CoA molecules). One gram fat provides about 2.5 times more energy than carbohydrates or proteins.

Animals digest proteins into amino acids, if it is in excessive quantity or body is starved then amino acids can be used as fuel. The size of R-group determines whether the carbon chain is oxidizing in glycolysis (Pyruvate) or in the Krebs cycle or cetyl CoA.

Amino acids are degraded, the amine group is removed to yield ammonia this process is called deamination reaction.

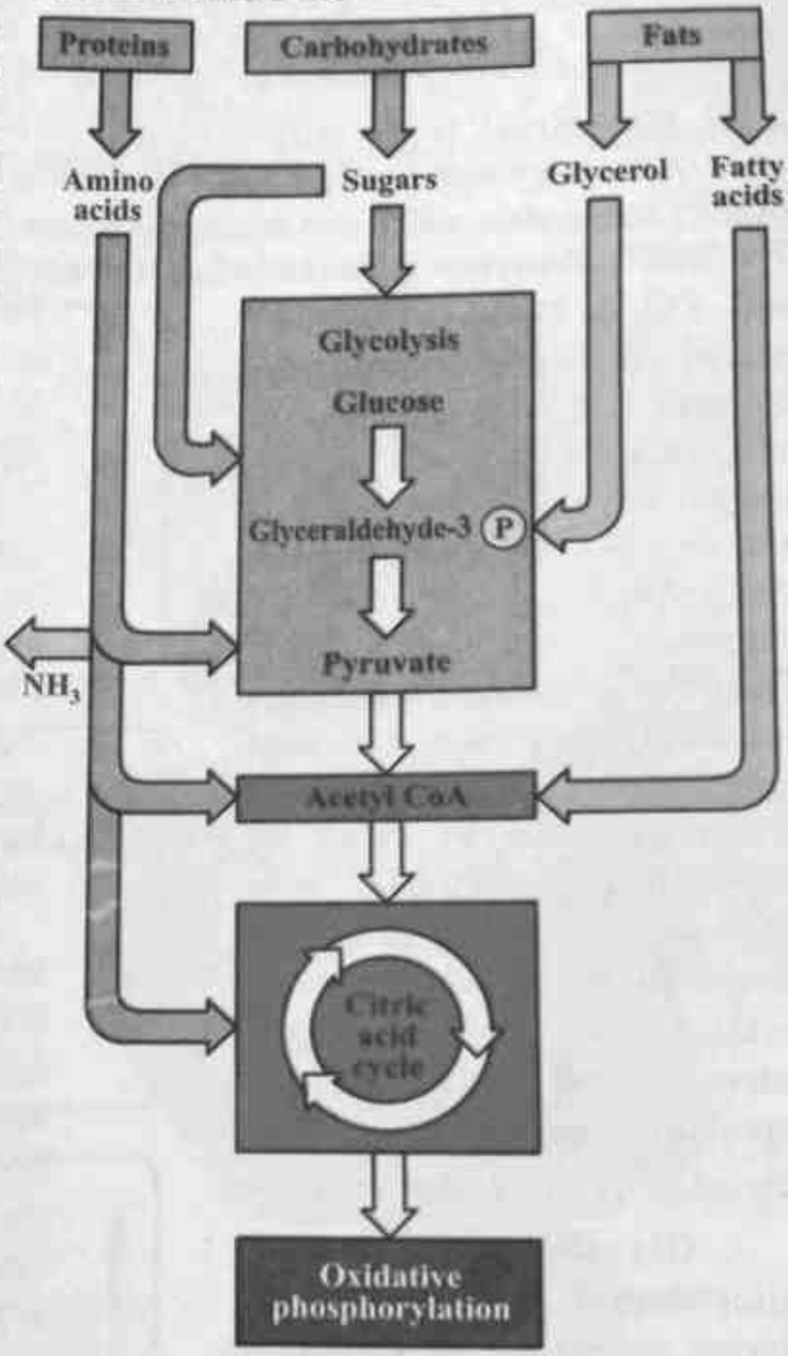


Fig. 4.15 Cellular Respiration of Proteins and Fats

4.3 Photorespiration

This process occurs only in photosynthesizing cells of the plants. It is opposite to photosynthesis, because in it oxygen is used instead of CO_2 and instead of oxygen, carbon dioxide is released (like respiration). It differs from ordinary respiration of cell which occurs in mitochondria at night and in non-green tissues of plant while photorespiration takes place in the presence of light and only in photosynthetic cell. The oxygen is absorbed but unlike respiration do not produce energy (ATP).

4.3.1 How RuBP reacts with oxygen in photorespiration?

Photorespiration is related to the functioning of the enzyme ribulose biphosphate (RuBP) carboxylase which also acts as oxygenase (combines with O_2 instead of CO_2). The RuBP carboxylase is also known as **Rubisco**. When rubisco acts as carboxylase it adds CO_2 to RuBP (an acceptor molecule) to produce two molecules of PGA while during oxygenase, it adds oxygen to RuBP and produces one molecule of PGA and one phosphoglycolate. The phosphoglycolate loses its phosphate to become glycolate. There are some algae which can excrete glycolate but higher plants cannot excrete it. Therefore, plants must convert it back to intermediate in the Calvin cycle. The conversion of glycolate into glycine amino acid takes place by a series of reactions in mitochondria, chloroplast and other cellular parts especially in peroxisomes.

Glycolate $\longrightarrow$ glycine amino acid

Glycine diffuses into mitochondria where every two glycine molecules are converted into serine amino acid and CO_2.

2 glycine $\longrightarrow$ Serine + CO_2

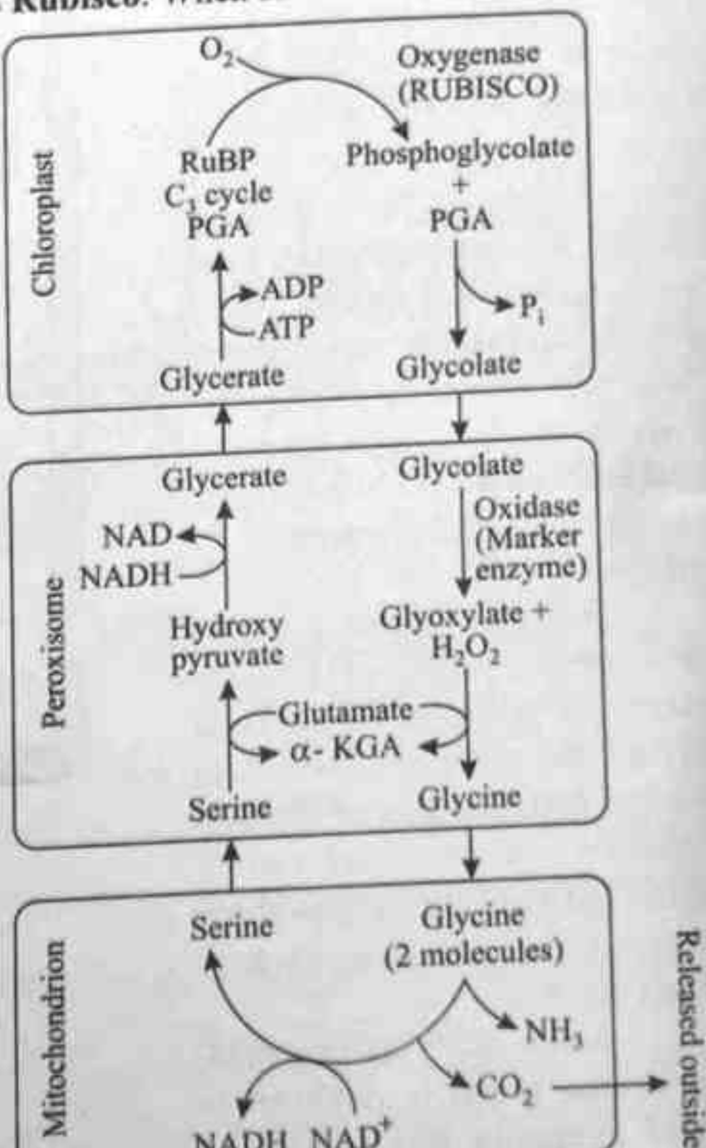


Fig. 4.16 Photorespiration

This entire pathway is called photorespiration in which RuBP is converted into serine and CO_2 which uses ATP and $NADPH_2$ produced during light reaction like Calvin cycle.

4.3.2 Disadvantages of photorespiration

It is reverse to Calvin cycle (here CO_2 is released instead of being fixed into carbohydrates). Photorespiration reduces the amount of carbon fixation into carbohydrates by 25%. The role of photorespiration in plants is not thoroughly understood. It is presumed that photorespiration may be necessary for the assimilation of nitrates from the soil.

4.3.3 Photosynthesis in C4 plants

In normal process of photosynthesis a 3-C compound called PGA is formed as a first detectable product of photosynthesis. Therefore, these plants are called C_3 plants. However, there are some plants growing in dry and hot conditions which produce a four carbon compound (C4) called oxaloacetate as the first product of photosynthesis in dark reaction. These plants are called C4 plants and this type of photosynthesis is called C4 photosynthesis.

C3 plants use rubisco to react CO_2 with RuBP, on the other hand C4 plants use a different enzyme called phosphoenol pyruvate carboxylase **(PEPCO)** to fix CO_2 to a compound known as phosphoenol pyruvate (PEP). The PEP is reduced into another molecule called malate. The malate carry CO_2 to a special type of cells called bundle sheath cells where Calvin cycle proceeds.

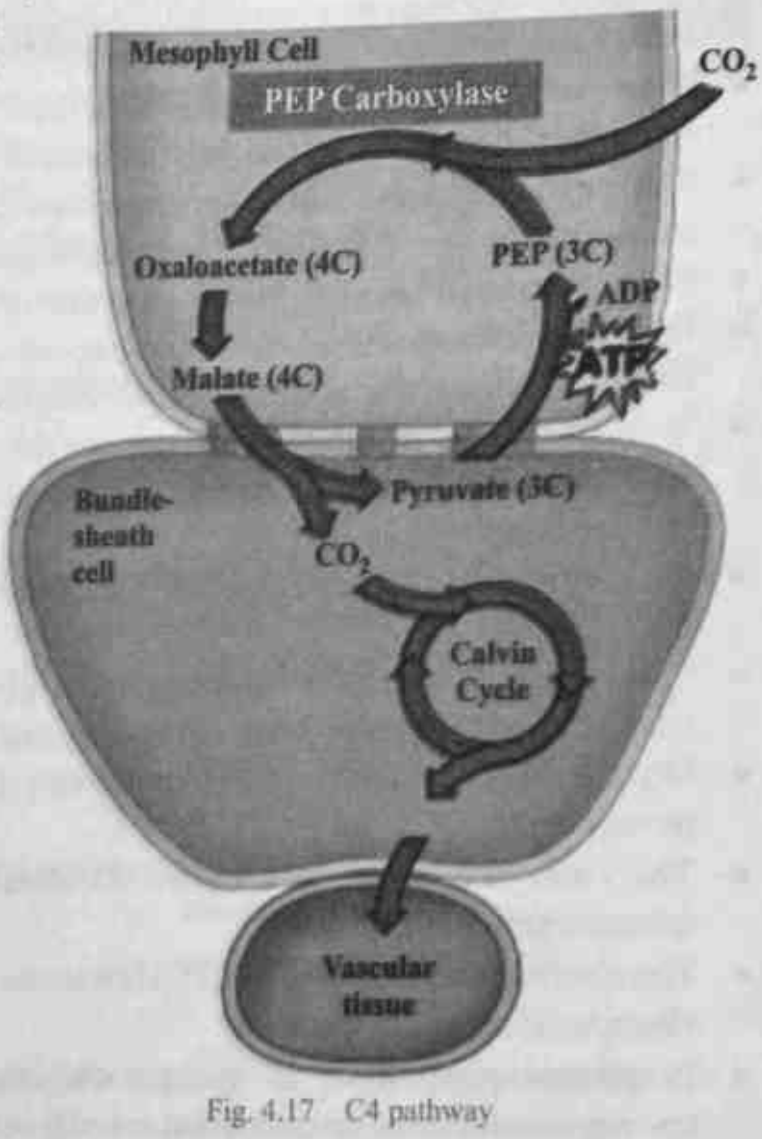


Fig. 4.17 C4 pathway

Table 4.2 Comparison between C_3 and C_4 Plants

C_3 Plants	C_4 Plants
In C_3 chloroplasts are located only in mesophyll cells of leaf.	In C_4 chloroplasts are present both in mesophy cells as well as in bundle sheath cells.
In these plants all the mesophyll cells carry out Calvin cycle.	In these plants only mesophyll cells fix CO_2 b using PEPCO while the bundle sheath cells car out Calvin cycle.
In high temperature photosynthesis is low.	In high temperature the rate of photosynthesis high.
Example: Most of the plants are C_3 plants such as pea, wheat, rice and all woody trees.	*Example:* They are found only in angiosperm such as sugar cane, maize and mostly grasses.

SUMMARY

- Photosynthesis is the only biological process that captures energy of sunlight a converts it into organic compounds (carbohydrates).
- The internal membranes of chloroplasts are organized into sac-like thylakoids wh are stacked on one another in columns called grana.
- Photosynthesis takes place in two steps: they are light reaction and dark reaction.
- Each photosystem consists of a light-harvesting complex and a core complex. E core complex contains a reaction center with the pigment (either P700 or P680).
- To build organic molecules, cells use raw materials provided by the light reacti ATP provided by cyclic and noncyclic photophosphorylation while NAD provided by photosystem I.
- Cellular respiration is the process in which cells acquire energy by breaking down organic compounds.
- Cellular respiration involves four phases: glycolysis, the preparatory reaction, citric acid cycle, and the electron transport chain.
- Glycolysis is the breakdown of (6-carbon) glucose into two (3-carbon) pyru molecules.
- The citric acid cycle is a cyclic metabolic pathway located in the matrix mitochondria.

EXERCISE

Section 1: Objective Questions

Multiple Choice Questions

A. Choose the best correct answer from the following.

1. Which among the following conditions is favourable for cyclic photo-phosphorylation:
   (a) Aerobic
   (b) Aerobic and low light intensity
   (c) Aerobic and optimum light
   (d) Anaerobic and low light intensity
2. During the dark reaction of photosynthesis:
   (a) Water is split off
   (b) CO_2 is reduced to organic compounds
   (c) Chlorophyll is activated
   (d) Glucose is broken down
3. The enzyme that fixes atmospheric CO_2 in C4 plants is:
   (a) PEP carboxylase (b) Rubisco
   (c) RuBP carboxylase (d) Hydrogenase
4. The number of carbon atoms in RuBP which accepts CO_2 are in C3 plants is:
   (a) 2 (b) 3
   (c) 5 (d) 6
5. Chlorophyll *a* differs from chlorophyll *b* in having a:
   (a) -CHO group (b) -COOH group
   (c) $-CH_3$ group (d) $-NH_2$ group
6. NADP is:
   (a) An enzyme (b) A part of rRNA
   (c) A coenzyme (d) A part of tRNA
7. The compound that enters the Krebs cycle from glycolysis is:
   (a) Citric acid (b) Oxaloacetate
   (c) Pyruvic acid (d) Acetyl coenzyme A

B. Fill in the blanks.

1. Breakdown of water molecule during PS II of light reaction is called______.

2. ATP production during light reaction is called as ____________.
3. In peroxisomes glycolate is converted into ____________.
4. The addition of inorganic phosphate to any organic molecule is known as ____________.
5. Citrate is converted into ____________ in Krebs cycle.
6. Anaerobic respiration is also known as ____________.
7. Calvin cycle is also called ____________ pathway.
8. Plastocyanin is a copper containing ____________ in nature.
9. Hydrocarbon chain of chlorophyll is a long chain of alcohol ____________.

Section II: Write short answers.

1. Write few lines about absorption spectrum.
2. Briefly describe role of CO_2 in photosynthesis.
3. Write the names of electron acceptors of PS II and PS I.
4. Draw the Z-scheme of light reaction.
5. Explain the reduction phase of Calvin cycle.
6. Define aerobic and anaerobic respiration.
7. Write first three steps of Krebs cycle.
8. What is the importance of PGAL?

Section III: Extensive Questions.

1. Explain the mechanism of photosynthesis.
2. Briefly describe the four phases of cellular respiration.
3. What are the main events of glycolysis? How ATP is formed?
4. What is fermentation, and how does it differ from glycolysis?
5. What are the main events of the citric acid cycle?
6. Describe different steps of Electron Transport Chain.