

BIOENERGETICS

Chapter

4

Major Concept

In this Unit you will learn:

- Photosynthesis
- Cellular Respiration
- Photorespiration

Syed Ali Academy



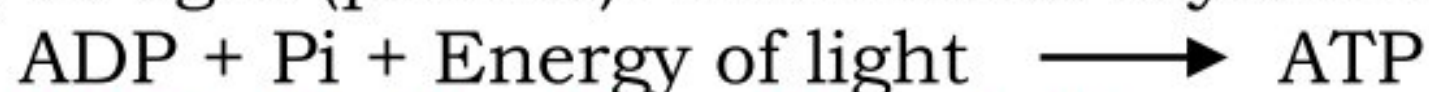


Introduction:

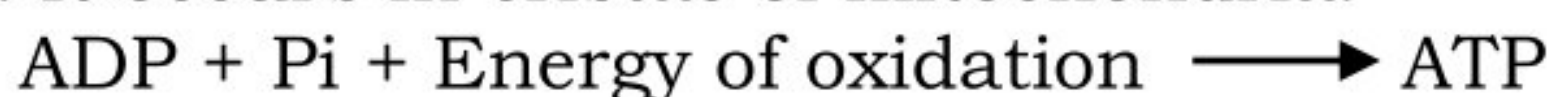
All living things and cells carry out numerous activities e.g. they generally assemble macromolecules from raw materials, waste products are produced and excreted, genetic instructions flow from the nucleus to cytoplasm, vesicles to Golgi bodies and then to plasma membrane; ions are pumped across the membranes etc. For these activities, a cell needs energy. The energy is used as fuel for life, this energy is derived from light energy which is trapped by plant and converted into energy rich compounds like ATP, NADPH₂ and FADH₂ which then stored in food molecules like carbohydrate and lipids. Other organisms, which do not have the ability to trap light energy and its conversion, obtain their energy by eating plants or by eating those organisms which eat plants. Capturing and conversion of this energy from one form to another in the living system and its utilization in metabolic activities is called **Bioenergetics**. In other words, bioenergetics is the quantitative study of energy relationships and conversion into biological system. This biological energy transformations obeys the laws of thermodynamics.

The whole biological energy transformation contains, formation and utilization of energy rich molecule ATP. Plant trap light energy and utilize it in the formation of ATP. In living organisms some organic molecules oxidise to produce energy, some of this energy is used to produce ATP. This process of ATP formation from ADP and phosphate is called phosphorylation. There are three types of phosphorylation found in living organisms.

(i) Photophosphorylation: The type of ATP formation which utilize energy of light (photon). It occurs in thylakoid membrane of chloroplast.



(ii) Oxidative Phosphorylation: Type of phosphorylation where ATP is formed by using energy of oxidation, produce during metabolic reactions in cell. It occurs in cristae of mitochondria.



(iii) Substrate level phosphorylation: Type of phosphorylation where one substrate provides phosphate and energy to another substrate.

Under cellular condition ATP formation requires 7.3 Kcal/mole energy, whereas Pi means, phosphate from inorganic source (molecule) like H₃PO₄. For ATP formation living organisms has two processes i.e., photosynthesis and respiration.

4.1 PHOTOSYNTHESIS:

The living process where light energy converts into chemical energy (ATP, NADPH₂) and then into energy rich organic food molecules like carbohydrate called **Photosynthesis** or we can say that Photosynthesis is the biochemical anabolic process during which carbohydrates are



synthesized from carbon dioxide (CO_2) and water in chlorophyllous cells in the presence of light.

4.1.1 Role of light in Photosynthesis

Light is a form of energy, has dual nature, described both as a wave and a particle nature. It is composed of packet of energy called quanta and photon. Plants are capable of using only a very small portion of visible light that falls on leaves, absorbed by the pigment complex, present in chloroplast. Each pigment has its own absorption spectrum.

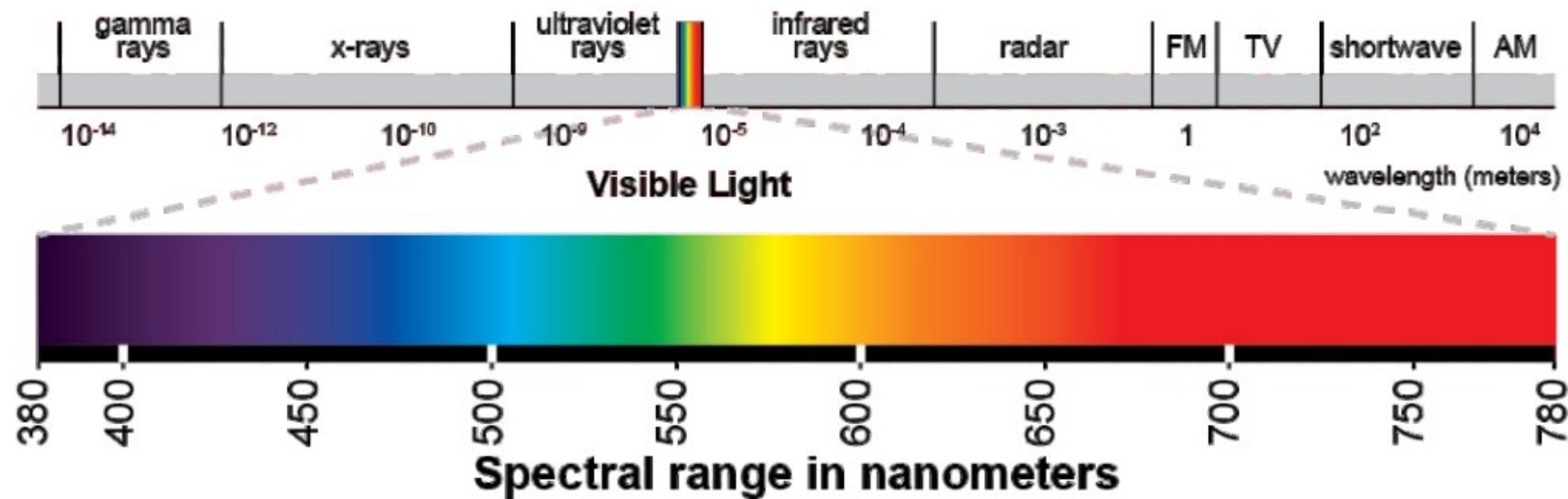
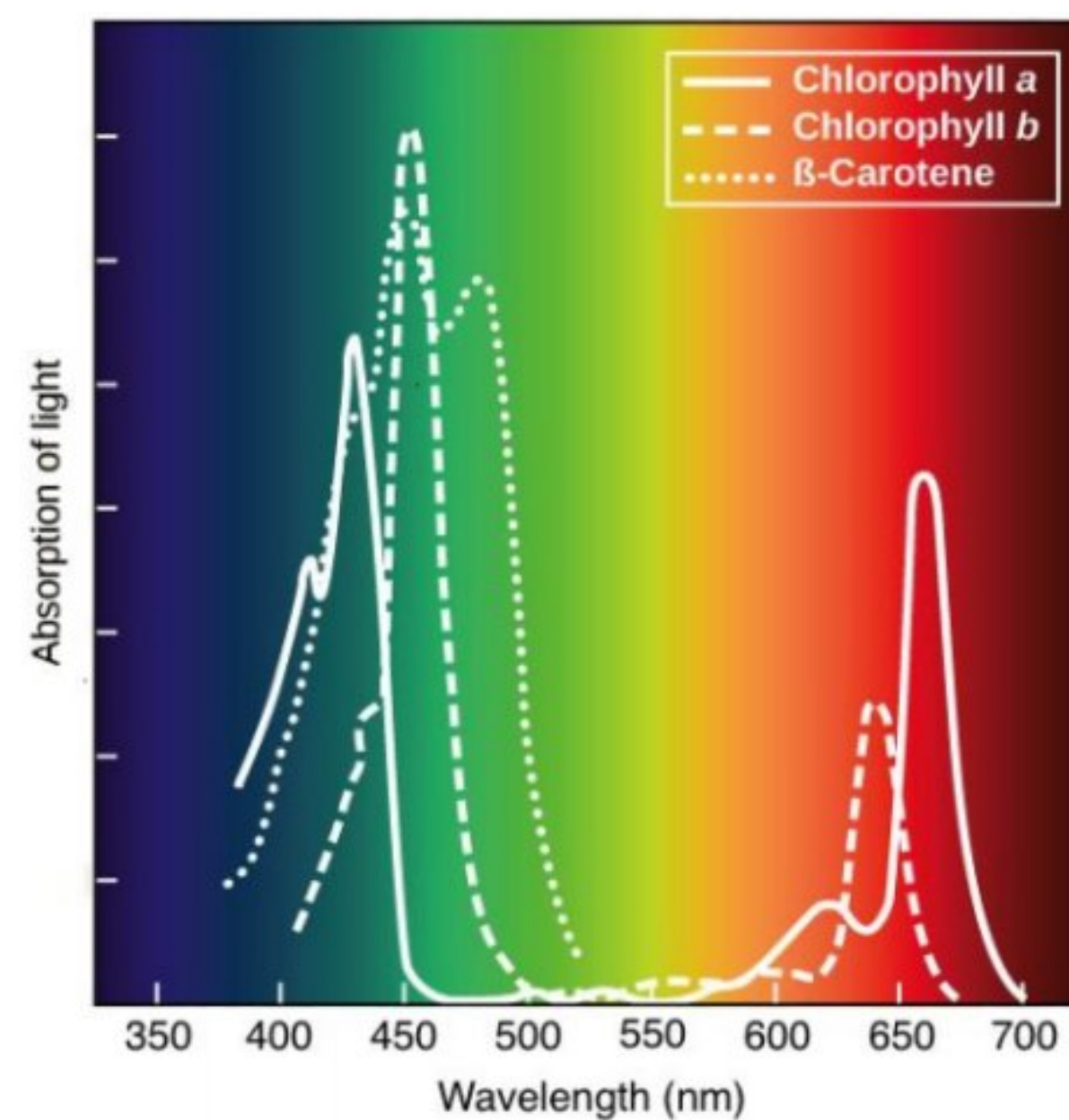


Fig 4.1 Electromagnetic spectrum

Light energy captured by the light harvesting complexes which is efficiently and rapidly transferred to the chlorophyll molecules present in the photosynthetic reaction center.

Each pigment has its own absorption spectrum. Absorption spectrum for chlorophyll indicates that absorption is maximum in blue and red parts of the spectrum, two absorption peak are observed in between 430nm and 670nm, respectively. Absorption peaks of carotenoids are different from those of chlorophyll.

Differential absorption spectrum by photosynthetic pigment also plays an important role in photosynthetic activity. Relative effectiveness of different wave length (colour) of light in driving photosynthesis is called action spectrum of photosynthesis.



**Fig 4.2
Absorption and action
spectrum of pigments**

It is observed from above graphs that the absorption spectrum and action spectrum of chlorophyll are not parallel. By comparing these peaks in absorption spectrum and the peaks in action spectrum are broader and

the valley is narrower not as deep. This difference occurs due to the accessory pigments, the carotenoids. The light absorbed in this zone pass on to chlorophyll and then convert to chemical energy. Red and blue part of spectrum is more efficient in photosynthesis.

4.1.2 Photosynthetic Pigments

As light is flashed on matter, it may be reflected, transmitted or absorbed. Substances in plants that absorb visible light are called **pigments**. Different pigments absorb light of different wave lengths. These pigments are important in the conversion of light energy to chemical energy. The most important pigments required in the process are the chlorophylls and carotenoids.

Chlorophyll can be distinguished into a, b, c, d and e. The empirical formula of the **chlorophyll-a** molecule is $C_{55}H_{72}O_5N_4Mg$ and **chlorophyll-b** is $C_{55}H_{70}O_6N_4Mg$.

A chlorophyll molecule has two main parts one flat, square, light absorbing hydrophilic head and the other long hydrophobic, hydrocarbon tail. The head is complex porphyrin ring, made up of four smaller pyrrole rings joined by Mg with Nitrogen (N) of porphyrin rings. Long hydrocarbon tail which is attached to one of the pyrrole rings is phytol ($C_{20}H_{39}$). The chlorophyll molecule is embedded in the hydrophobic core of thylakoid membrane by this tail.

Chlorophyll molecules mainly absorb violet-blue and orange-red from visible light. Green, yellow and indigo are least absorbed by chlorophylls therefore plants appear green.

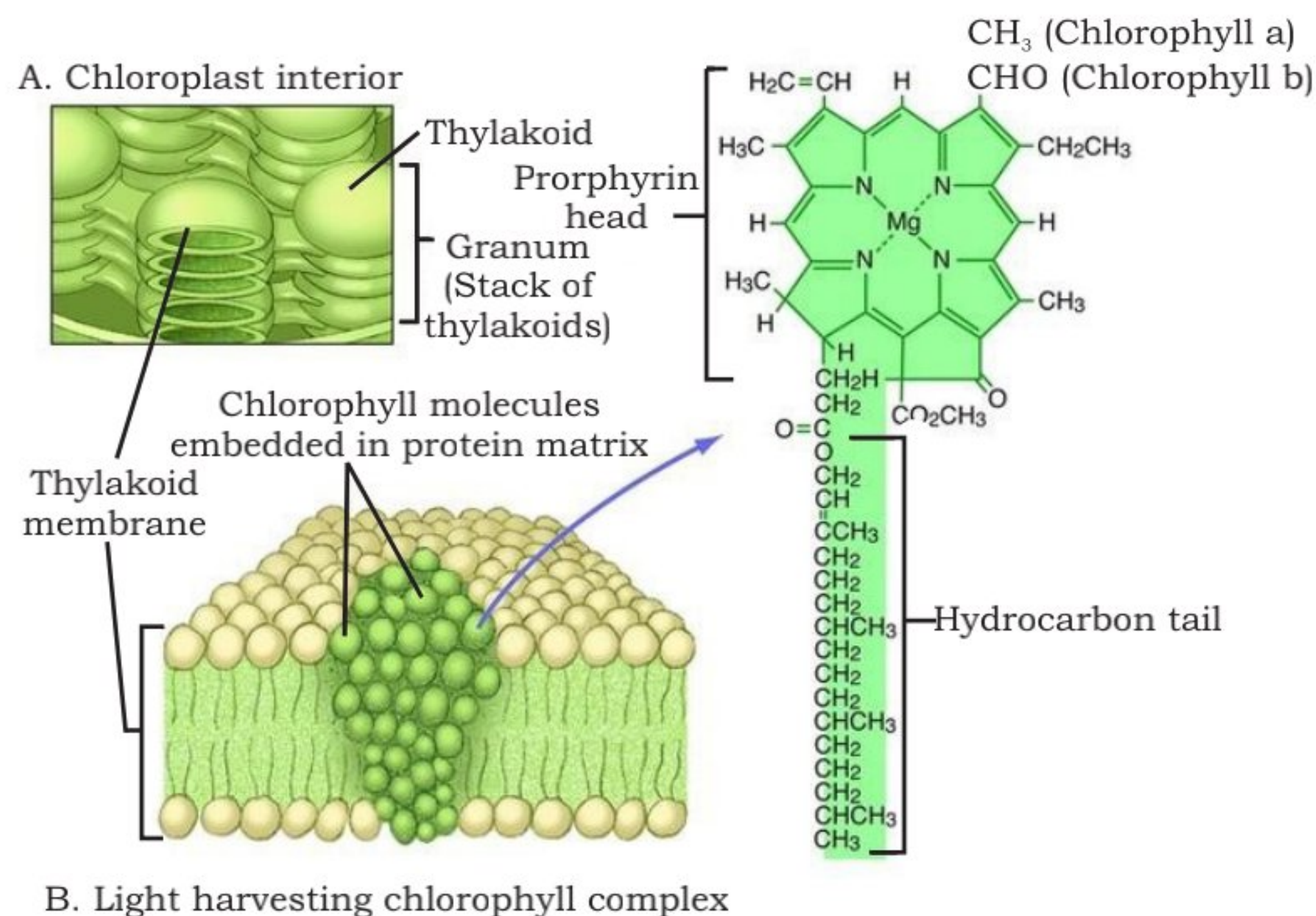


Fig 4.3 Chlorophyll molecules



Chlorophyll-a is the most abundant and the most important photosynthetic pigment because it directly takes part in light dependent reactions to convert light energy into chemical energy. It exists in several forms differing slightly in their red absorbing peaks i.e. 670, 680, 690, 700 nm. Chlorophyll-b is found along with chlorophyll-a in all green plants and green algae.

Carotenoids

Carotenoids are yellow and red to orange pigments that absorb the light of blue-violet range efficiently, which is different from absorption range of chlorophyll. The broad absorption spectra of light provide more energy for photosynthesis.

The carotenoids transfer their energy to chlorophyll-b and then to chlorophyll-a, from here energy transfer to light reaction. The order of energy transfer is shown below:

Carotenoids → **Chlorophyll-b** → **Chlorophyll-a**

Some carotenoids also protect chlorophyll molecules from high intensity of light by absorption and dissipation of extra energy. In human eye carotenoids are also present which protect human eye.

4.1.3 Role of photosynthetic pigment in absorption and conversion of light energy

As we have already discussed that each pigment has its own absorption spectra due to their slight structural differences. The light of same wave lengths are not absorbed by chlorophyll a but very effectively absorbed by chlorophyll b and vice versa. Such differences in structure of different pigments increase the range of wave length which are absorbed by different pigments. All accessory pigments transfer the energy to chlorophyll-a and then to photosynthesis for conversion through photosystems, already discussed above.

4.1.4 Absorption spectrum of chlorophyll a and b

As we have already discussed that due to structural differences both chlorophyll a and b has different absorption spectra. This absorption spectra of chlorophyll-a and chlorophyll-b pigments in visible range is measured in a solvent. Chlorophyll-a absorbs violet and orange light (650 to 700 nm) while chlorophyll-b (450 to 500 nm) absorbs mostly blue and yellow light.

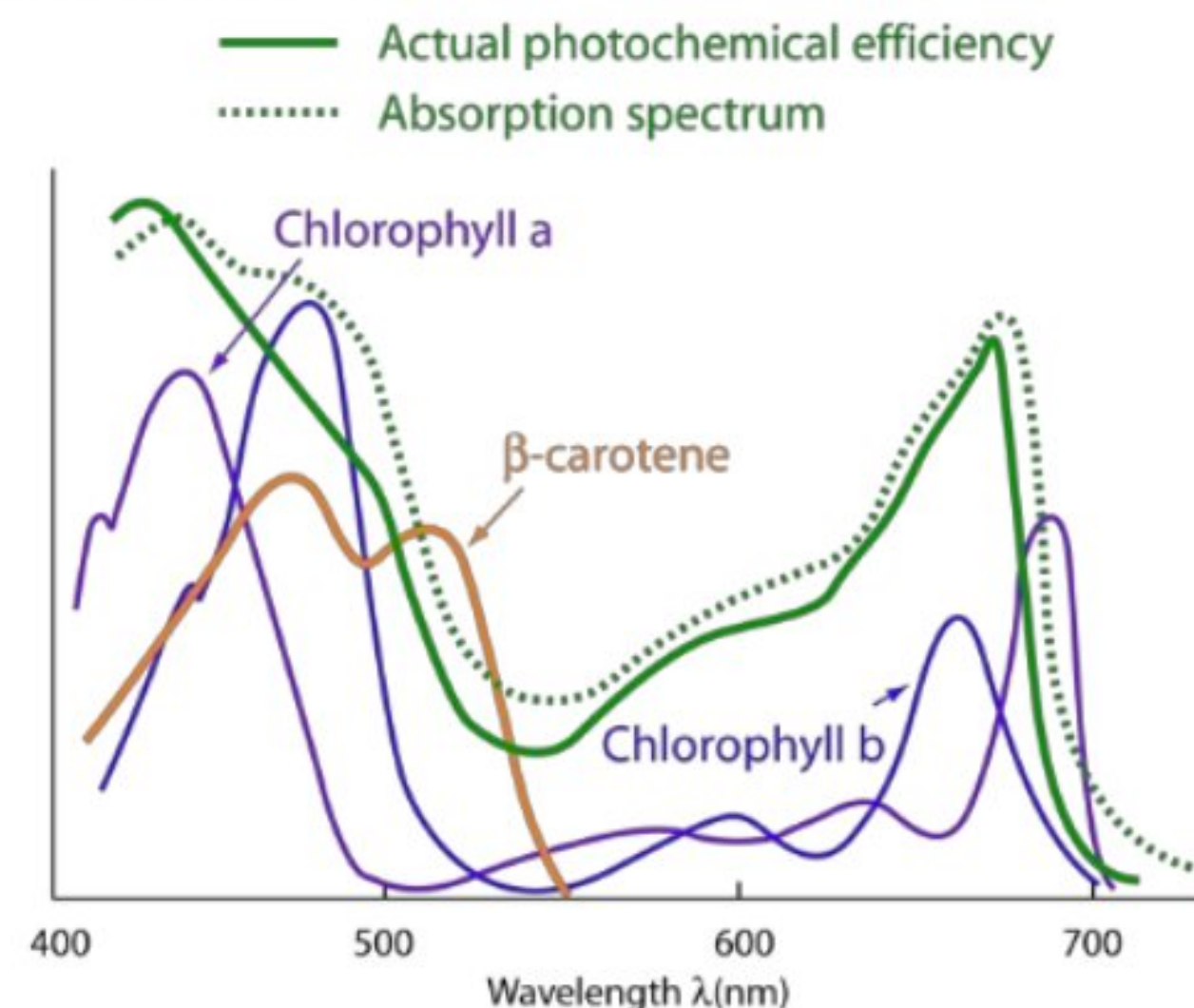


Fig 4.4 Absorption graph

4.1.5 Arrangement of Photosynthetic pigments in the form of photosystem I and photosystem II

As described in previous sections energy of light is absorbed by pigments and perform photosynthesis. Chlorophyll is organized with other molecules into photosystem, which has light gathering **“antenna complex”**, consist of a cluster of few hundred chlorophyll-a, chlorophyll-b and carotenoid molecules. When any antenna molecule absorbs energy of a photon, this energy is transmitted from one pigment molecule to other pigment molecule until it reaches a particular chlorophyll a, which is structurally similar to other chlorophyll molecule but located in the region of photosystem called **“reaction center”** where first light driven chemical reaction of photosynthesis occur. It means that the photosystem consist of two parts (a) Antenna complex (b) reaction center. The reaction center consists of one or more molecule of chlorophyll-a along with many e^- (electron) carriers.

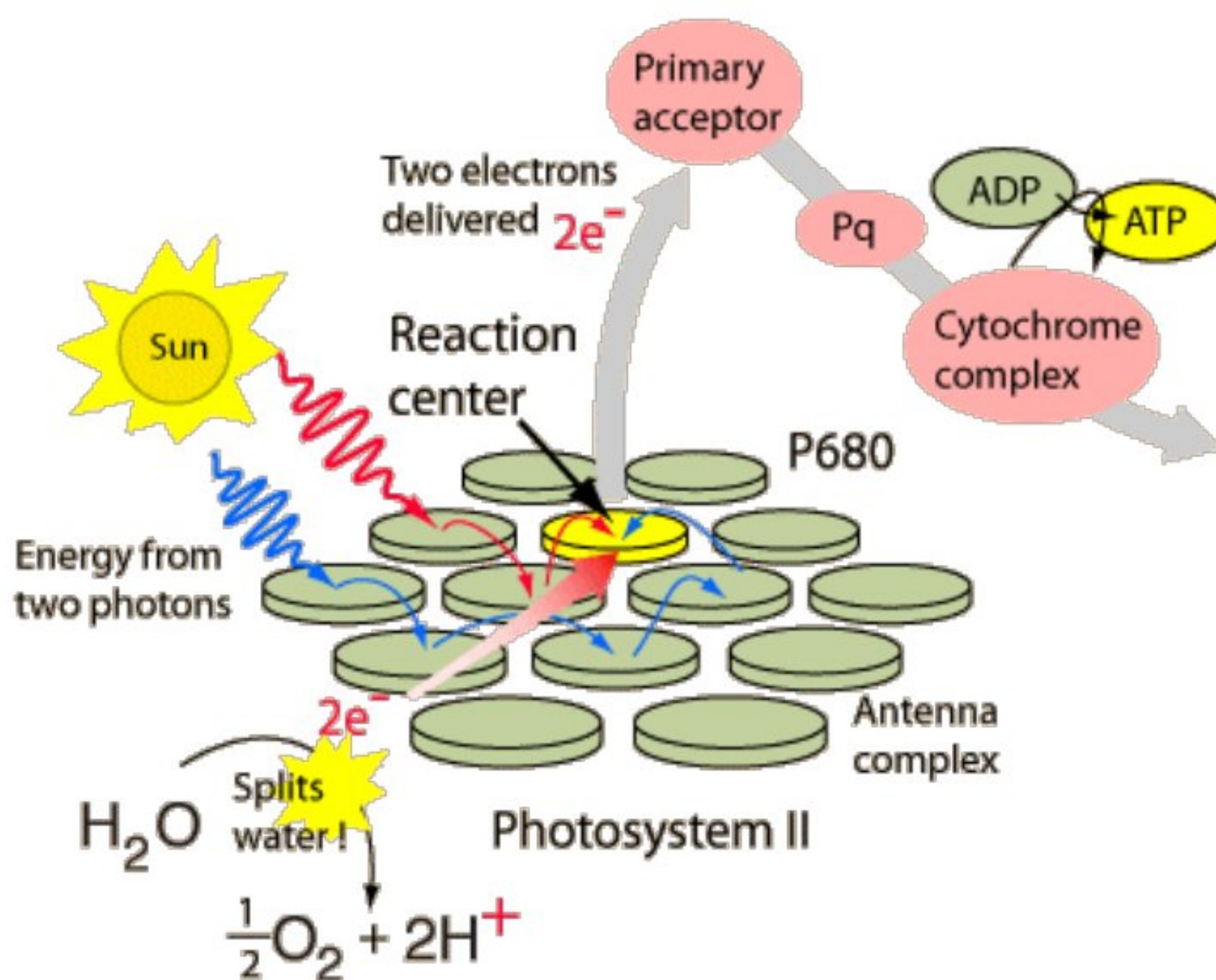


Fig 4.5 Photosystem

4.1.6 Role of CO_2

The final product of photosynthesis is carbohydrate which contain carbon atoms as basic skeleton attached with Hydrogen and oxygen atoms. The carbon form basic skeleton is provided by carbon dioxide during light independent reaction i.e. C_3 cycle.

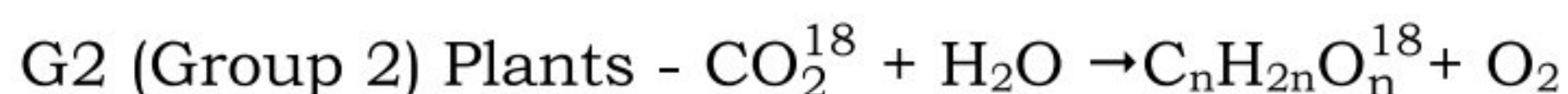
Scientists had studied that CO_2 with air enter in the intercellular spaces through stomata of leaves. This CO_2 get dissolved in the water absorbed by the cell-wall of mesophyll cells. This entry of CO_2 into leaves depends on the opening of stomata on leaves.



4.1.7 Role of water

It is clear from above discussion that carbon dioxide provides carbon to $C_nH_{2n}O_n$. It is also clear that H_2O provides hydrogen to $C_nH_{2n}O_n$ but the confusion was developed that which raw material either CO_2 or H_2O provide oxygen to $C_nH_{2n}O_n$. In 1930 Von Neil hypothesized that plant split water as a source of Hydrogen and release oxygen as by product. His hypothesis was based on the by-products of photosynthetic bacteria which produce sulphur instead of oxygen.

Neil's hypothesized that the source of oxygen released during photosynthesis is water, not carbon dioxide. It was later confirmed experimentally by other scientists during 1940 by radio-labelling of O^{18} isotopes with H_2O and CO_2 . They made two groups of plants in first group they supplied CO_2 and H_2O , the oxygen of this water molecule were labelled with O^{18} and CO_2 has normal O^{16} . Plants of second group were supplied with normal O_2 containing H_2O but with O^{18} containing CO_2 . It was observed that the plants of group 1 produced oxygen gas with O_2^{18} isotopes and no oxygen of O^{18} was found in sugar. On the other hand in the plants of second group the oxygen gas produced did not contain any O_2 with O^{18} while sugar molecules contain O^{18} isotopes. It was cleared that water is thus one of the raw materials of photosynthesis, hydrogen produced by splitting of water reduces NADP to $NADPH_2$, ($NADPH + H^+$)



4.1.8 Light Dependent Reaction: The event of cyclic and non-cyclic photophosphorylation

The first phase of photosynthesis where energy of photon is captured and converted into chemical energy. The energy of photon is stored in special molecules i.e. ATP and $NADPH_2$. The energy of ATP and $NADPH_2$ will utilize to produce carbohydrate during light independent phase.

In chloroplast the light capturing chlorophyll molecules, membrane bounded proteins and electron carriers all together constitute the electron transport chain. Four major groups of complexes are present in the membrane. These are photosystem-I (PSI), Photosystem-II (PS-II), the cytochrome b/f and an ATPase complex. Some mobile electron carriers are present which carry excited electrons between complexes. These mobile carriers are plastoquinone (PQ), plastocyanin and ferredoxin (Fd).

Photosystem I and II both contain special chlorophyll-a molecules at their centers. These chlorophyll molecules are identical to all other



chlorophyll-a molecules. The change in absorbing spectra are due to their association with the chlorophyll bound proteins. The chlorophyll-a molecule at the reaction center of PS-I has maximum absorption at 700 nm while those of PS-II absorb at 680 nm. These reaction centers are called **P₇₀₀** and **P₆₈₀** where **P** simply stands for pigment.

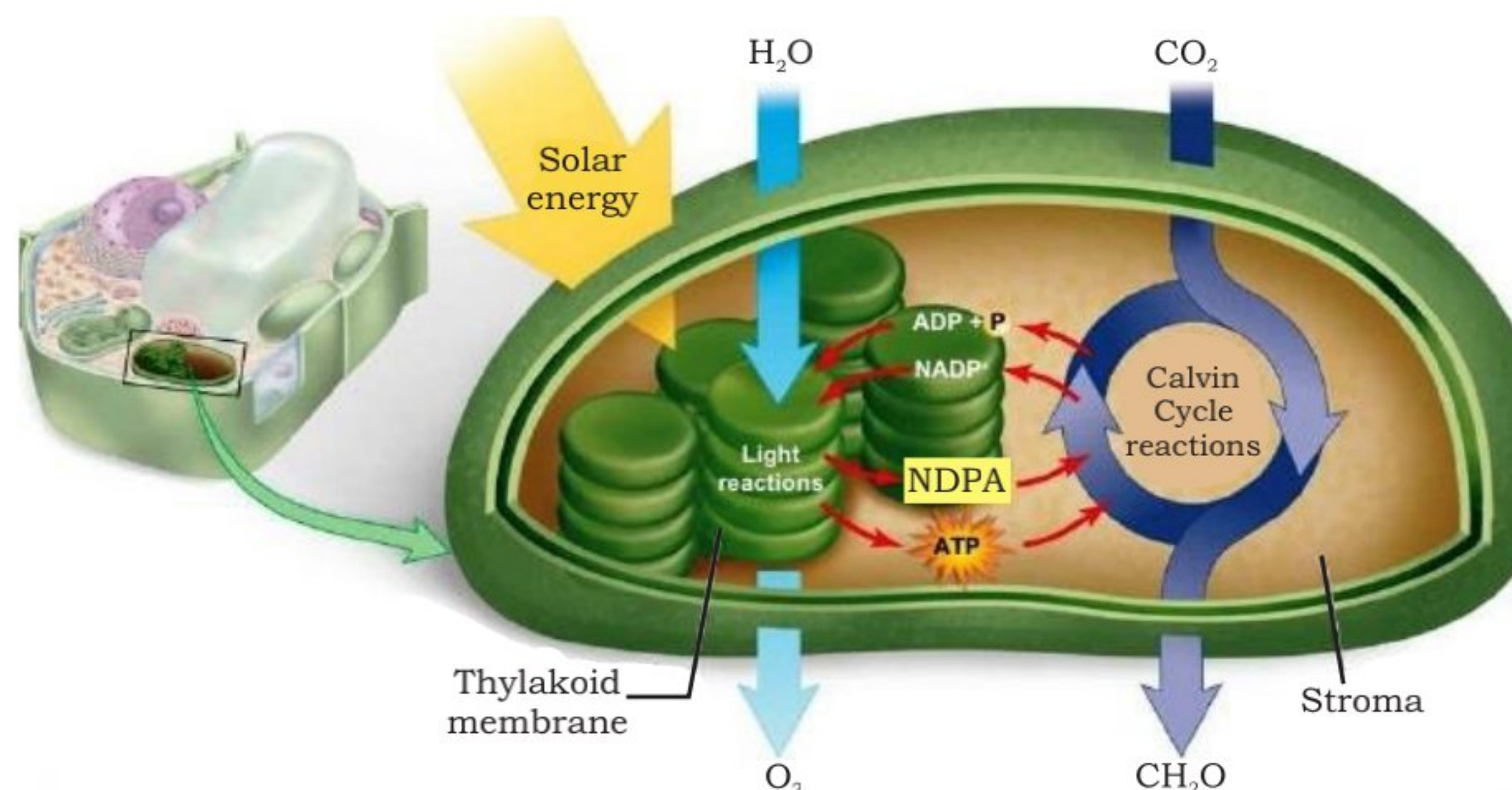


Fig 4.6 Light dependent reaction

(a) Electron Transport Chains:

The light reactions of photosynthesis start from reaction center of PS-II (**P₆₈₀**) which consist of chlorophyll-a dimer. When a photon of light hits these chlorophyll a molecule, the energy of these photons is absorbed and results in the excitation of an electron from ground state to excited state. The excited electron produced within **P₆₈₀** is rapidly transferred to primary \bar{e} acceptor **phaeophytin** and then to **plastoquinone** (PQ) molecules.

The **P₆₈₀⁺** produced by this primary charge separation and \bar{e} transport is compensated (re-reduced) by \bar{e} from **H₂O**. The water splitting complex is present on the luminal side of thylakoid membrane and consists of a manganese cluster, Z complex (the immediate electron donor to **P₆₈₀**) and an associated protein. The water splitting complex produces $4\bar{e}$ from two water molecules and released 4H^+ and one molecule of **O₂** into the lumen.

The excited electrons are transferred from primary \bar{e} acceptor to plastoquinone (PQ), the PQ molecules which accept two electrons and takes up two protons from the stroma. It carries electrons from the PS-II complex to the Cytb/f complex. This is thought to be the rate limiting step of electron transport. The PQ release protons into lumen. Finally the \bar{e} transfer to plastocyanin (PC), PC is reduced which is situated in the lumen.



Plastocyanin acts as an electrons donor to PS-I, the primary electron acceptor of photosystem-I, passes the photo excited electrons to a second e^- transport chain, which transmits them to ferredoxin (Fd) an iron containing protein. An enzyme called NADP reductase then transfers the electrons from Fd to NADP, this NADP with $2e^-$ received proton from stroma and reduced to NADPH_2 . It stores high energy which will provide reducing power for the synthesis of sugar during light independent reaction.

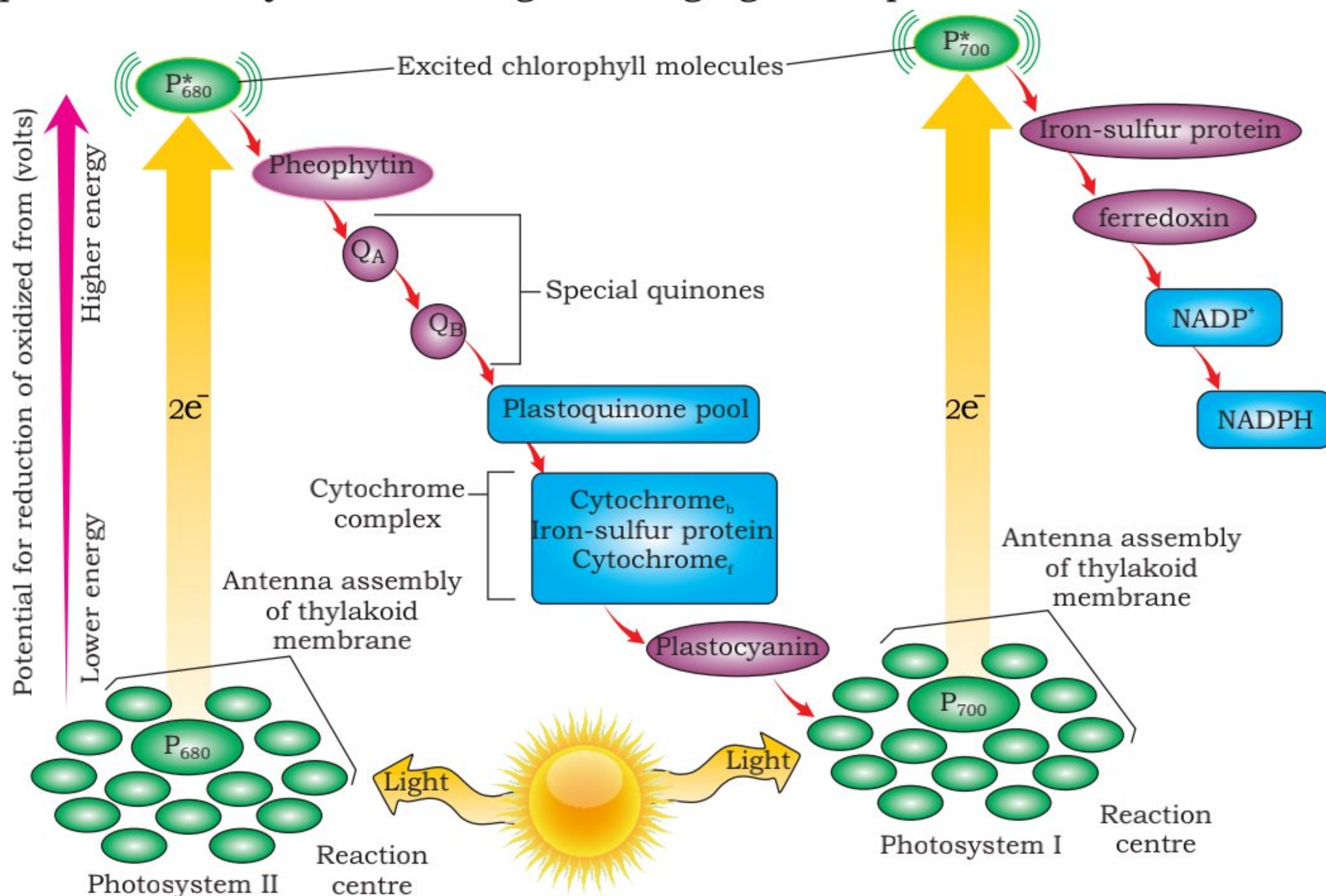


Fig 4.7 Light dependent reaction of photosynthesis

(b) Formation of ATP (Photophosphorylation)

The energy released during movement of excited e^- down the cytochrome system is coupled to build up ATP in an indirect manner. Some of the e^- carrier of the cytochrome system pump hydrogen ion (H^+) from stroma to thylakoid space (lumen). This thylakoid space acts as a reservoir for hydrogen ions because H^+ ion produced by splitting water during the process of photolysis accumulate here.

The high quantity of H^+ ion in thylakoid space as compared to stroma develop electrochemical gradient, these H^+ ions flow out of the thylakoid space to stroma through a channel protein present in membrane called **ATPase synthase complex**. Hydrogen ions move through this channel by providing energy which is released during down movement of

electrons in PS-II. This energy is utilized for the synthesis of ATP from ADP and P_i . This movement of H^+ through ATPase complex due to concentration gradient called **chemiosmosis or chemiosmotic ATP synthesis** because chemical and osmotic event join to permit ATP synthesis. The transport of three proton (H^+) through ATPase complex are normally required for the production of one ATP molecule.

The linear flow of electrons from water to $NADP^+$ coupled to ATP synthesis is called non-cyclic photophosphorylation because the electrons pass from water to a terminal acceptor and never back to its initial source.

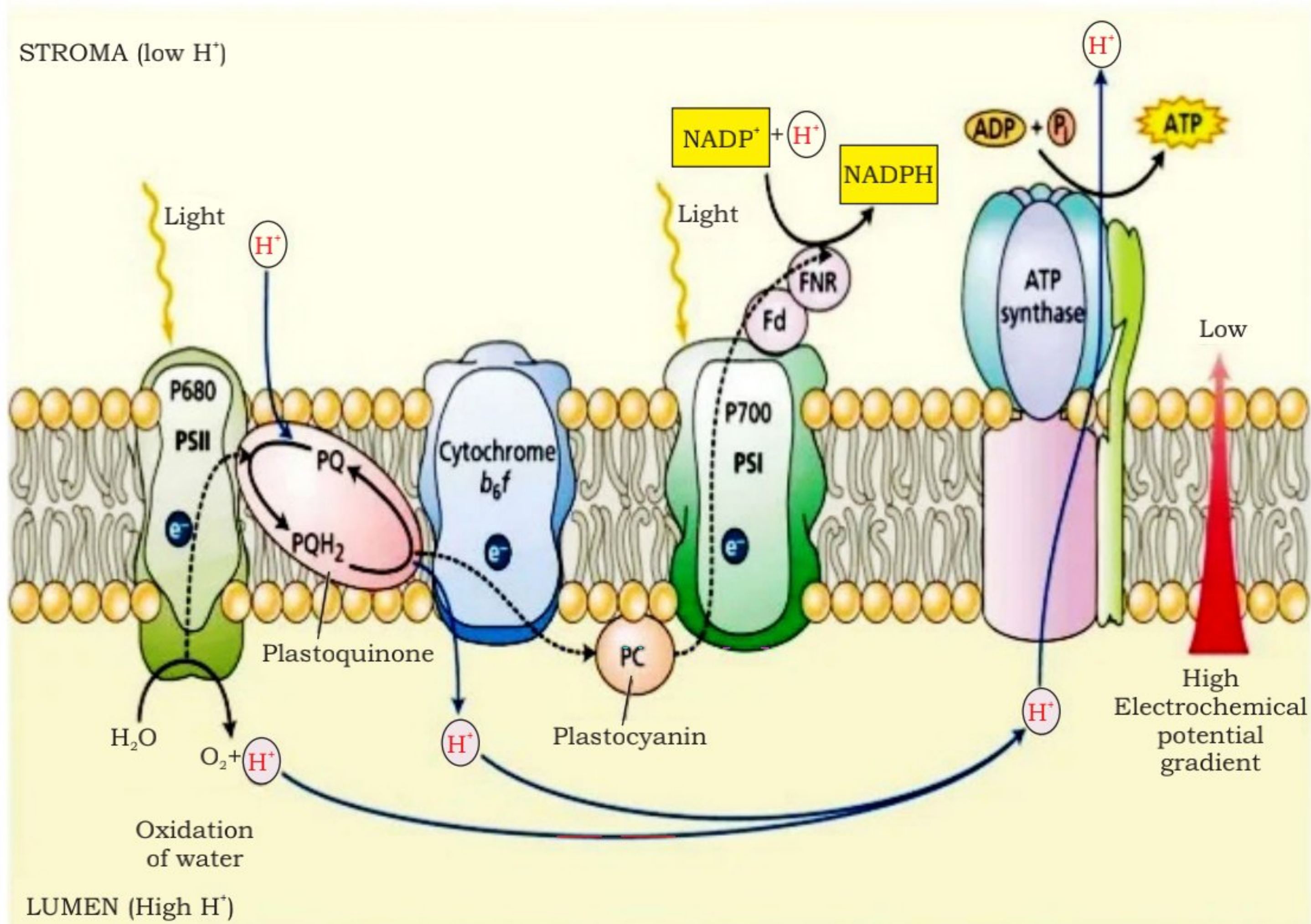


Fig 4.9 Linear flow of electrons

Finally four important events takes place during light dependent reaction of photosynthesis.

- (i) Photolysis of water
- (ii) Electron transport chain i.e. PS II and PS I
- (iii) Reduction of $NADP$ into ($NADPH_2$)
- (iv) Photophosphorylation



4.1.9 Cyclic Photophosphorylation

In some conditions like saturation of NADP, excited electrons do not move towards NADP, they take an alternative pathway i.e. cyclic electron flow. In this pathway they use only PS-I and have short cut. The e^- from primary electron acceptor to Fd and then to cytochrome complex, ultimately come back to P^{700} chlorophyll a molecule. ATP is generated by coupling of electron transport chain with chemiosmosis, no further NADP is reduced to produce $NADPH_2$ and production of O_2 is also stopped during this process. This process of ATP formation is called **cyclic photophosphorylation**, the generation of only ATP.

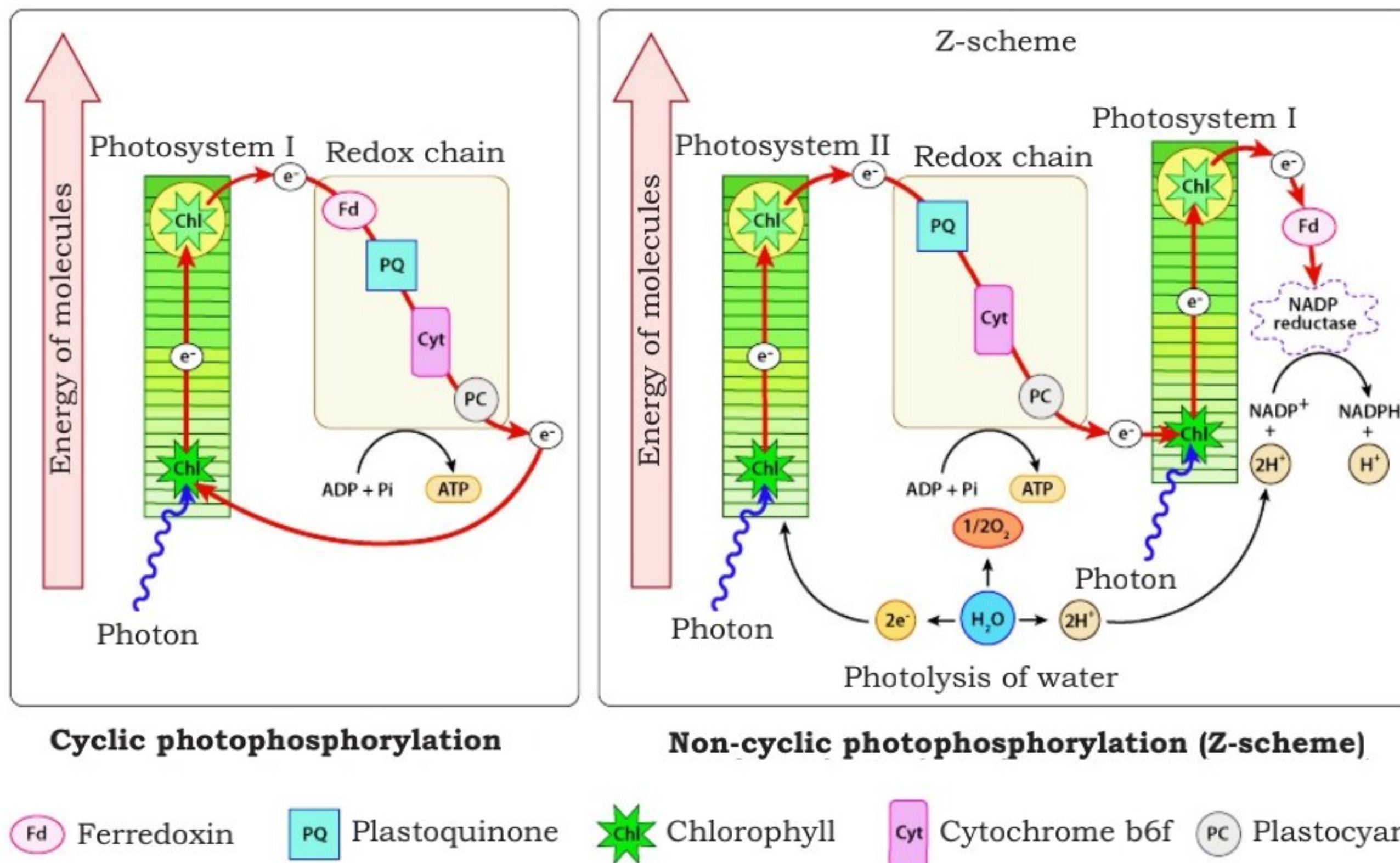


Fig 4.10 Cyclic and non-cyclic photophosphorylation

Possibly it happens when the chloroplast have low ATP and demand of ATP is high for Calvin cycle or $NADPH_2$ accumulate in chloroplast. The rise in $NADPH_2$ may stimulate a temporary shift from non-cyclic to cyclic electron flow until ATP supply meets the demand.

4.1.10 Light Independent Reaction or Calvin Benson Cycle

The second phase of photosynthesis, where carbohydrate molecules are formed by fixing atmospheric carbon dioxide. This part of photosynthesis does not require light energy directly, it requires chemical energy of ATP and $NADPH_2$ therefore it is **light independent reaction** or previously called **dark reaction**. The details of this phase were discovered by Melvin Calvin and his colleague Benson therefore it is also called **Calvin Cycle**. During this cycle CO_2 is reduced to triose phosphate i.e. 3-phosphoglycerose or dihydroxy acetone phosphate and subsequently via

other metabolic pathways to hexoses, sucrose and starch. The first stable product formed during this cycle is a three carbon containing acid i.e. 3-phosphoglyceric acid (3 phosphoglycerate abbreviated by 3-PGA) therefore, this cycle is also called **C₃ cycle** and the plants which carry this cycle only called **C₃ plants**. The Calvin cycle starts with a phosphorylated five carbon sugar i.e. Ribulose 1,5-biphosphate and ends on this sugar, therefore it is called a **cyclic process**.

Calvin cycle is divided into three distinct phases for the convenience to study.

- i) **Carboxylation:** It is the fixation of atmospheric carbon dioxide with five carbon sugar.
- ii) **Reduction:** Reduction of three carbon containing acid takes place to form triose.
- iii) **Regeneration:** Where reduced carbon utilize to regenerate 5-carbon sugar.

i) **Carboxylation:**

This is the first and key step of Calvin cycle where carbon dioxide is fixed with Ribulose 1,5-biphosphate (RuBP), as a result of this fixation a 6 carbon short lived intermediate compound is formed, which immediately breaks, into two molecules of three carbon containing acid called 3-phosphoglycerate (3PGA). This reaction is catalyzed by the enzyme called RuBiSCO (Ribulose 1,5-biphosphate Carboxylase / Oxygenase).

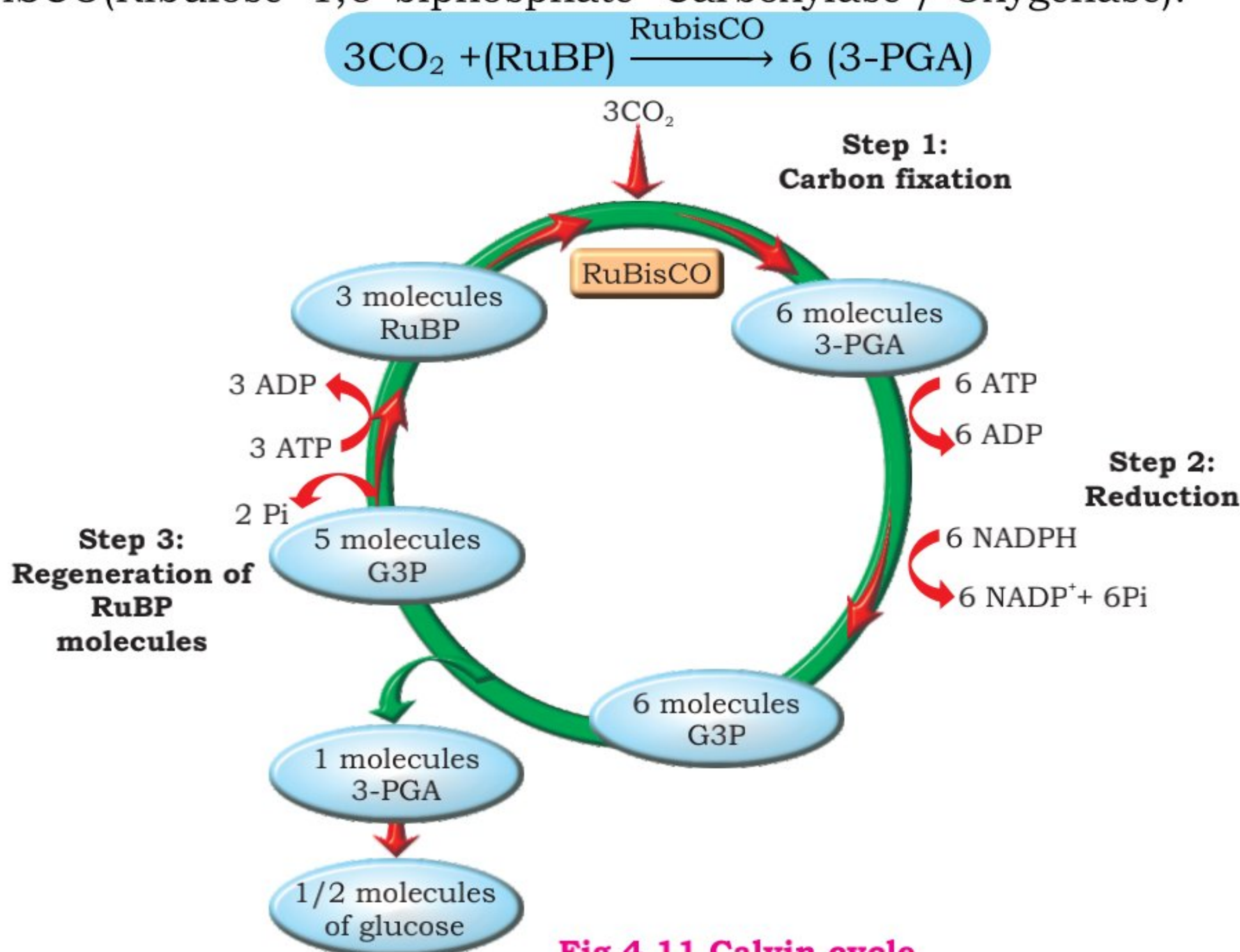
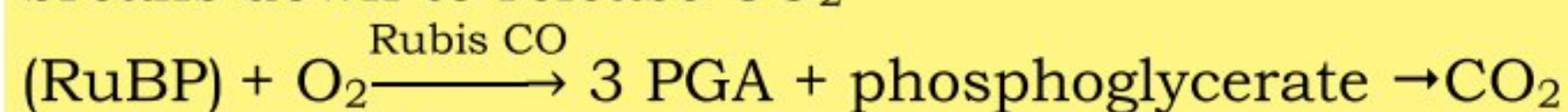


Fig 4.11 Calvin cycle



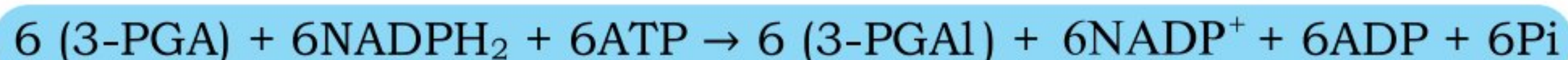
RuBiSCO an enzyme which function as carboxylase as well as oxygenase. If the supply of CO_2 inside the leaf is inadequate most of RuBiSCO combines with O_2 , giving one molecule of 3 PGA and one molecule of phosphoglycerate, where phosphoglycerate rapidly breaks down to release CO_2



this process is named as photorespiration because in the presence of light (Photon) oxygen is taken up and CO_2 is evolved (respiration).

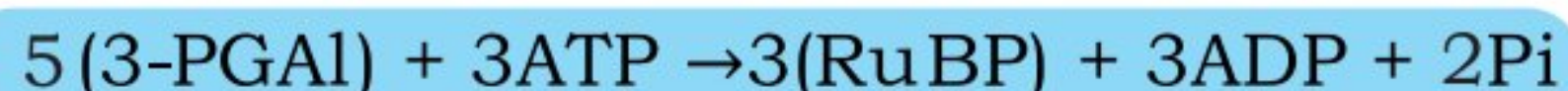
ii) Reduction:

This phase comprises of a series of reactions. Simply, during this phase 3-phosphoglycerate (3-PGA) reduce to glycerate 1,3-biphosphate by using ATP from light reaction and then to Triose phosphate by oxidation of NADPH_2 from light reaction, these triose phosphates are phosphate and 3-phosphoglyceraldehyde (3-PGAl).



iii) Regeneration:

Many carbon rearrangements take place during this phase, 5 molecules of Triose sugar (3-PGAl) in three interlinked C_3 cycles rearrange to reform three molecules of 5-carbon sugar (Rub 1-5, P_2) while one molecule of Triose sugar is formed as a gain of these three cycles.



During this cycle three molecules of CO_2 fix with three molecules of RuBP which produce six molecules of Triose sugars. These six molecules of Triose rearrange to three molecules of five carbon sugar (RuBP) and one molecules of Triose as net gain. Therefore, only one molecule of three carbon sugar i.e. Triose phosphate is produced which can (a) re-enter the cycle to produce hexose or (b) be used for starch synthesis within chloroplast or (c) be exported via phosphate translocator to cytosol for sucrose synthesis.

For the net synthesis of Triose molecule, the Calvin cycles consume a total of nine (09) molecules of ATP and six (06) molecules of NADPH_2 .

4.2 CELLULAR RESPIRATION:

Every living cell requires energy to carry out their functions. This energy comes from fuel molecules such as glucose. In cellular respiration glucose molecules are oxidized either in the absence of oxygen or in the presence of O_2 . Carbon-carbon bonds of glucose molecules break to release energy, some of this energy is stored in the form of ATP while other is lost. Thus, a cell transfer energy from glucose to ATP through reduction and oxidation process. This break down of glucose molecules by redox reaction



to synthesize ATP is called **respiration**. This ATP provides energy for metabolism wherever required by removing its terminal phosphate liberate energy ADP and P (Phosphate) are formed.

Anaerobic Respiration or Fermentation

Fermentation was originally defined by W. Pauster as respiration in the absence of air (O_2). It is an alternative term used for anaerobic respiration. The products of anaerobic respiration are either ethyl-alcohol or lactic acid. The type of fermentation where alcohol is formed is termed as **alcoholic fermentation** and the fermentation where lactic acid is formed called **lactic acid fermentation**.

A small but significant minority of organisms obtain energy by anaerobic respiration. Many micro-organisms including yeasts and some bacteria can respire anaerobically.

The anaerobic respiration as well as aerobic respiration has a common phase where glucose breaks anaerobically into two molecule of pyruvate (pyruvic acid) called **Glycolysis**.

4.2.1 Glycolysis

It is anaerobic break down of Glucose into two molecules of Pyruvate. It takes place in a series of steps, each catalyze by specific enzyme. All these enzymes are found in cytosol with these enzymes, ATP and NAD (Nicotinamide Adenine Dinucleotide) are also required.

Glycolysis can be divided into two phases:

- (i) A Preparatory Phase – Glucose to the formation of phosphorylated Triose.
- (ii) Oxidative Phase – Phosphorylated triose to the formation of Pyruvate.

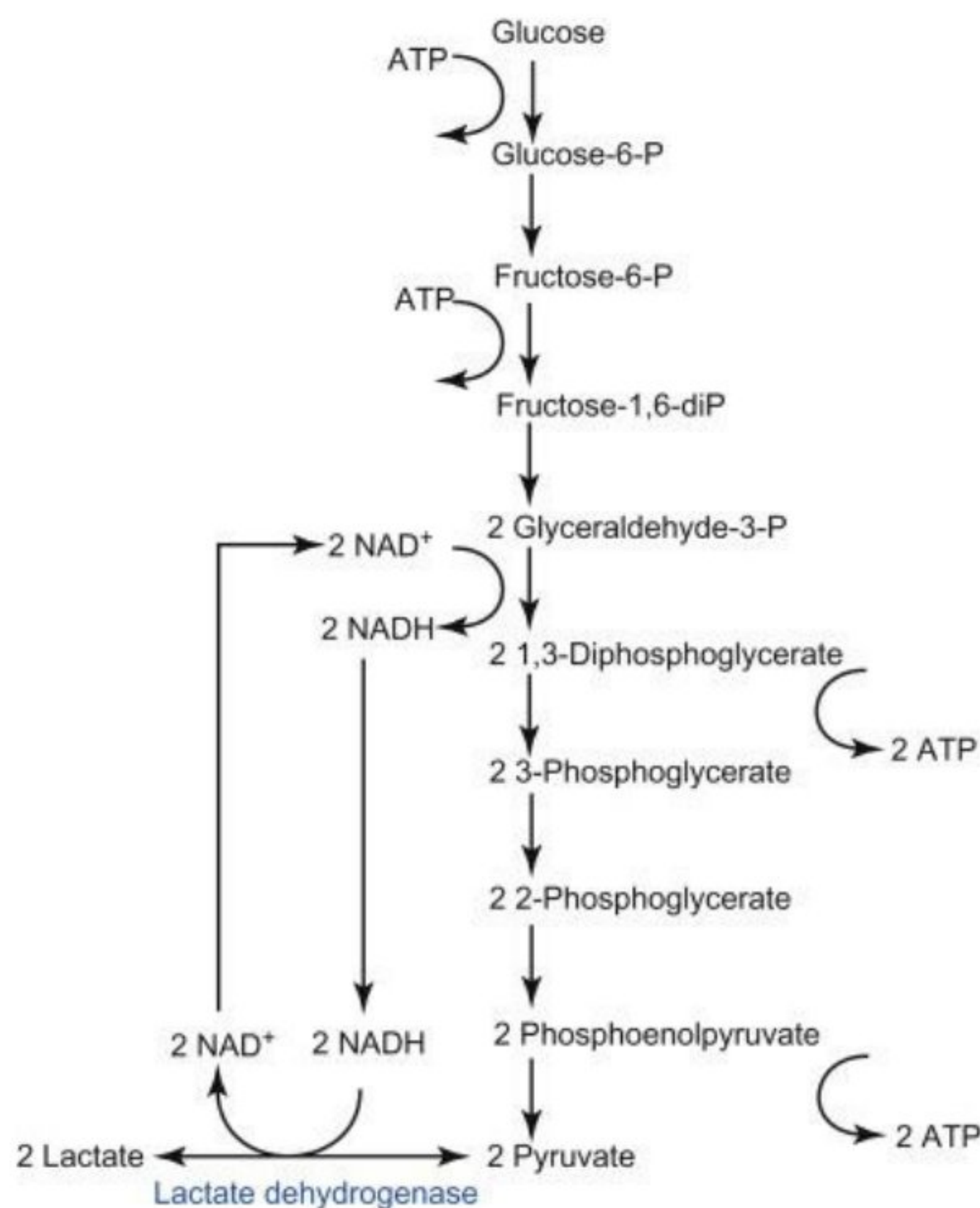


Fig 4.12 Glycolysis



(i) Preparatory Phase:

During this phase Glucose become phosphorylated into glucose-6-phosphate which then isomerized into Fructose-6-phosphate. This fructose 6-phosphate further phosphorylated into fructose 1,6-biphosphate. The phosphate comes from ATP molecule, 2 molecules of ATP consumed during this phase. Finally, Fructose 1,6-biphosphate breaks into two molecules of phosphorylated triose i.e. Dihydroxyacetone phosphate and 3- phosphoglyceraldehyde (3-Phosphoglycerose).

(ii) Oxidative Phase:

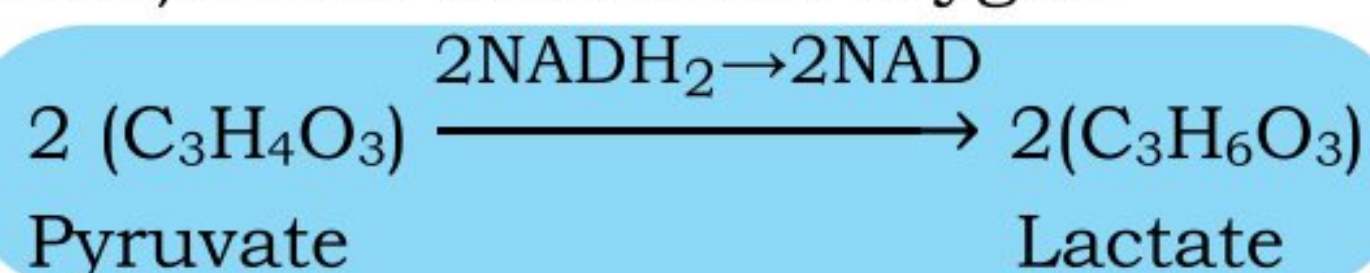
In this phase the molecules of triose phosphate are oxidised as well as two electrons and two proton (H^+) are removed from phosphorylated triose (3PGA1) and transfer to NAD to reduce it in $NADH_2$. Therefore, it is called Redox reaction. During this phase 4 ATP molecules are also produced by substrate level phosphorylation at two different steps of glycolysis. Finally, 2 molecules of pyruvate, 2 molecules of $NADH_2$ and 4ATP are formed, where as the net gain of 2 ATP takes place.

The Pyruvate produces at glycolysis have three metabolic pathways according to availability of enzyme in organisms. It may be anaerobic or aerobic.

4.2.2 Anaerobic Respiration (Pathway)

(i) Lactic Acid Fermentation

In this type of anaerobic respiration three carbon containing Pyruvate molecule directly converted into another three carbon containing acid lactate (Lactic Acid) in the absence of oxygen.

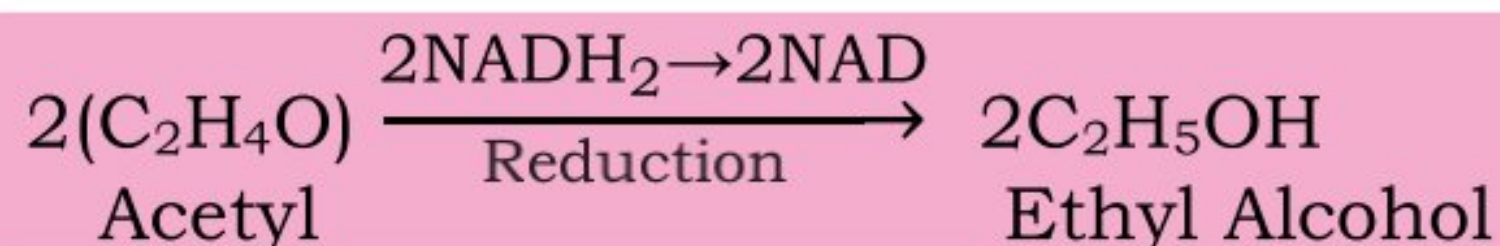


This form of anaerobic respiration occurs in muscle cells of human and other animals during extreme physical activities. Only two molecules of ATP is net gain of this type of respiration.

(ii) Alcoholic Fermentation

In this type of anaerobic respiration three carbon containing Pyruvate breaks its one carbon as carbon dioxide and remaining two carbon formed another compound i.e. Acetyl. In the next step this Acetyl converted into Ethyl Alcohol. Finally one molecule of carbon dioxide and one molecule of ethyl alcohol is formed from one molecule of Pyruvate, with these products one molecule of NAD is reduced to $NADH_2$ in first step

which is oxidized into NAD again in the next step. So a large amount of energy is produced in comparison of lactic acid fermentation i.e. net gain 2ATP and 2NADH₂. It occurs in bacteria, yeast etc.



4.2.3 Aerobic Respiration (Pathway)

The third pathway of Pyruvate is towards aerobic respiration where aerobic break down of Pyruvate occurs.

(i) Oxidation of Pyruvate

Pyruvate does not enter in Kreb's Cycle directly, the pyruvate break down occur in one molecule of CO₂ and one molecule of Acetyl. The Acetyl is 2 carbon radical, enters into mitochondria and combine with co-enzyme. During this phase NAD is reduced to NADH₂, the 2 molecules of Pyruvate which produce as the end product of glycolysis now produce two molecules of CO₂, two molecule of Acetyl CoA and two molecules of NADH₂.

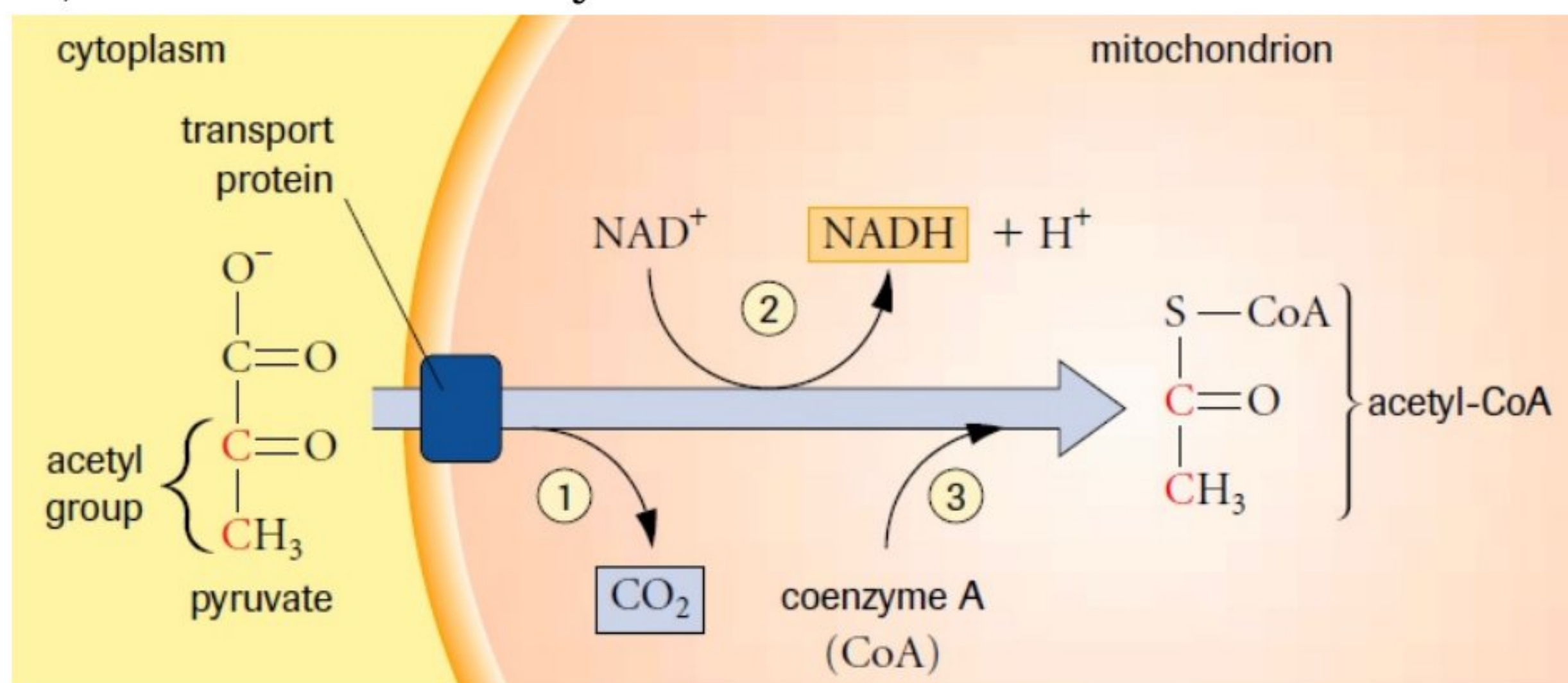


Fig 4.13 Pyruvate oxidation

Kreb's Cycle

Acetyl Co-A now enters in a cyclic series of chemical reactions during which oxidation of glucose is completed in the form of oxidation of Acetyl. This cyclic series is called Kreb's cycle or Citric Acid Cycle or Tri-carboxylic Acid cycle. Kreb's cycle is named after the name of H.A. Kreb who discovered it. The citric acid cycle is named due to the reason that first compound formed during this cycle is Citric acid and this Citric acid has three carboxylic acid groups in its structures, therefore it is also called Tri-carboxylic Acid Cycle (TCA). This cycle starts with four carbon acid i.e.



oxaloacetate (oxaloacetic acid) and ends at the same, the events are given in (Fig 4.13). As a result of it, one ATP by substrate level phosphorylation, three NADH_2 and one molecule of FADH_2 are formed. Complete oxidation of one glucose molecule requires two Krebs's cycles, where double amount of these molecules are formed.

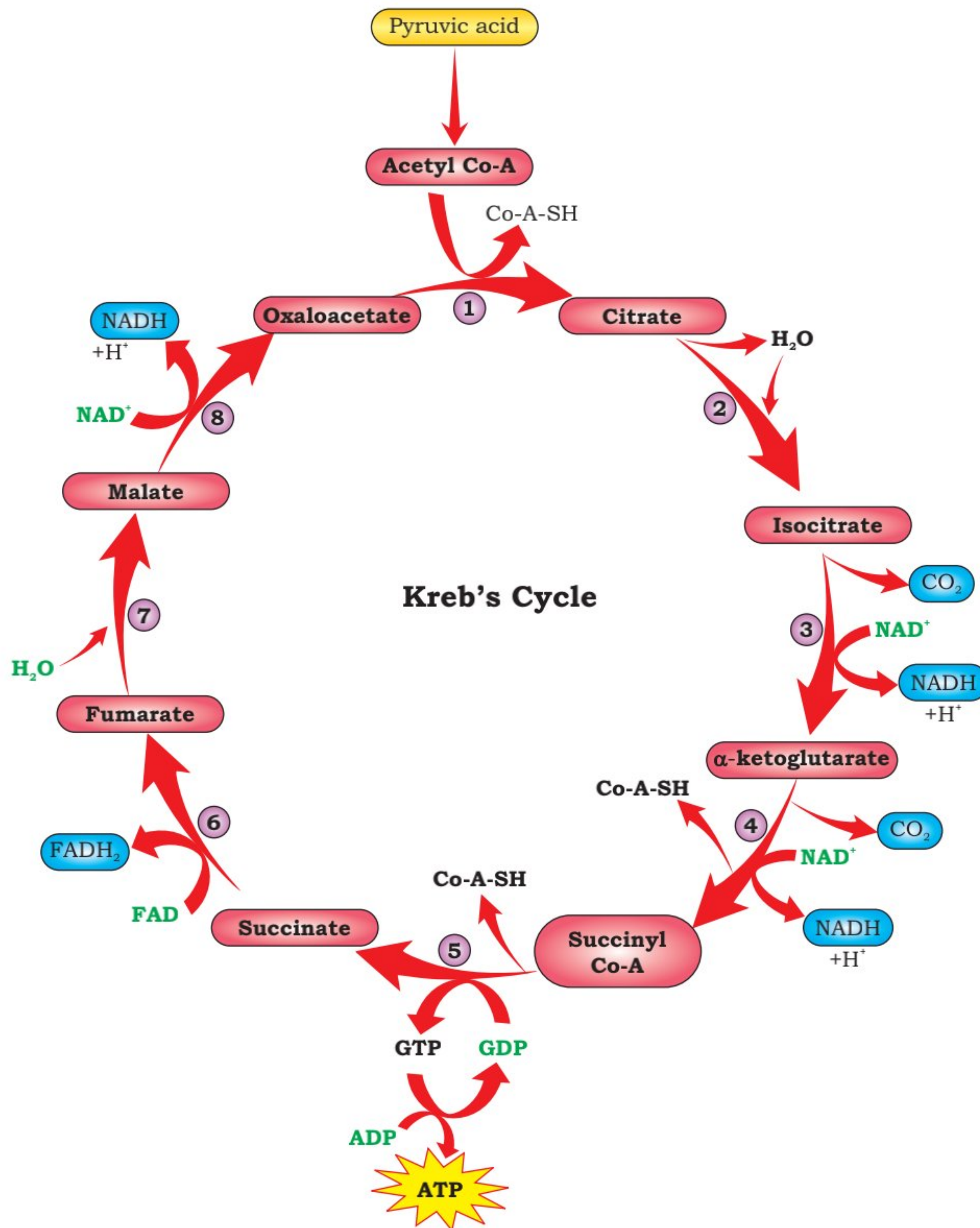


Fig 4.14 Krebs's cycle

(iii) Electron Transport Chain

It is the third phase of aerobic respiration, the NADH_2 and FADH_2 are produced during glycolysis, intermediate phase and Kerb's cycle are now oxidized here to liberate oxidation energy. The oxidation energy will utilize to produce ATP. This type of phosphorylation is called oxidative phosphorylation. During this process electrons and protons transfer to electron transport chain coupled with chemiosmosis.

The substances which reduced and oxidized take part in this chain are as follow:

- (i) A co-enzyme Q
- (ii) A series of cytochrome from Cyt b, Cyt c, Cyt a to Cyt a_3
- (iii) ATPase complex (H^+ Pump)

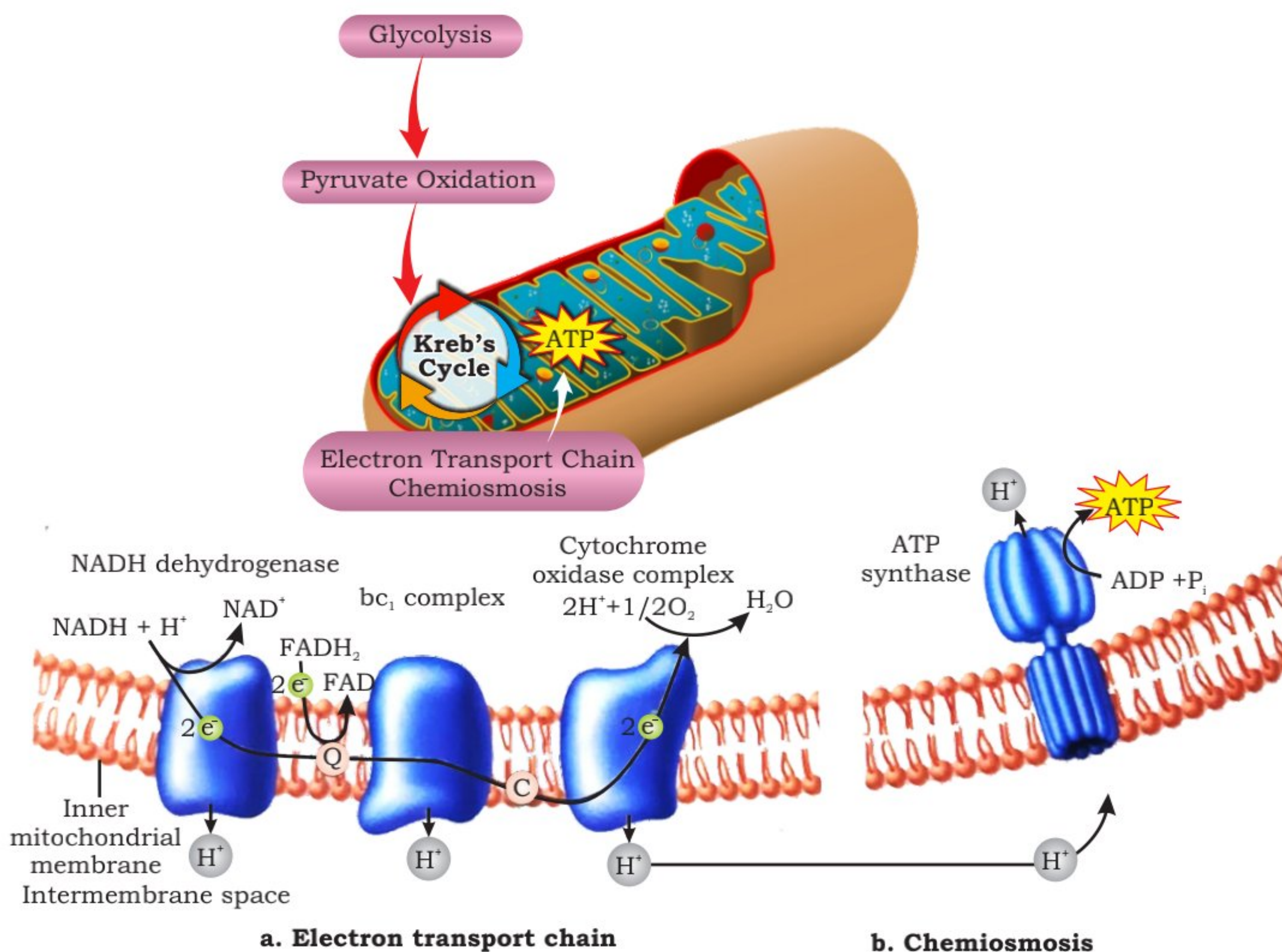


Fig 4.15 Electron transport chain during oxidative phosphorylation

It starts with the oxidation of NADH_2 which release $2e^-$ and 2H^+ , the energy is also released, this energy will utilize to synthesis first molecule of ATP. This NADH_2 is oxidized by co-enzyme Q. The FADH_2 is also oxidized by co-enzyme Q. the co-enzyme Q is now oxidized by cytochrome b, which after that oxidized by cytochrome c. At this stage enough energy is



liberated it is also coupled with ATPase complex. This energy is utilized for synthesis of another molecule of ATP. After it cytochrome is oxidized by two enzyme cytochrome a and a_3 . In the last, cytochrome a_3 is oxidized by an atom of oxygen and the electrons arrived with proton. A molecule of water is formed by these combinations.

In addition, the enough energy is liberated which is also coupled with ATPase to synthesize third and final ATP molecule from one molecule of NADH_2

The synthesis of ATP during electron transport chain in the presence of oxygen is called **oxidative phosphorylation**. As discussed above ATP molecules are formed at three steps of respiratory chain. It takes place in the inner membrane (Cristae) of mitochondria.

Complete oxidation of glucose molecule results in a net gain of 36 ATP molecules which are released in cytoplasm available for different metabolic reactions.

4.2.4 Cellular Respiration of Protein and Fats

In the absence of enough sugar, living organisms use fats and during illness proteins are also used to produce energy. Fats hydrolyze and produce glycerol and three molecules of fatty acid. The glycerol convert into 3-phosphoglycericaldehyde. Which is one of the triose-sugar molecule produce during glycolysis. The fatty acids converts into Acetyl-CoA which enters the Krebs's cycle.

The amino acids of protein also convert into amyl group, whose R-group determine the site of it oxidation either the carbon chain is oxidized in glycolysis or Kerb's cycle, when amino acid undergoes deamination, this NH_3 (ammonia) enters in the urea cycle.

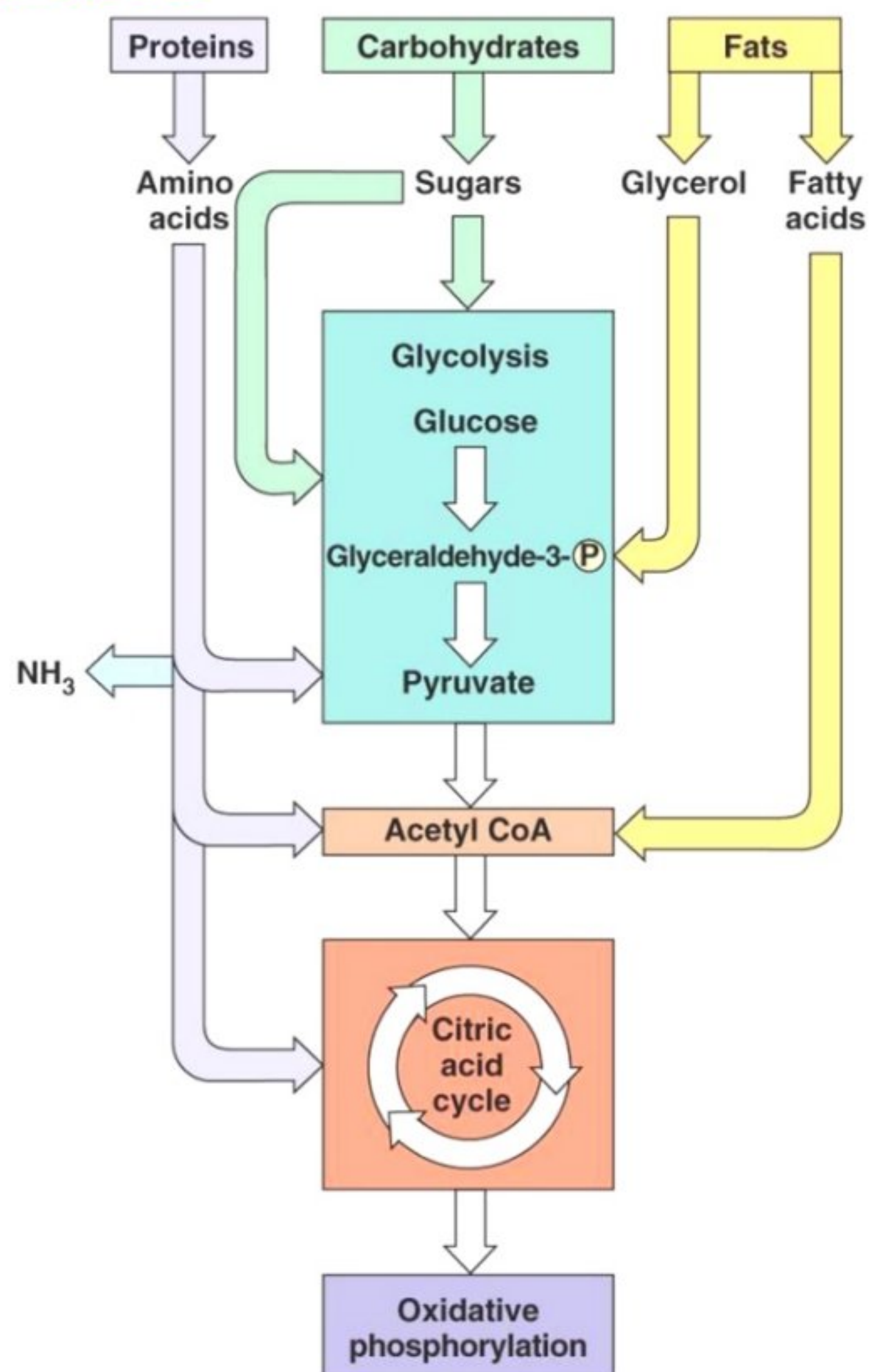


Fig 4.16 Cellular respiration

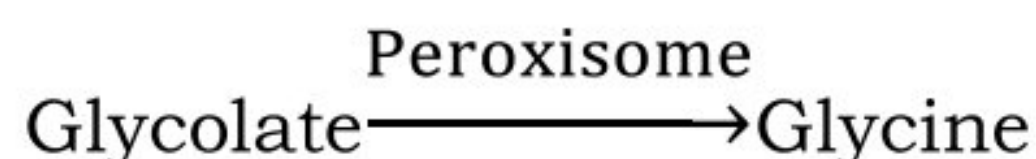
4.3 PHOTORESPIRATION

Sometimes plants oxidized sugar in chloroplast during day time without production of energy or ATP called **photorespiration**. During this process carbon dioxide is released and oxygen is absorbed like aerobic respiration. It means that the photorespiration is the process in which RuBiSCO perform oxygenation instead of carboxylation.

During photorespiration RUBP react with oxygen produces one molecule of 3 phosphoglycerate (3 carbon compound) and one molecule of glycolate (2 carbon compound)



The glycolate produced during oxygenare this process diffuses into the membrane bounded organelles known as **peroxisome**. Where the glycolate is converted into an amino acid i.e. glycine through a series of reactions



The glycine rapidly diffuses into the mitochondria where two glycine molecules are converted into another amino acid serine and a molecule of carbon dioxide is also formed.

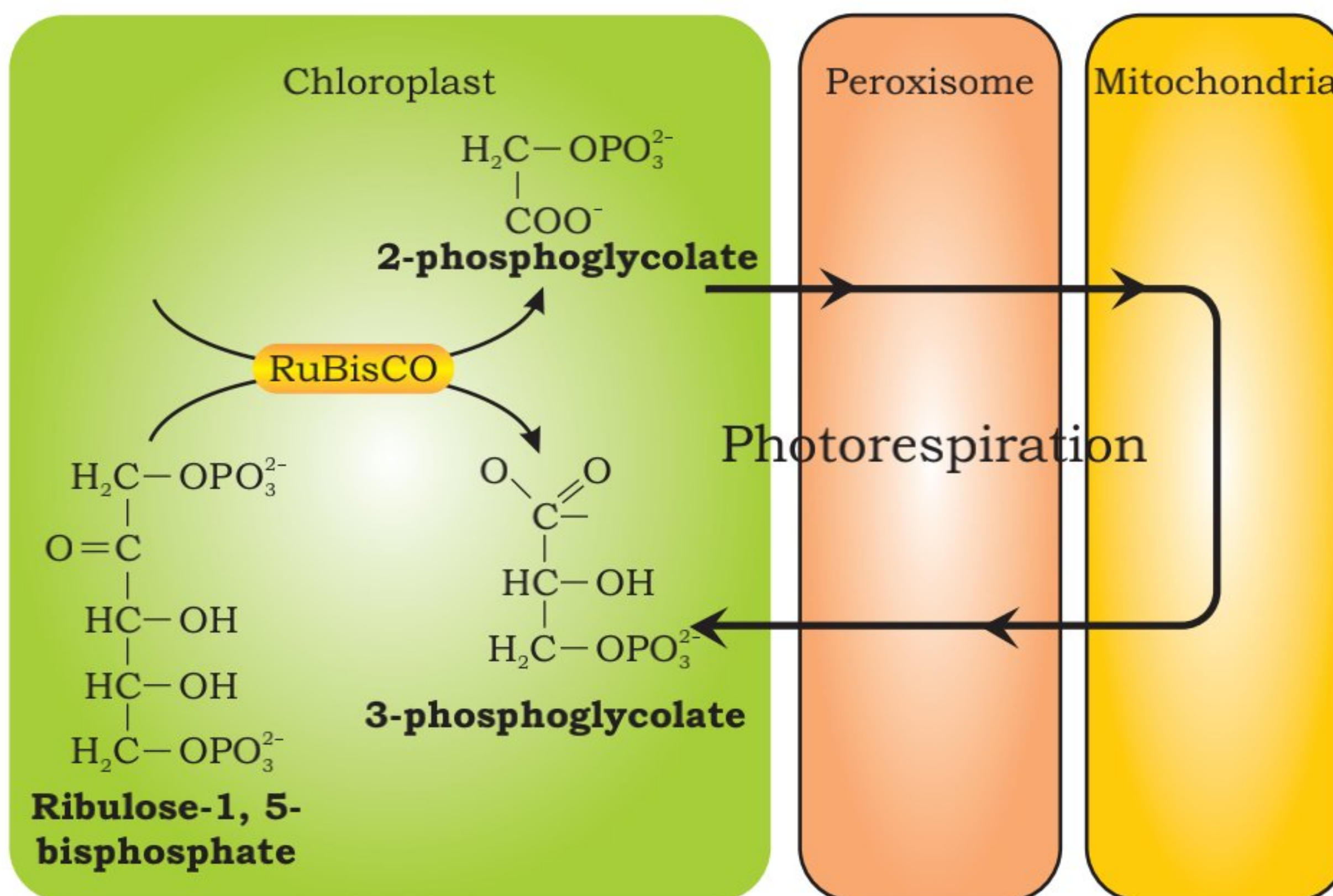
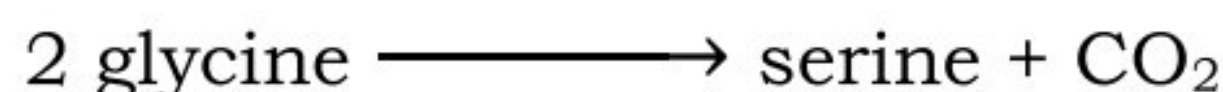


Fig 4.17 Photorespiration



4.3.1 How disadvantageous process of photorespiration evolve

Photorespiration is considered as wasteful process because during photorespiration energy is not evolved, ATP and NADH_2 do not synthesize on contrary ATP and NADPH_2 produced during light reaction also consumed. During this process CO_2 is released, instead of its fixation into carbohydrates. The growth of plant is also reduced up to 25% due to photorespiration.

Apparently photorespiration reduces the photosynthetic process. It is thought that the photorespiration is not essential for plant. It is also observed that if photorespiration is inhibited chemically, the plant can grow so question arises here that why does photorespiration evolved and Exist? We can answer this questions in a way that the RUBISCO had evolved to bind both carbon dioxide and oxygen at its active site. In the beginning it was not a problem because the oxygen was very low in atmosphere at that time, it could not compete with carbon dioxide, only carbon dioxide binding site of Rubisco remained active. This problem starts to occur when oxygen quantity increased in atmosphere.

4.3.2 Effect of Temperature on Photorespiration

On hot, dry day, most of the plants close their stomata to conserve their water. This response also reduces photosynthesis yield by limiting access to CO_2 , when stomata close carbon dioxide concentration decreases in the air spaces of leaves, while light reaction continues which continuously produce oxygen, which remains inside the air spaces of leaves due to closer of stomata. In this condition concentration of CO_2 decreases and oxygen increases in these air spaces of leaves. This condition favours the oxygenation of Rubisco ultimately to photorespiration.

4.3.3 Alternative mechanisms of CO_2 fixation to avoid photorespiration

To avoid photorespiration some plants adapt themselves by developing following alternative mode of carbon dioxide fixation.

- (i) C_4 cycle
- (ii) Crassulacean acid metabolism (CAM)

(i) C_4 cycle

Some plants develop another metabolic cycle to fix CO_2 in the presence of high oxygen concentration, these plants are called C_4 plants. They develop some anatomical and physiological modification, develop some tissues around vascular bundle called **bundle sheath**, shift C_3 cycle in these cells from mesophyll cells, while in mesophyll cells they develop another cycle for carbon dioxide fix. The CO_2 fix here will transfer to C_3 cycle in bundle sheath. In this way two cycles are linked together. In these plant atmospheric carbon is fixed by a three carbon compound Phospho

Enol Pyruvate (PEP) instead of RuBP. As a result of CO_2 fixation a four carbon compound is formed called oxaloacetate (oxaloacetic acid) therefore this cycle is called C_4 cycle.

The oxaloacetate transfer carbon through malate to RuBP for C_3 cycle in bundle sheath. Among C_4 plants some important b^2 plant agriculture are sugar cane and corn.

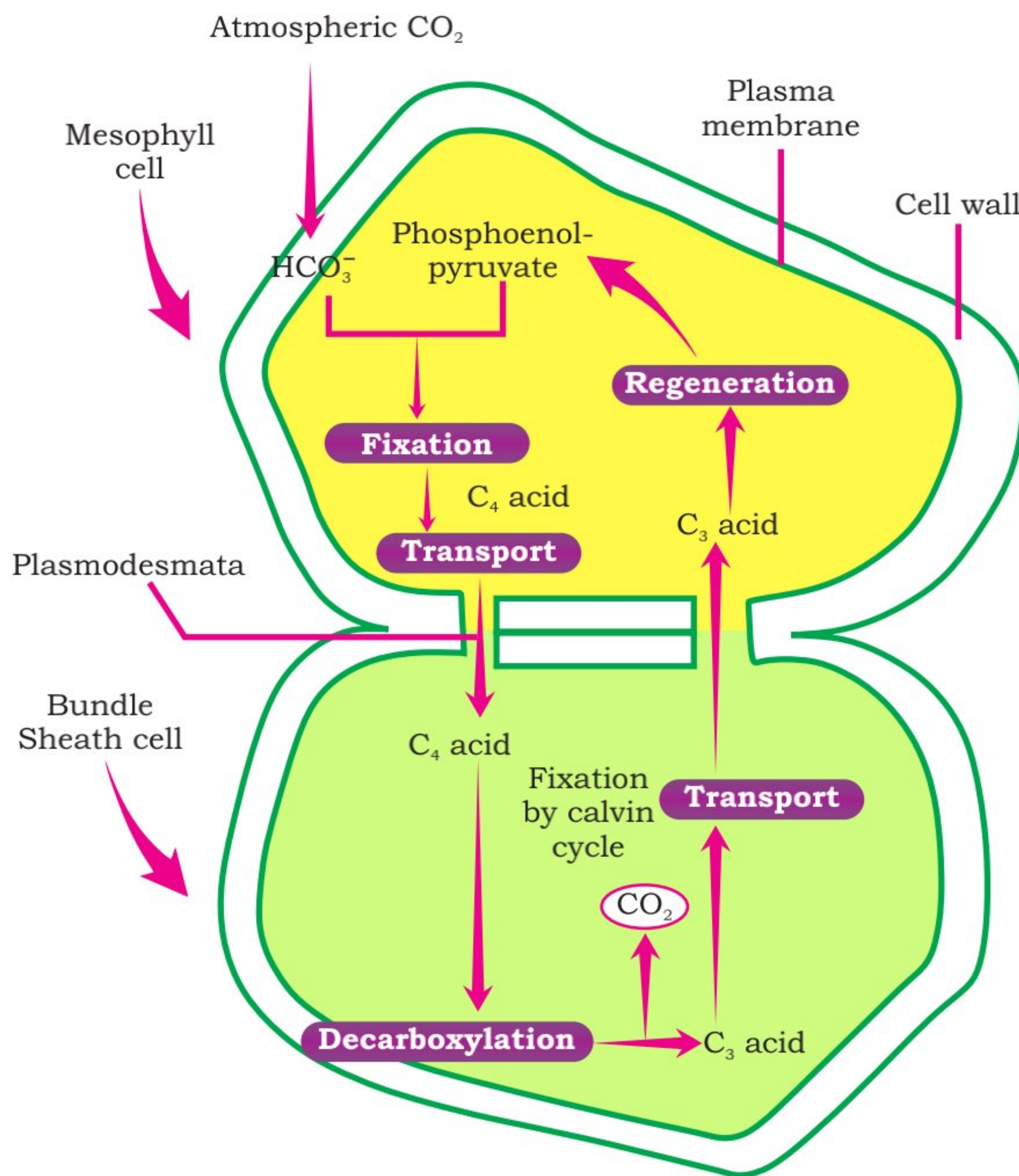


Fig 4.18 C_4 cycle



(ii) Crassulacean Acid Metabolism (CAM)

Another adaption to avoid this condition has evolved in succulent plants like cacti, pineapples and many others. These plants open their stomata during night and close them during the day, just reverse of normal behavior. Closing stomata during day helps these plants to conserve water. During the night, when their stomata are open, these plants take up CO_2 and incorporate it into a variety of organic acids. This mode of carbon dioxide fixation is called **crassulacean acid metabolism** or CAM.

The plants are called CAM plants (CAMP). The CAM plants store these organic acids with CO_2 moving in their vacuoles.

During the day, when the light reactions supply ATP and NADPH_2 for Calvin cycle. These acids release CO_2 to compete with O_2 . In this way ratio of CO_2 maintains inside leaves. This CO_2 is fixed through C_3 cycle.

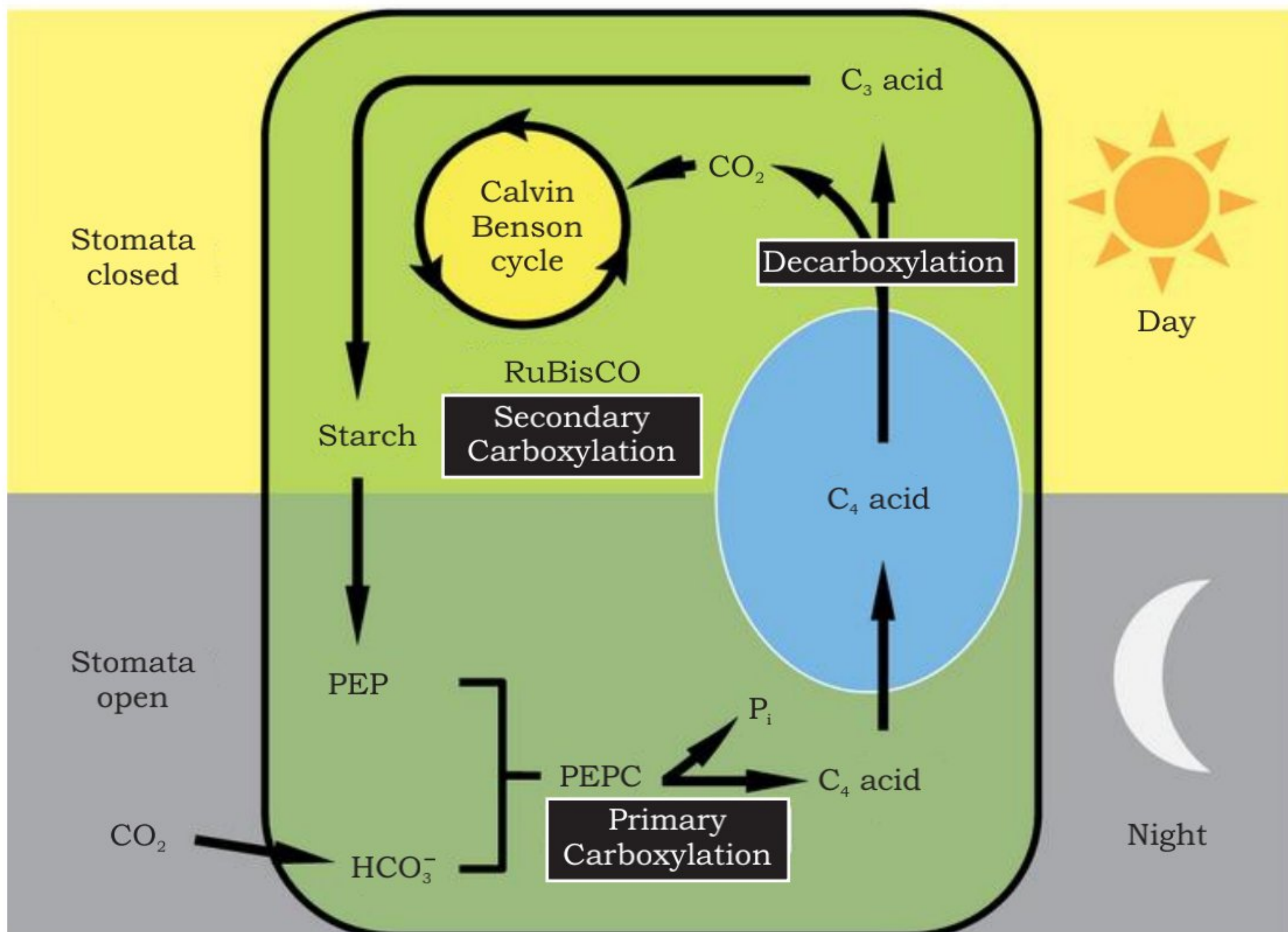


Fig 4.19 Crassulacean acid metabolism



SUMMARY

- Capturing and conversion of energy from one form to another in living system and its utilization in metabolic activities is called bioenergetics.
- Biological energy transformation obeys the laws of thermodynamics.
- The living process where light energy converts into chemical energy (ATP, NADPH₂) and then into energy rich organic food molecules like carbohydrate called photosynthesis.
- Light is a form of energy, has dual nature, described both as a wave and a particle nature.
- Substance in plants that absorb visible light are called pigments.
- Chlorophyll is organized with other molecules into photosystem, which has light gathering “antenna complex”.
- Neil’s hypothesized that the source of oxygen released during photosynthesis is water.
- The first phase of photosynthesis where energy of photon is captured and converted into chemical energy.
- The linear flow of electrons from water to NADP⁺ coupled to ATP synthesis is called non-cyclic photophosphorylation.
- The second phase of photosynthesis, where carbohydrate molecules are formed by fixing atmospheric carbon dioxide.
- Break down of glucose molecules by redox-reaction to synthesis ATP is called respiration.
- Glycolysis is anaerobic break down of glucose into two molecules of pyruvate.
- Oxidation of glucose is completed in the form of oxidation of acetyl. This cyclic series is called kreb’s cycle or citric acid cycle.
- The synthesis of ATP during electron transport chain in the presence of oxygen is called oxidative phosphorylation.
- Sometimes plants oxidized sugar in chloroplast during day time without production of energy or ATP called photorespiration.
- On hot and dry day their stomata remains close to conserve their water
- Some plants develop another metabolic cycle to fix CO₂ in the presence of high oxygen concentration, these plants are called C4 plants



EXERCISE

1. Encircle the correct choice

- (i) Chlorophyll-a is almost identical to chlorophyll-b but slight structural difference between them is enough to give
- (a) Similar energy during the light reaction
 - (b) Different absorptive spectrum
 - (c) Different product during the Calvin cycle
 - (d) All of these
- (ii) Chlorophyll is organized along with other molecules into photosystem, which has light gathering
- (a) Reaction Centre
 - (b) Carotenoid compound
 - (c) Antenna complex
 - (d) Cytochrome
- (iii) Select the correct statement
- (a) PSI and ATP synthase complexes are located in the appressed part of thylakoid.
 - (b) PSI and NADP reductase are located in the appressed part of thylakoid membrane
 - (c) Appressed part Contain NADP reductase and ATP synthase
 - (d) Non appressed (non-stacked) Having PSI
- (iv) The linear flow of electrons from water to NADP^+ coupled to ATP synthesis is
- (a) Cyclic photophosphorylation
 - (b) Non-Cyclic photophosphorylation
 - (c) Chemiosmotic phosphorylation
 - (d) Oxidative phosphorylation
- (v) The intermediate carbon fixing compound in the member of grass family to pass CO_2 to calvin cycle is
- (a) Citric acid
 - (b) Oxaloacetic acid
 - (c) Pyruvic acid
 - (d) Crassulacean acid
- (vi) Oxidative decarboxylation of isocitrate form?
- (a) α -ketoglutarate
 - (b) Succinate
 - (c) Cis-aconitate
 - (d) Fumarate
- (vii) How many ATP molecules are forms during substrate level phosphorylation in kreb's cycle when one glucose is consumed?
- (a) One
 - (b) Two
 - (c) Three
 - (d) Four



- (viii) Enzyme involved during carboxylation
- (a) Rubisco oxygenase
 - (b) Rubisco carboxylase
 - (c) Rubisco dehydrogenase
 - (d) No need of enzyme during carboxylation
- (ix) The oxygen consumed during cellular respiration is involved directly in which process or events?
- (a) Glycolysis
 - (b) Accepting electrons at the end of the electron transport chain
 - (c) The citric acid cycle
 - (d) The oxidation of pyruvate to acetyl CoA
- (x) How many carbon atoms are fed into the citric acid cycle as a result of the oxidation of one molecule of pyruvate?
- (a) 2
 - (b) 4
 - (c) 6
 - (d) 8

2. Write short answers of the following questions:

1. Why antenna complex contains other pigments with chlorophyll?
2. Why photosynthesis is called redox process?
3. How cyclic photophosphorylation helpful in photosynthesis?
4. Why ATP is called common energy currency of living system?
5. Why Calvin cycle is also called C₃ cycle?
6. Why CAM plant close stomata in day time?
7. Why oxidation of pyruvate provide more energy than lactic acid fermentation?

3. Write detailed answers of the following questions:

1. Explain in detail light independent phase of photosynthesis.
2. What is cellular respiration? Explain types of respiration in detail.
3. Explain event takes place in breaking of glucose in cytosol.
4. Discuss cyclic and non-cyclic photophosphorylation during light reaction.
5. Describes tricarboxylic acid cycle in detail.
6. Explain alternative mechanism of CO₂ fixation in plant
7. Explain chemiosmosis and oxidative phosphorylation.