

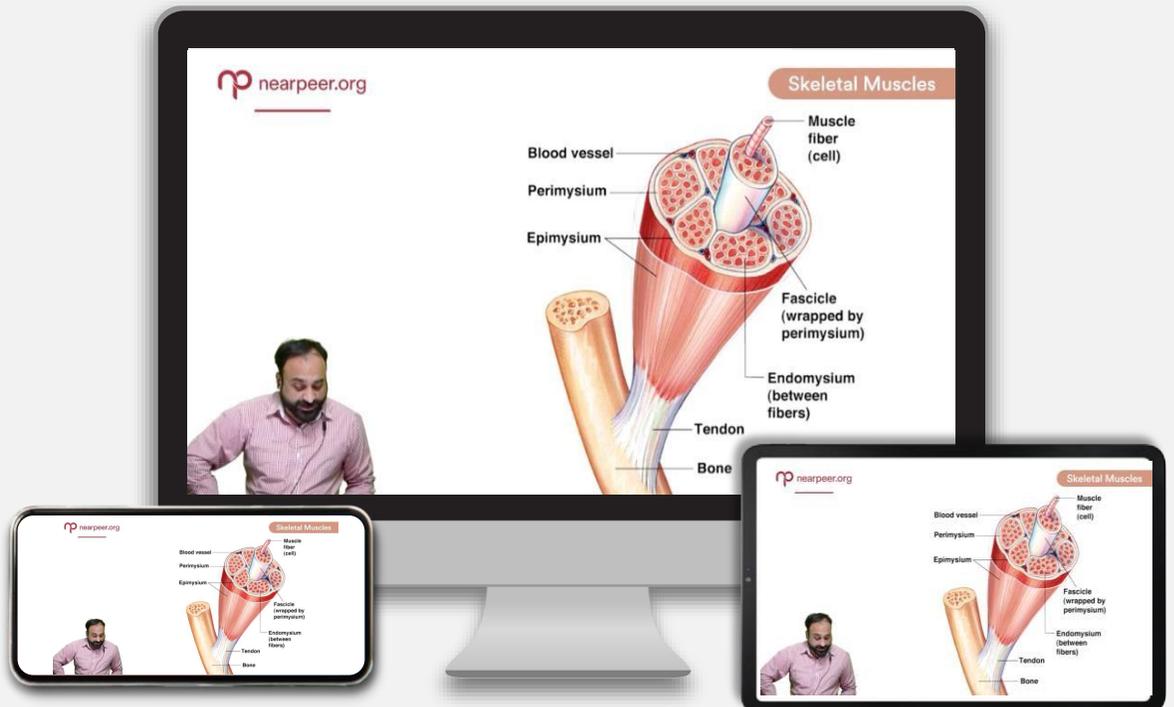
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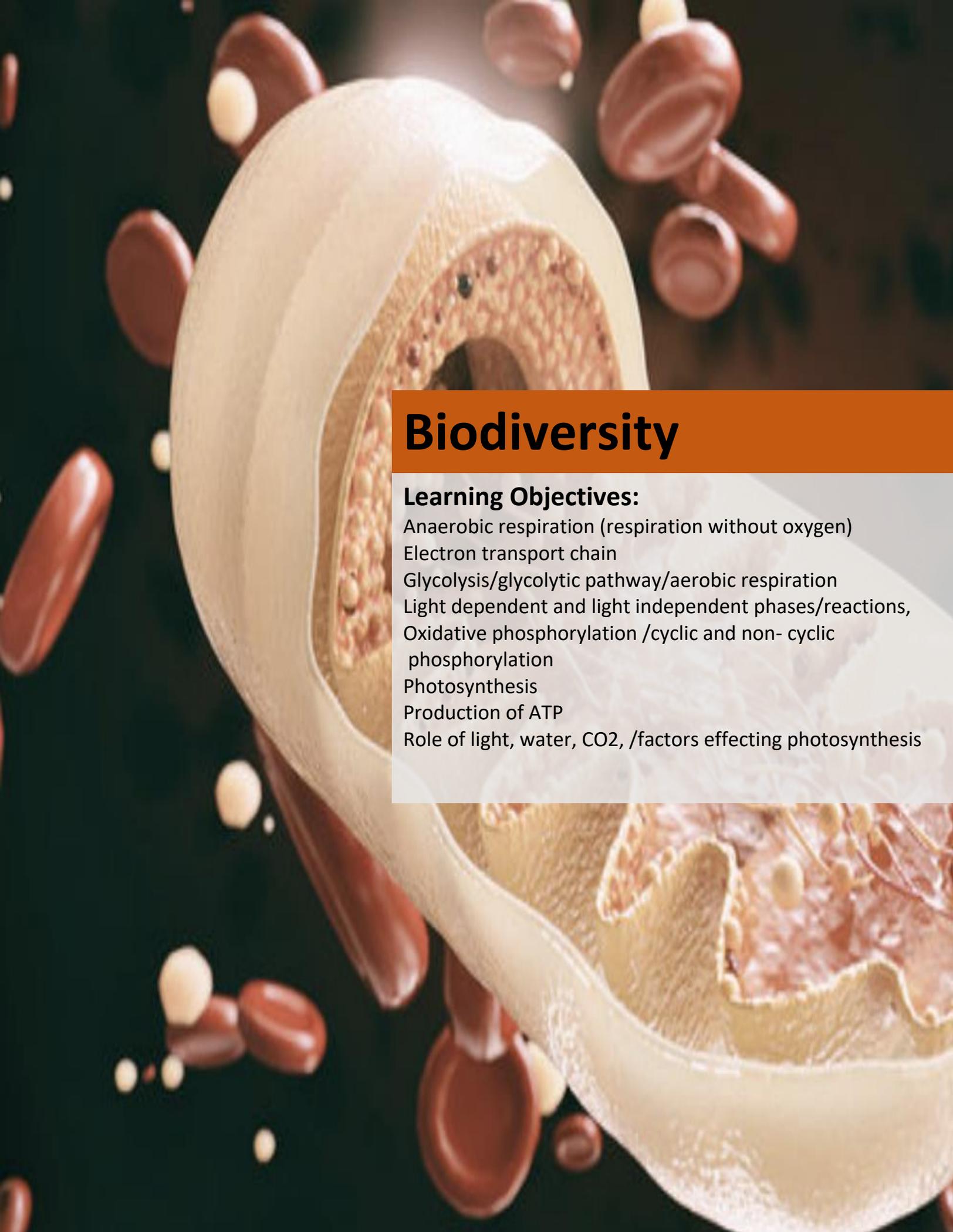
Biology

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Biodiversity

Learning Objectives:

Anaerobic respiration (respiration without oxygen)

Electron transport chain

Glycolysis/glycolytic pathway/aerobic respiration

Light dependent and light independent phases/reactions,

Oxidative phosphorylation /cyclic and non- cyclic phosphorylation

Photosynthesis

Production of ATP

Role of light, water, CO₂, /factors effecting photosynthesis

Bioenergetics

Bioenergetics is the quantitative study of energy relationships and energy conversions in biological systems. Biological energy transformations obey the laws of thermodynamics.

Chemical energy

All organisms need free energy for keeping themselves alive and functioning. All life on this planet Earth is powered, directly or indirectly, by solar energy. But no organism can make direct use of sunlight as source of energy for metabolism; all can use chemical energy in the food such as sugars etc. The chloroplasts of the plants capture light energy coming from the sun and convert it into chemical energy that gets stored in sugar and then in other organic molecules.

ATP a Chemical Link

With the emergence of photosynthesis on earth, molecular oxygen began to accumulate slowly in the atmosphere. The presence of free oxygen made possible the evolution of respiration. Respiration releases great deal of energy, and couples some of this energy to the formation of adenosine triphosphate (ATP) molecules. ATP is a kind of chemical link between **catabolism** and **anabolism**.

Photosynthesis

The process of photosynthesis helps understand some of the principles of energy transformation (**Bioenergetics**) in living systems. Photosynthetic organisms (higher land plants for instance) use solar energy to synthesize organic compounds (such as carbohydrates) that can not be formed without the input of energy.

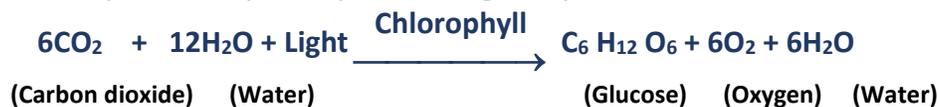
Respiration

Energy stores in these molecules can be used later to power cellular processes and can serve as the energy source for all forms of life. Whereas photosynthesis provides the carbohydrate substrate, **glycolysis** and respiration are the processes where by the energy stores in carbohydrate is released in a controlled manner. So the photosynthesis acts as an energy-capturing while respiration as an energy releasing process.

Photosynthesis

(Conversion of solar energy into chemical energy)

Photosynthesis can be defined as the process in which energy-poor inorganic oxidized compounds of carbon (i.e. CO₂) and hydrogen (i.e. mainly water) are reduced to energy-rich carbohydrate (i.e. sugar-glucose) using the light energy that is absorbed and converted into chemical energy by chlorophyll and some other photosynthetic pigments. The process of photosynthesis in green plants can be summarized as:



Photosynthetic Reactants and Products

From above overall reaction of photosynthesis it become evident that carbon dioxide, water and light are the reactants while glucose and oxygen are the products. Water appears on both sides of the equation because water is used as reactant in some reactions and released as product in other. However, because there is no net yield of H₂O.

Equation of Photosynthesis

We can simplify the summary equation of photosynthesis for purpose of discussion:



This is almost exactly opposite to the overall equation of aerobic respiration



Photosynthesis uses the products of respiration and respiration uses the products of photosynthesis. There is another important difference between the two processes: Photosynthesis occurs only during day time, whereas respiration goes on day and night.

During darkness

During darkness leaves (and other actively metabolizing cells) respire and utilize oxygen and release carbon dioxide.

At dawn and dusk

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

During day time

As the light intensity increases, so does the rate of photosynthesis and hence the requirement for more carbon dioxide increases which respiration alone cannot supply. Similarly, the oxygen produced during photosynthesis is more than the need of the respiring cells, so the result is the net release of oxygen coupled with the uptake of carbon dioxide.

Neil's Hypothesis

Water and Photosynthesis

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

Van Neil's Hypothesis

In 1930s, Van Neil's hypothesized that plants split water as a source of hydrogen, releasing oxygen as a by-product. Neil's hypothesis was based on his investigations on photosynthesis in bacteria that make carbohydrate from carbon dioxide, but do not release oxygen.

Experimental verification

Neil's hypothesis that source of oxygen released during photosynthesis is water and not carbon dioxide, was later confirmed by scientists during 1940s when first use of an isotopic tracer (O^{18}) in biological research was made. Water and carbon dioxide containing heavy-oxygen isotope O^{18} were prepared in the laboratory. Experimental green plants in one group were supplied with H_2O containing O^{18} and with CO_2 containing common oxygen O^{16} . Plants in the second group were supplied with H_2O containing common oxygen O^{16} but with CO_2 containing O^{18} .

It was found that plants of first group produced O^{18} but the plants of second group did not.



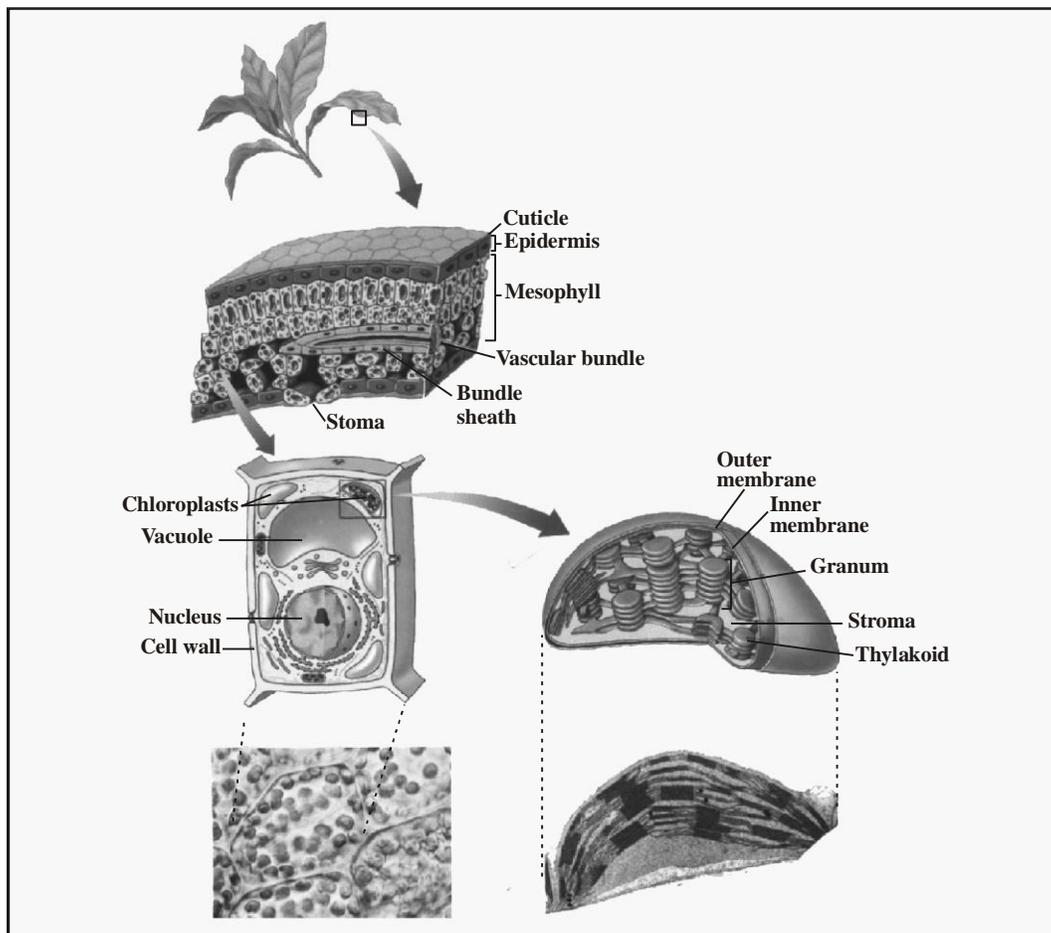
Confirmation of Neil's hypothesis

Water is thus one of the raw materials of photosynthesis, other being carbon dioxide. Hydrogen produced by splitting of water reduces NADP to $NADPH_2$ ($NADPH + H^+$).

$NADPH_2$ is the "reducing power" which, along with ATP also formed during '**light reaction**', is used to reduce CO_2 to form sugar during '**dark reaction**'.

Chloroplasts – The Sites of Photosynthesis in Plants

All green parts of a plant have chloroplasts, but the leaves are the major sites of photosynthesis in most plants.



Number of Chloroplast

Chloroplasts are present in very large number, about half a million per square millimeter of leaf surface. Chloroplasts are present mainly in the cells of mesophyll tissue inside the leaf. Each mesophyll cell has about 20-100 chloroplasts.

Structure of chloroplast

Chloroplast has a double membrane envelope that encloses dense fluid-filled region, the stroma which contains most of the enzymes required to produce carbohydrate molecules. Another system of membranes is suspended in the stroma.

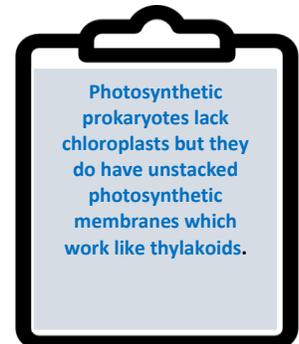
Thylakoid and Grana

These membranes form an elaborate interconnected set of flat, disc like sacs called **thylakoids**. The thylakoid membrane encloses a fluid-filled '**thylakoid interior-space**' or **lumen**, which is separated from the stroma by thylakoid membrane. In some places, thylakoid sacs are stacked in columns called **grana** (sing **granum**).

Role of Thylakoid

Chlorophyll (and other photosynthetic pigments) are found embedded in the thylakoid membranes and impart green colour to the plant. Electron acceptors of photosynthetic 'Electron Transport Chain' are also parts of these membranes. Thylakoid membranes are thus involved in ATP synthesis by **chemiosmosis**.

Chlorophyll (and other pigments) absorb light energy, which is converted into chemical energy of ATP and NADPH, the products which are used to synthesize sugar in the stroma of chloroplast.



Photosynthetic Pigments

Pigments

Light can work in chloroplasts only if it is absorbed. Pigments are the substances that absorb visible light (380-750) nm in wave length). Different pigments absorb light of different wave lengths (colours), and the wave lengths that are absorbed disappear.

Spectrophotometer

An instrument called **Spectrophotometer** is used to measure relative abilities of different pigments to absorb different wavelengths of light.

Absorption spectrum

A graph plotting absorption of light of different wave lengths by a pigment is called **absorption spectrum** of the pigment.

Kinds of Photosynthetic Pigments

- ◆ Thylakoid membranes contain several kinds of pigments, but **chlorophylls** are the main photosynthetic pigments.
- ◆ Other, accessory photosynthetic pigments present in the chloroplasts include yellow and red to orange **carotenoids**; **carotenes** are mostly red to orange and xanthophylls are yellow to orange. These broaden the absorption and utilization of light energy.

Chlorophylls

There are known many different kinds of chlorophylls. Chlorophyll a, b, c and d are found in eukaryotic photosynthetic plants and algae, while the other are found in photosynthetic bacteria and are known as **bacteriochlorophylls**.

Absorption range

Chlorophylls absorb mainly violet-blue and orange-red wave lengths. Green, yellow and indigo wave lengths are least absorbed by chlorophylls and are transmitted or reflected, although the yellows are often masked by darker green colour. Hence plants appear green, unless masked by other pigments (Fig. 11.4).

Structure of chlorophyll

A chlorophyll molecule has two main parts.

Porphyrin head

One flat, square, light absorbing hydrophilic head and the other long, anchoring, hydrophobic hydrocarbon tail. The head is complex **porphyrin ring** which is made up of 4 joined smaller pyrrole rings composed of carbon and nitrogen atoms. An atom of magnesium is present in the center of porphyrin ring and is coordinated with the nitrogen of each pyrrole ring (Fig. 11.2) That is why magnesium deficiency causes yellowing in plants.

Haem portion of haemoglobin is also a porphyrin ring but containing an iron atom instead of magnesium atom in the center.

Phytol tail

Long hydrocarbon tail which 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.

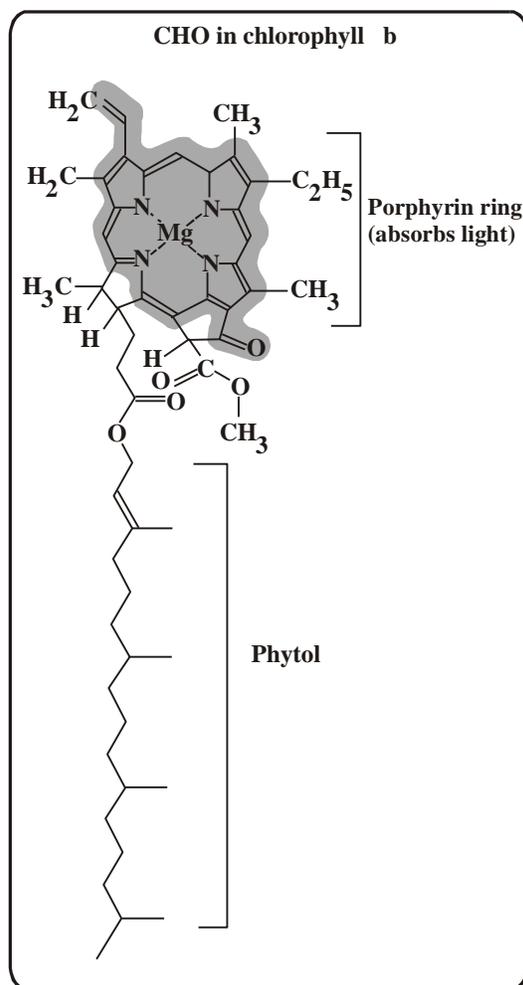
Difference between chlorophyll a and b

Chlorophyll a and chlorophyll b differ from each other in only one of the functional groups bonded to the porphyrin; the methyl group ($-CH_3$) in chlorophyll a is replaced by a terminal carbonyl group ($-CHO$) in chlorophyll b.

The molecular formulae for chlorophyll a and b are:

- ◆ Chlorophyll a : $C_{55}H_{72}O_5N_4Mg$
- ◆ Chlorophyll b : $C_{55}H_{70}O_6N_4Mg$

Due to this slight difference in their structure, the two chlorophylls show slightly different absorption spectra and hence different colours. Some wave lengths not absorbed by chlorophyll a are very effectively absorbed by chlorophyll b and vice-versa.



Such differences in structure of different pigments increase the range of wave lengths of the light absorbed. Chlorophyll a is blue-green while chlorophyll b is yellow-green.

Most abundant and important

Of all the chlorophylls, chlorophyll a is the most abundant and the most important photosynthetic pigment as it takes part directly in the light-dependent reactions which convert solar energy into chemical energy. It is found in all photosynthetic organisms except photosynthetic bacteria. Chlorophyll a itself exists in several forms differing slightly in their red absorbing peaks e.g. at 670, 680, 690, 700 nm.

Chlorophyll b is found along with chlorophyll a in all green plants (embryophytes) and green algae.

Chlorophylls are insoluble in water but soluble in organic solvents, such as carbon tetrachloride, alcohol etc.

Carotenoids-accessory pigments

Carotenoids are yellow and red to orange pigments that absorb strongly the blue-violet range, different wave lengths than the chlorophyll absorbs. So they broaden the spectrum of light that provides energy for photosynthesis.

Role of Accessory Pigments

These and chlorophyll b are called **accessory pigments** because they absorb light and transfer the energy to chlorophyll a, which then initiates the light reactions. It is generally believed that the order of transfer of energy is:

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

Some carotenoids protect chlorophyll from intense light by absorbing and dissipating excessive light energy, rather than transferring energy to chlorophyll. (Similar carotenoids may be protecting humans eye).

Light – The Driving Energy

Light is a form of energy called electromagnetic energy or radiations. Light behaves as waves as well as sort of particles called **photons**. The radiations most important to life are the **visible light** that ranges from about 380 to 750 nm in wave length.

It is the sunlight energy that is absorbed by chlorophyll, converted into chemical energy, and drives the photosynthetic process. Not all the light falling on the leaves is absorbed. Only about one percent (1%) of the light falling on the leaf surface is absorbed, the rest is reflected or transmitted.

Absorption spectrum

Absorption spectrum for chlorophylls (Fig. 11.4) indicates that absorption is maximum in blue and red parts of the spectrum, two absorption peaks being at around 430 nm and 670 nm respectively. Absorption peaks of carotenoids are different from those of chlorophylls.

Action spectrum

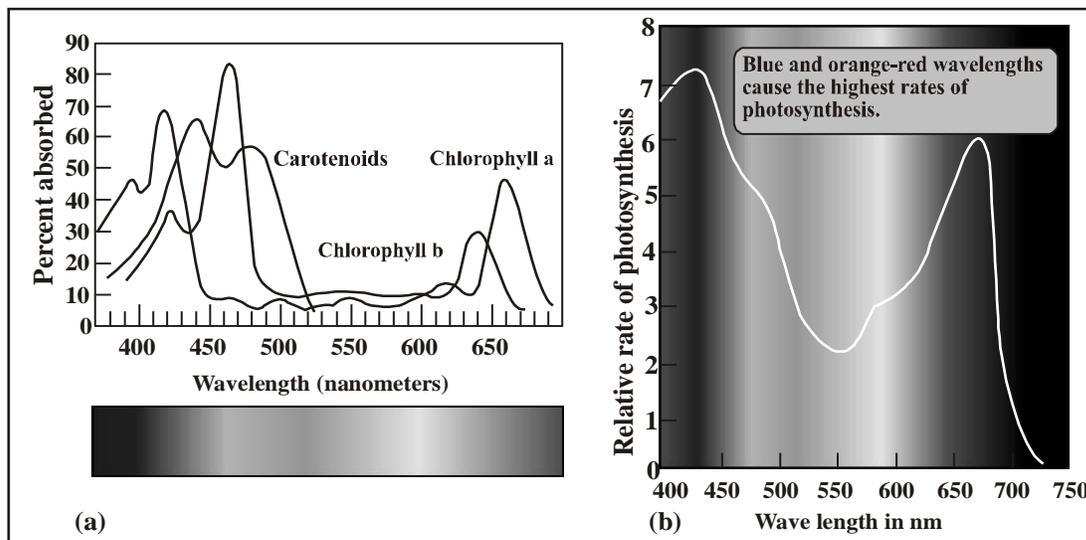
Different wavelengths are not only differently absorbed by photosynthetic pigments but are also differently effective in photosynthesis.

Graph showing relative effectiveness of different wavelengths (colours) of light in driving photosynthesis is called action spectrum of photosynthesis.

First action spectrum

The first action spectrum was obtained by German biologist, T.W.Engelmann in 1883. He worked on Spirogyra.

Action spectrum can be obtained by illuminating plant with light of different wavelengths (or colours) and then estimating relative CO₂ consumption or oxygen release.



during photosynthesis.

- Absorption spectrum of chlorophyll and carotenoids.
- Action spectrum for photosynthesis.

As is evident from above figure 11.4, action spectrum of photosynthesis corresponds to absorption spectrum of chlorophyll. The same two peaks and the valley

are obtained for absorption of light as well as for CO₂ consumption. This also shows that chlorophyll is the photosynthetic pigment.

Difference Between Absorption and Action Spectrum

However, the action spectrum of photosynthesis does not parallel the absorption spectrum of chlorophyll exactly. Compared to the peaks in absorption spectrum, the peaks in action spectrum are broader, and the valley is narrower and not as deep.

(Photosynthesis in the most absorbed range is more than the absorption itself. Likewise, photosynthesis in 500-600 nm (including green light) is more than the absorption of green light by the chlorophyll).

Accessory Pigments

This difference occurs because the accessory pigments, the carotenoids, absorb light in this zone and pass on some of the absorbed light to chlorophylls which then convert light energy to chemical energy.

- ◆ When equal intensities of light are given there is more photosynthesis in red than in blue part of spectrum.

Role of Carbon Dioxide:

A Photosynthetic Reactant:

Sugar is formed during **light – independent reactions** of photosynthesis by the reduction of CO₂, using ATP and NADPH, the products of **light – dependent reactions**. Obviously photosynthesis does not occur in the absence of CO₂.

CO₂ from water or air

About 10 percent of total photosynthesis is carried out by terrestrial plants, the rest occurs in oceans, lakes and ponds. Aquatic photosynthetic organisms use dissolved CO₂, bicarbonates and soluble carbonates that are present in water as carbon source. Air contains about 0.03 – 0.04 percent CO₂. Photosynthesis occurring on land utilizes this atmospheric CO₂.

Stomata

Carbon dioxide enters the leaves through **stomata** and gets dissolved in the water absorbed by the cell walls of mesophyll cells. Stomata are found in a large number in a leaf; their number being proportional to the amount of gas diffusing into the leaf. Stomata cover only 1 – 2 percent of the leaf surface but they allow proportionality much more gas to diffuse.

Opening of stomata

The entry of CO₂ into the leaves depends upon the opening of stomata. The guard cells guarding the stoma, because of their peculiar structure and changes in their shape, regulate the opening and closing of stomata.

Stomata are adjustable pores that are usually open during the day when CO₂ is required for photosynthesis and partially closed at night when photosynthesis stops.

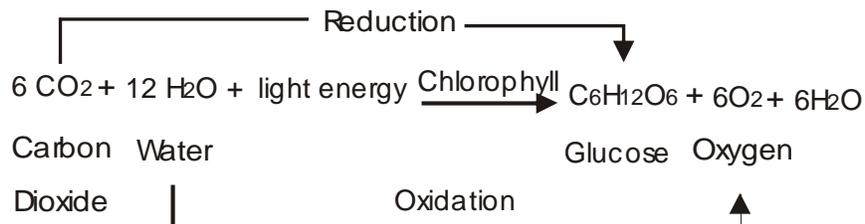
Rhythmic opening and closing of stomata

- ◆ Daily rhythmic opening and closing of stomata is also due to an internal clock located in the guard cells.
- ◆ Even if a plant is kept in a dark closet, stomata will continue their daily rhythm of opening and closing.

Reactions of Photosynthesis

Redox Process

Photosynthesis is a '**redox process**' that can be represented by the following simplified summary equation:



However, it is not a simple, single step process, but is a complex one that is completed by a series of simple steps or reactions. These reactions of photosynthesis consist of two parts:

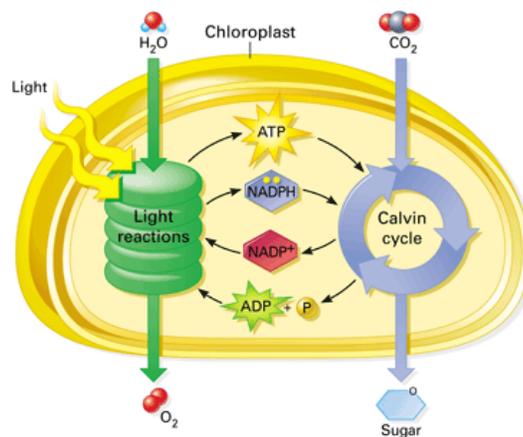
The light-dependent reactions (light reactions) which use light directly and

The light-independent reactions (dark reactions) which do not use light directly.

Light reactions

Light dependent reactions constitute that phase of photosynthesis during which light energy is absorbed by chlorophyll and other photosynthetic pigment molecules and converted into chemical energy. As a result of this energy conversion, **reducing** and **assimilating power** in the form of NADPH_2 ($\text{NADPH} + \text{H}^+$) and ATP, are formed, both temporarily storing energy to be carried along with H to the light independent reactions.

Dark reactions



NADPH_2 provides energized electron (and H^+), while ATP provides chemical energy for the synthesis of sugar by reducing CO_2 , using reducing power and chemical energy of NADPH_2 and ATP respectively, produced by light reactions. The energy is thus stored in the molecules of sugar. This phase of photosynthesis is also called **dark reactions** because these reactions do not use light directly and can take place equally well both in light and dark provided NADPH_2 and ATP of light reactions are available.

An overview of photosynthesis: Light – Depend Reactions (Energy – conversion) and Light – Independence Reactions (Energy – conservation)

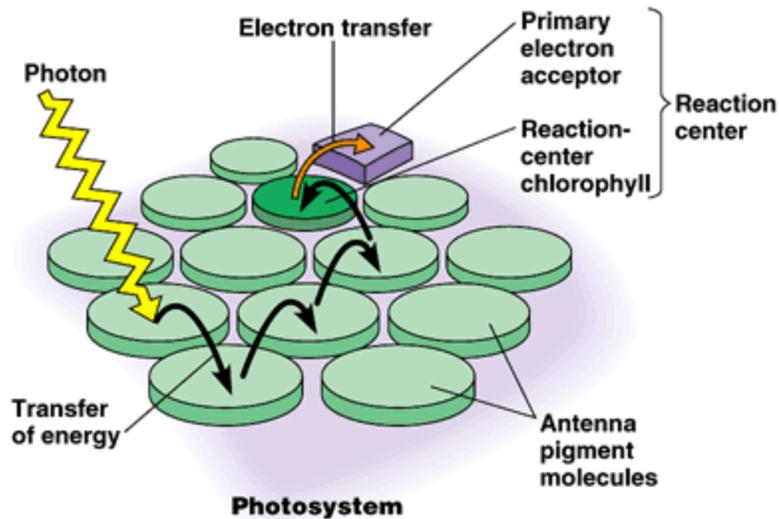
Light Dependent Reactions

(Energy-Conversion Phase; Formation of ATP and NADPH)

Photo System

As has been described previously, sunlight energy which is absorbed by photosynthetic pigments drives the process of photosynthesis. Photosynthetic pigments

are organized into clusters, called **photosystems**, for efficient absorption and utilization of solar energy thylakoid membranes.



Light harvesting photosystem. Energy of light (photon) absorbed by photosynthetic pigment molecules is transferred from molecule to molecule, and finally reaches the reaction center where actual energy conversion begins.

Each **photosystem** consists of a light-gathering '**antenna complex**' and a '**reaction centre**'.

Antenna Complex

The antenna complex has many molecules of chlorophyll a, chlorophyll b and carotenoids, most of them channeling the energy to reaction center.

Reaction Center

Reaction center has one or more molecules of chlorophyll a along with a **primary electron acceptor**, and associated electron carriers of '**electron transport system**'. Chlorophyll a molecules of reaction center and associated proteins are closely linked to the nearby electron transport system. Electron transport system plays role in generation of ATP by **chemiosmosis**. Light energy absorbed by the pigment molecules of antenna complex is transferred ultimately to the reaction center. There the light energy is

converted into chemical energy.

Types of Photo System

There are two photosystems, **photosystem I (PS I)** and **photosystem II (PS II)**. These are named so in order of their discovery.

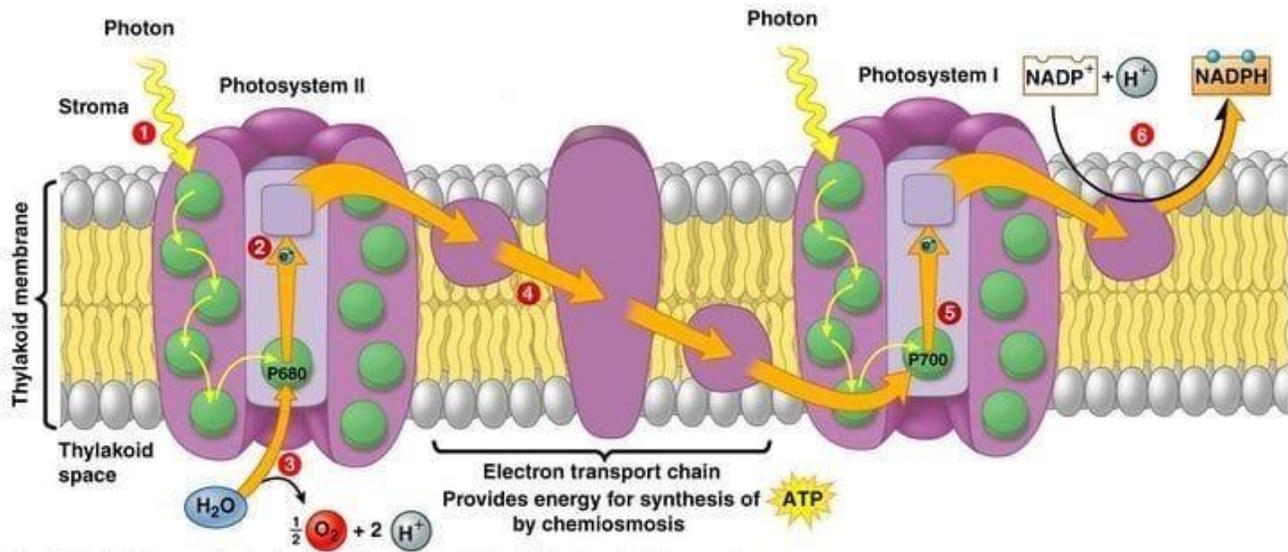


Photo system I

Photo-system I has chlorophyll a molecule which absorbs maximum light of 700 nm and is called **P₇₀₀**, **Photo-system II** whereas reaction center of photo-system II has P₆₈₀, the form of chlorophyll a which absorbs best the light of 680 nm. A specialized molecule called, **primary electron acceptor** is also associated nearby each reaction centre. This acceptor traps the high-energy electrons from the reaction center and then passes them on to the series of electron carriers. During this energy is used to generate ATP by chemiosmosis.

Non-Cyclic Electron Flow

In predominant type of electron transport called **non-cyclic electron flow**, the electrons pass through the two photo systems. In less common type of path called cyclic **electron flow** only photo system I is involved. Formation of ATP during non-cyclic electron flow is called **non-cyclic phosphorylation** while that during cyclic electron flow is called **cyclic phosphorylation**.

Non-cyclic Phosphorylation

1. Absorption of light by photo system II

When photo system II absorbs light, an electron excited to a higher energy level in the reaction centre chlorophyll P_{680} is captured by the primary electron acceptor of PS II. The oxidized chlorophyll is now a very strong oxidizing agent; its electron “hole” must be filled.

2. Photolysis of water

This hole is filled by the electrons which are extracted, by an enzyme, from water. This reaction splits a water molecules into two hydrogen ions and an oxygen atom, which immediately combines with another oxygen atom to form O_2 . This water splitting step of photosynthesis that releases oxygen is called **photolysis**. The oxygen produced during photolysis is the main source of replenishment of atmospheric oxygen.

3. 1st Electron transport chain

Each photoexcited electron passes from the primary electron acceptor of photo system II to photo system I via an **electron transport chain**. This chain consists of an electron carrier called **plastoquinone** (Pq), a complex of two **cytochromes** and a copper containing protein called **plastocyanin** (Pc).

4. Photophosphorylation

As electrons move down the chain, their energy goes on decreasing and is used by thylakoid membrane to produce ATP. This ATP synthesis is called **photophosphorylation** because it is driven by light energy. Specifically, ATP synthesis during non-cyclic electron flow is called **non-cyclic photophosphorylation**. This ATP generated by the light reactions will provide chemical energy for the synthesis of sugar during the Calvin cycle, the second major stage of photosynthesis.

5. Filling of electron hole of PSI

The electron reaches the “bottom” of the electron transport chain and fills an electron “hole” in P_{700} , the chlorophyll a molecules in the reaction center of photosystem I. This hole is created when light energy is absorbed by molecules of P_{700} and drives an electron from P_{700} to the primary acceptor of photo system I.

6. 2nd electron transport chain

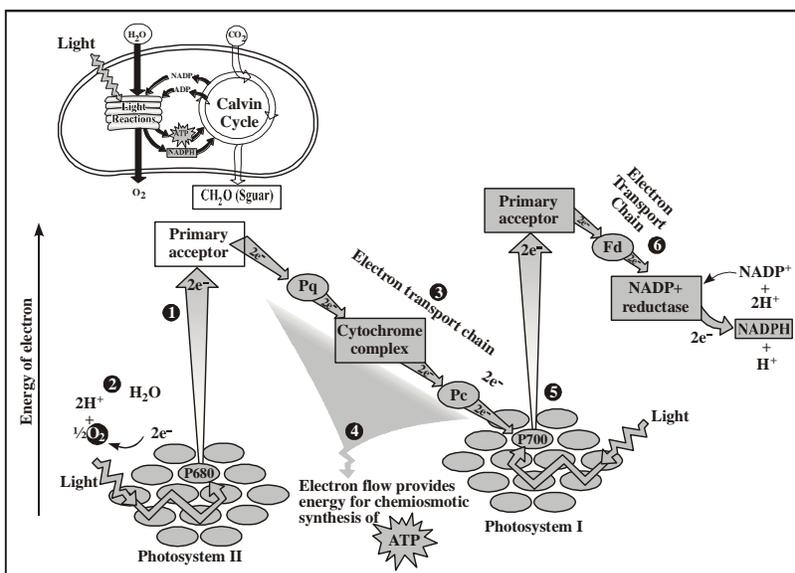
The primary electron acceptor of photo system I passes the photoexcited electrons to a second electron transport chain, which transmits them to **ferredoxin (Fd)**, an iron containing protein. An enzyme called NADP reductase then transfers the

electrons from **Fd to NADP**. This is the redox reaction that stores the high-energy electrons in NADPH. The NADPH molecule will provide reducing power for the synthesis of sugar in the Calvin cycle.

The path of electrons through the two photosystems during non-cyclic photophosphorylation is known as **Z-scheme** from its shape.

Products of Z-scheme

Non-cyclic electron flow during photosynthesis generates ATP, NADPH and oxygen. (Each photon of light excite single electron).



Non-cyclic electron flow during photosynthesis ATP, NADPH and oxygen are generated. The arrows trace the current of light-driven electrons from water to NADPH. Each photon of light excites single electron, but the diagram tracts two electrons at a time, the number of electrons required to reduce NADP+. The numbered steps are described in the text.

Cyclic Phosphorylation

Under certain conditions, photoexcited electrons take an alternative path called **cyclic electron flow**. This path uses photosystem I but not photosystem II.

Conditions for non-cyclic phosphorylation

Possibly it happens when

- The chloroplast runs low on ATP for the Calvin cycle.
- The cycle slows down
- NADPH accumulate in chloroplast.

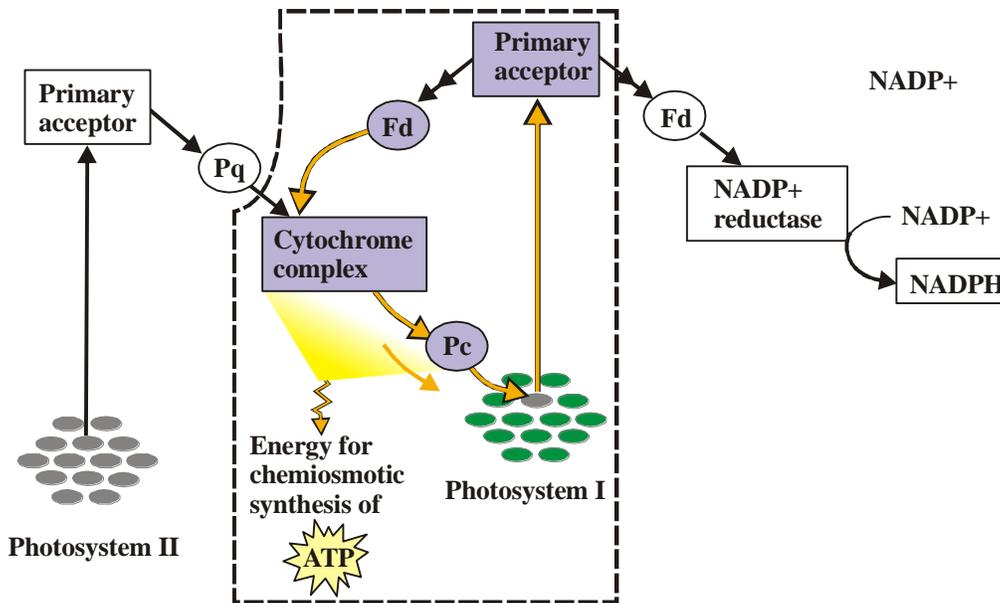
This rise in NADPH may stimulate a temporary shift from non-cyclic to **cyclic electron flow** until ATP supply meets the demand.

Short Circuit

The cyclic flow is short circuit: The electrons cycle back from primary electron acceptor to **ferredoxin (Fd)** to the **cytochrome complex** and from there continue on to the P700 chlorophyll. ATP is generated by the coupling of ETC by chemiosmosis.

Products of non-cyclic flow

- ◆ There is no production of NADPH and no release of oxygen.
- ◆ Cyclic flow does, however, generate ATP. This is called cyclic photosynthesis.



Cyclic electron flow in box. Only PS I involved. ATP is generated but no NADPH and oxygen.

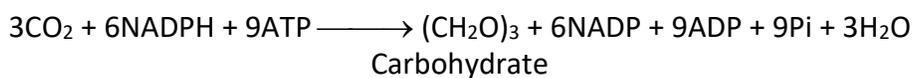
Light Independent (Or Dark) Reactions

Calvin cycle: carbon fixation and reduction phase, synthesis of sugar

The dark reactions take place in the stroma of chloroplast. These reactions do not require light directly and can occur in the presence or absence of light provided the assimilatory power in the form of ATP and NADPH, produced during light reactions is available. Energy of these compounds is used in the formation of carbohydrates from CO₂, and thus stored their in.

Equation of Calvin cycle

These reactions can be summarized as follows :



Discovery of Calvin Cycle

The details of path of carbon in these reactions were discovered by Melvin Calvin and his colleagues at the University of California. Calvin was awarded Nobel Price in 1961.

The cyclic series of reactions, catalyzed by respective enzymes, by which the carbon is fixed and reduced resulting in the synthesis of sugar during the dark reactions of photosynthesis is called **Calvin Cycle**.

Phase of Calvin Cycle

The **Calvin cycle** can be divided into three phases:

- ◆ Carbon fixation
- ◆ Reduction
- ◆ Regeneration of CO₂ acceptor (RUBP) (Fig 11.10).

Phase 1: Carbon fixation

Carbon fixation refers to the initial incorporation of CO₂ into organic material. Keep in mind that we are following three molecules of CO₂ through the reaction (because 3 molecules of CO₂ are required to produce one molecule of carbohydrate, a triose). The Calvin cycle begins when a molecule of CO₂ reacts with a highly reactive phosphorylated five – carbon sugar named **ribulose biphosphate (RUBP)**.

Rubisco

This reaction is catalyzed by the enzyme **ribulose biphosphate carboxylase**, also known as **Rubisco** (it is the most abundant protein in chloroplasts, and probably the most abundant protein on Earth). The product of this reaction is an highly unstable, six – carbon intermediate that immediately breaks into two molecules of three – carbon

compound called **3 – phosphoglycerate (phosphoglyceric acid-PGA)**. The carbon that was originally part of CO₂ molecule is now a part of an organic molecule; the carbon has been “fixed”. Because the product of initial carbon fixation is a three – carbon compound, the Calvin cycle is also known as **C₃ pathway**.

Phase 2: Reduction:

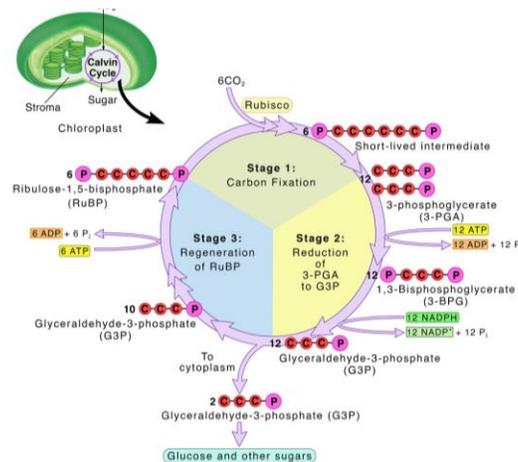
Each molecule of (PGA) receives an additional phosphate from ATP of light reaction, forming **1,3 – bisphosphoglycerate** as the product. 1,3 bisphosphoglycerate is reduced to **glyceraldehyde 3-phosphate (G3P)** by receiving a pair of electrons donated from NADPH of light reactions. G3P is the same three-carbon sugar which is formed in glycolysis (first phase of cellular respiration) by the splitting of glucose. In this way fixed carbon is reduced to energy rich G3P with the energy and reducing power of ATP and NADPH (both the products of light-dependent reactions), having the energy stored in it. Actually G3P, and not glucose, is the carbohydrate produced directly from the Calvin cycle. For every three molecules of CO₂ entering the cycle and combining with 3 molecules of five-carbon RuBP, six molecules of G3P can be counted as a net gain of carbohydrate. Out of every six molecule of G3P formed, only one molecule leaves the cycle to be used by the plant for making glucose, sucrose starch or other carbohydrates, and other organic compounds; the other five molecules are recycled to regenerate the three molecules of five-carbon RuBP, the CO₂ acceptor.

Phase 3: Regeneration of CO₂ acceptor, RuBP:

Through a complex series of reactions, the carbon skeletons of five molecules of three-carbon G3P are rearranged into three molecules of five-carbon **ribulose phosphate (RuP)**. Each RuP is phosphorylated to ribulose bisphosphate (RuBP), the very five-carbon CO₂ acceptor with which the cycle started. Again three more molecules of ATP of light reactions are used for this phosphorylation to three RuP molecules. These RuBP are now prepared to receive CO₂ again, and the cycle continues.

Respiration

Living organisms need energy to carry on their vital activities. This energy is provided from within the cells by the phenomenon of respiration. Respiration is the



universal process by which organisms' breakdown complex compounds containing carbon in a way that allows the cells to harvest a maximum of usable energy.

Two ways of Respiration

In biology the term respiration is used in two ways.

- ◆ External respiration
- ◆ Cellular respiration

External Respiration

More familiarly the term respiration means the exchange of respiratory gases (CO₂ and O₂) **between** the organism and its environment. This exchange is called **external respiration**.

Cellular Respiration

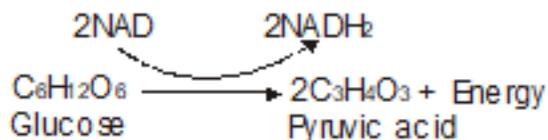
The cellular respiration is the process by which energy is made available to cells in a step by step breakdown of C-chain molecules in the cells.

Aerobic and Anaerobic Respiration

The most common fuel used by the cell to provide energy by cellular respiration is glucose.

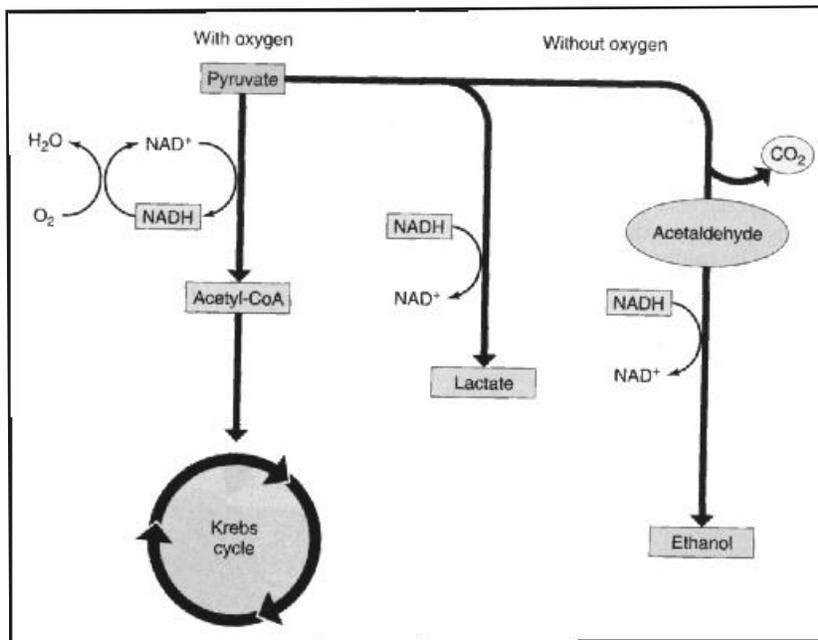
Glycolysis (1st step of cellular respiration)

The way glucose is metabolized depends on the availability of oxygen. Prior to entering a mitochondrion, the glucose molecule is split to form two molecules of pyruvic acid. This reaction is called glycolysis (glycolysis literally means splitting of sugar), and occurs in the cytosol and is represented by the equation:



This reaction occurs in all the cells and biologists believe that an identical reaction may have occurred in the first cell that was organized on earth.

The next step in cellular respiration varies depending on the type of the cell and the prevailing conditions



pyruvate, the end product of glycolysis, follows different catabolic pathways depending on the organisms and the metabolic condition.

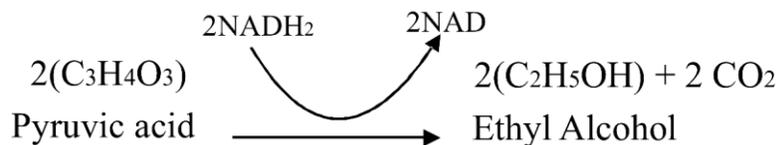
Pyruvic Acid

Cell processes pyruvic acid in three major ways:

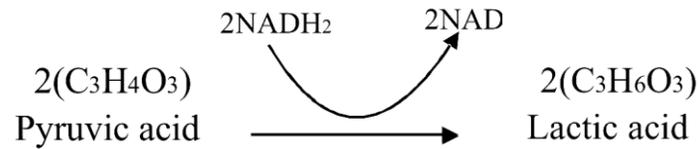
- ◆ Alcoholic fermentation
- ◆ Lactic acid fermentation
- ◆ Aerobic respiration.

The first two reactions occur in the absence of oxygen and are referred to as anaerobic (without oxygen). The complete breakdown of glucose molecule occurs only in the presence of oxygen, i.e. in aerobic respiration. During aerobic respiration glucose is oxidized to CO₂ and water and energy is released.

(i) **Alcoholic Fermentation:** In primitive cells and in some eukaryotic cells such as yeast, pyruvic acid is further broken down by alcoholic fermentation into alcohol (C₂ H₅ OH) and CO₂.



- (ii) **Lactic acid fermentation:** In lactic acid fermentation, each pyruvic acid molecule is converted into lactic acid $C_3H_6O_3$ in the absence of oxygen gas:



This form of anaerobic respiration occurs in muscle cells of humans and other animals during extreme physical activities, such as sprinting, when oxygen cannot be transported to the cells as rapidly as it is needed.

Energy yield

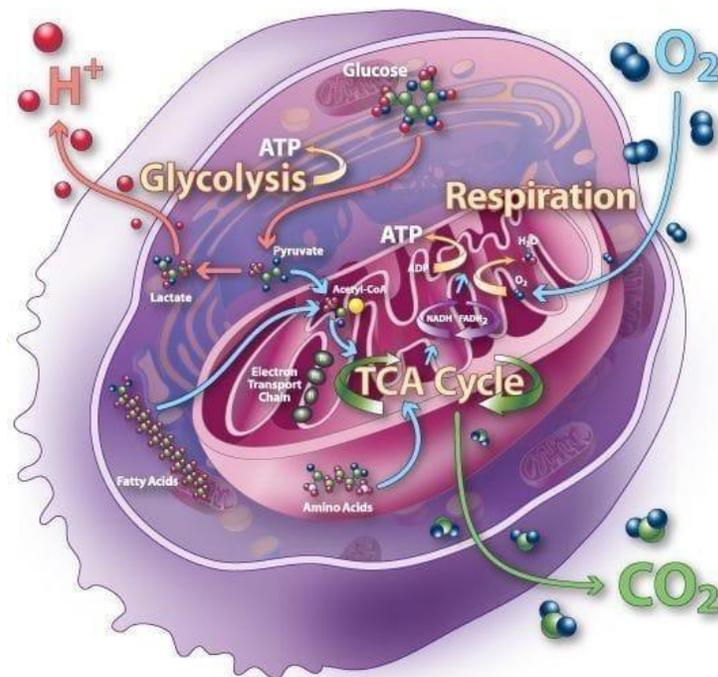
Both alcoholic and lactic acid fermentations yield relatively small amounts of energy from glucose molecule. Only about 2% of the energy present within the chemical bonds of glucose is converted into adenosine triphosphate (ATP).

Aerobic respiration (Discussed in detail under cellular respiration)

Role of Mitochondria In Respiration

Structure

Mitochondria are large granular or filamentous organelles that are distributed throughout the cytoplasm of animals and plant cells. Each mitochondrion is constructed of an outer enclosing membrane and an inner membrane with elaborate folds or **cris**tae that extend into the interior of the organelle.

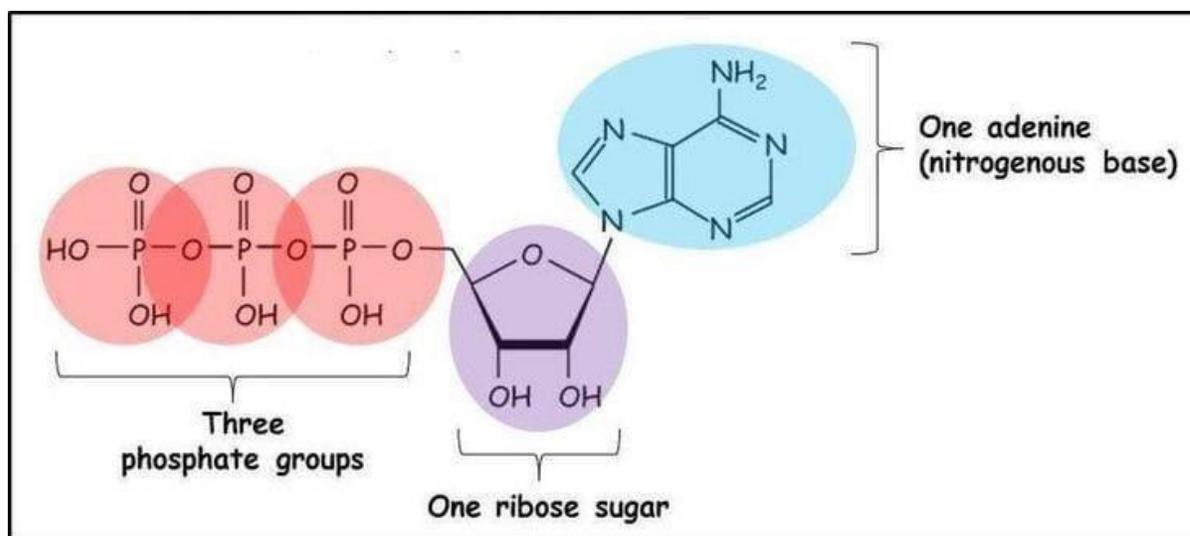


Function

Mitochondria play a part in cellular respiration by transferring the energy of the organic molecules to the chemical bonds of ATP. A large “battery” of enzymes and coenzymes slowly release energy from the glucose molecules. Thus mitochondria are the “**Power houses**” that produce energy necessary for many cellular functions.

Adenosine triphosphate and its importance

Adenosine triphosphate, generally abbreviated ‘ATP’ is a compound found in every living cell and is one of the essential chemicals of life. It plays the key role in most biological energy transformations.



Conventionally, ‘P’ stands for the entire phosphate group. The second and the third phosphate represent the so called “high energy” bonds. If these are broken by hydrolysis, far more free energy is released as compared to the other bond in the ATP molecule.

Energy yield

The breaking of the terminal phosphate of ATP releases about 7.3 K cal. of energy. The high energy ‘P’ bond enables the cell to accumulate a great quantity of energy in a very small space and keeps it ready for use as soon as it is needed.

Use of ATP

The ATP molecule is used by cells as a source of energy for various functions for example:

- ◆ Synthesis of more complex compounds
- ◆ Active transport across the cell membrane
- ◆ Muscular contraction
- ◆ Nerve conduction, etc.

Biological Oxidation

The maintenance of living system requires a continual supply of free energy which is ultimately derived from various oxidation reduction reactions. Except for photosynthetic and some bacterial chemosynthetic processes, which are themselves oxidation reduction reactions, all other cells depend ultimately for their supply of free energy on oxidation reactions in respiratory processes.

Dehydrogenase

In some cases biological oxidation involves the removal of hydrogen, a reaction catalyzed by the dehydrogenases linked to specific coenzymes. Cellular respiration is essentially an oxidation process.

Cellular Respiration

Cellular respiration may be sub-divided into 4 stages:

- i. Glycolysis
- ii. Pyruvic acid oxidation
- iii. Krebs cycle or citric acid cycle
- iv. Respiratory chain

Out of these stages the first occurs in the cytosol for which oxygen is not essential, while the other three occur within the mitochondria where the presence of oxygen is essential.

1. Glycolysis

Glycolysis is the breakdown of glucose upto the formation of pyruvic acid. Glycolysis can take place both in the absence of oxygen (anaerobic condition) or in the presence of oxygen (aerobic condition). In both, the end product of glucose breakdown is **pyruvic acid**. The breakdown of glucose takes place in a series of step, each catalyzed by a specific enzyme. All these enzymes are found

dissolved in the cytosol. In addition to the enzymes, ATP and **coenzymes NAD (nicotinamide adenine dinucleotide)** are also essential.

Phases of glycolysis

Glycolysis can be divided into two phases.

- ◆ Preparatory phase
- ◆ Oxidative phase

In the preparatory phase breakdown of glucose occurs and energy is expended. In the oxidative phase high energy phosphate bonds are formed and energy is stored.

I. Preparatory Phase

1. Phosphorylation of glucose

The first step in glycolysis is the transfer of a phosphate group from ATP to glucose. As a result a molecule of glucose-6-phosphate is formed.

2. Rearrangement (Isomerization)

An enzyme catalyzes the conversion of glucose-6-phosphate to its isomer, fructose-6-phosphate.

3. Phosphorylation of fructose 6-bisphosphate

At this stage another ATP molecule transfers a second phosphate group.

4. Splitting of fructose 1, 6-bisphosphate

The product is fructose 1,6-bisphosphate into two fragments. Each of these molecules contains three carbon atoms. One is called 3-phospho-glyceraldehyde, 3-PGAL or Glyceraldehyde **3-phosphate (G3P)** while the other is **dihydroxyacetone phosphate**.

5. Interconversion (isomerization)

These two molecules (G₃P and DAP) are isomers and in fact are readily interconverted by yet another enzyme of glycolysis.

II. Oxidative (Payoff) Phase

1. Oxidation and phosphorylation

The next step in glycolysis is crucial to this process. Two electrons or two hydrogen atoms are removed from the molecule of 3-phosphoglyceraldehyde (PGAL) and transferred to a molecule of NAD. This is of course, an oxidation-reduction reaction, with the PGAL being oxidized and the NAD being reduced. During this reaction, a second phosphate group is donated to the molecule from inorganic phosphate present in the cell. The resulting molecule is called **1,3 Bisphosphoglycerate (BPG)**.

2. ATP formation

The oxidation of PGAL is an energy yielding process. Thus a “high energy” phosphate bond is created in this molecule. At the very next step in glycolysis this phosphate group is transferred to a molecule of adenosine diphosphate (ADP) converting it into ATP. The end product of this reaction is **3-phospho glycerate (3-PG)**.

3. Rearrangement (isomerization)

In the next step 3-PG is converted to **2-Phosphoglycerate (2PG)**.

4. Dehydration and PEP formation

From 2PG a molecule of water is removed and the product is **phosphoenolpyruvate (PEP)**.

5. Pyruvic acid formation

PEP then gives up its ‘high energy’ phosphate to convert a second molecule of ADP to ATP. The product is pyruvate, pyruvic acid ($C_3 H_4 O_3$).

- ◆ It is equivalent to half glucose molecule that has been oxidized to the extent of losing two electrons (as hydrogen atoms).

Pyruvic Acid Oxidation

Pyruvic acid (pyruvate), the end product of glycolysis, does not enter the Krebs cycle directly.

- ◆ The pyruvate (3-carbon molecule) is first changed into 2-carbon **acetic acid** molecule. One carbon is released as CO_2 (decarboxylation).
- ◆ Acetic acid on entering the mitochondrion unites with **coenzyme-A (CoA)** to form acetyl CoA (**active acetate**).
- ◆ In addition, more hydrogen atoms are transferred to NAD (Fig 11.13).

Krebs Cycle or Citric Acid Cycle:

Acetyl CoA now enters a cyclic series of chemical reactions during which oxidation process is completed. This series of reactions is called the Krebs cycle (after the name of the biochemist who discovered it), or the citric acid cycle.

Citrate formation

The first step in the cycle is the union of acetyl CoA with **oxalocetate** to form **citrate**. In this process, a molecule of CoA is regenerated and one molecule of water is used. Oxaloacetate is a 4-carbon acid. Citrate thus has 6 carbon atoms.

Isocitrate formation

After two steps that simply result in forming an isomer of citrate, isocitrate.

Oxidative decarboxylation (ketoglutarate formation)

It is conversion of isocitrate into ketoglutarate.

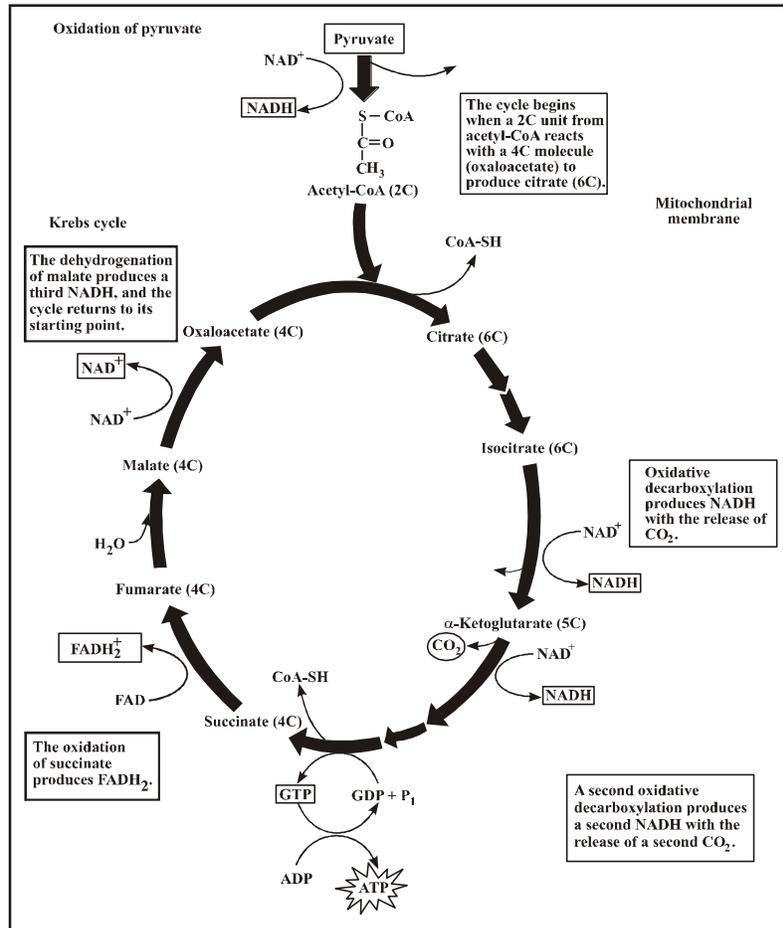
Here NAD-mediated oxidation takes place. This is accompanied by the removal of a molecule of CO₂. The result is **ketoglutarate**.

Succinate formation

ketoglutarate in turn, undergoes further oxidation ($\text{NAD} + 2\text{H} \rightarrow \text{NADH}_2$) followed by decarboxylation (CO₂) and addition of a molecule of water. The product then has one carbon atom and one oxygen atom less. It is succinate. The conversion of α -ketoglutarate into succinate is accompanied by a free energy change which is utilised in the synthesis of an ATP molecule.

Oxidation of succinate

The next step in the Krebs cycle is the oxidation of succinate to **fumarate**. Once again, two hydrogen atoms are removed, but this time the oxidizing agent is a coenzyme called **flavin adenine dinucleotide (FAD)**, which is reduced to **FADH₂**.



Outline of the Kerbs cycle. The brackets give the number of carbon atom in each intermediate of the cycle.

Malate Formation

With the addition of another molecule of water, fumarate is converted to malate.

Oxidation of Malate

Another NAD mediated oxidation of malate produces **oxaloacetate**, the original 4-carbon molecule. This complete the cycle. The oxaloacetate may now combine with another molecule of acetyl CoA to enter the cycle and the whole process is repeated (Fig 11.13).

Respiratory Chain

In the Krebs cycle NADH and H⁺ are produced from NAD⁺. NADH then transfers the hydrogen atom to the respiratory chain (also called **electron transport system**) where electrons are transported in a series of oxidation-reduction steps to react, ultimately, with molecular oxygen. (Fig. 11.14).

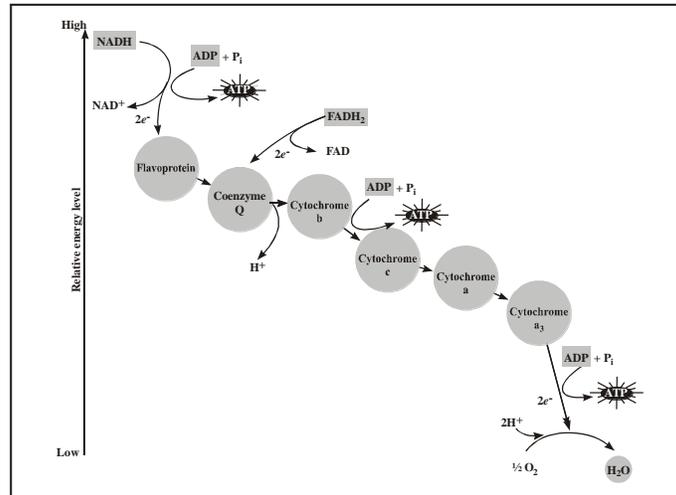
Components of Respiration Chain

The oxidation reduction substances which take part in respiratory chain are:

- i. A coenzyme called coenzyme Q
- ii. A series of cytochrome enzymes (b,c,a,a₃)
- iii. Molecular oxygen (O₂)

Cytochrome

Cytochromes are electron transport intermediates containing haem of related prosthetic groups, that undergo valency changes of iron atom. Heam is the same iron containing group that is oxygen carrying pigment in heamoglobin. The path of electrons in the reparatory chain appears to be as follows.



Steps in Electron Transport Chain

i. Oxidation of NADH

NADH is oxidized by **coenzyme Q**. This oxidation yields enough free energy to permit the synthesis of a molecule of ATP from ADP and inorganic phosphate.

ii. Oxidation of Co-enzyme Q

Coenzyme Q is in turn oxidized by **cytochrome b** which is then oxidized by **cytochrome c**. This step also yields enough energy to permit the synthesis of a molecule of ATP.

iii. Reduction of cytochrome c

Cytochrome c then reduces a complex of two enzymes called **cytochrome a** and **a₃** (for convenience the complex is referred as cytochrome a).

iv. Oxidation of cytochrome a

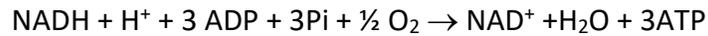
Cytochrome a is oxidized by an atom of oxygen and the electrons arrive at the bottom end of respiratory chain. Oxygen is the most electronegative substance and the final acceptor of the electrons. A molecule of water is produced. In addition, this final oxidation provides enough energy for the synthesis of a third molecule of ATP.

v. Oxidative phosphorylation

Synthesis of ATP in the presence of oxygen is called oxidative phosphorylation. Normally, oxidative phosphorylation is coupled with the respiratory chain. As already described ATP is formed in three steps of the respiratory chain (Fig. 11.14).

Equation of ETC

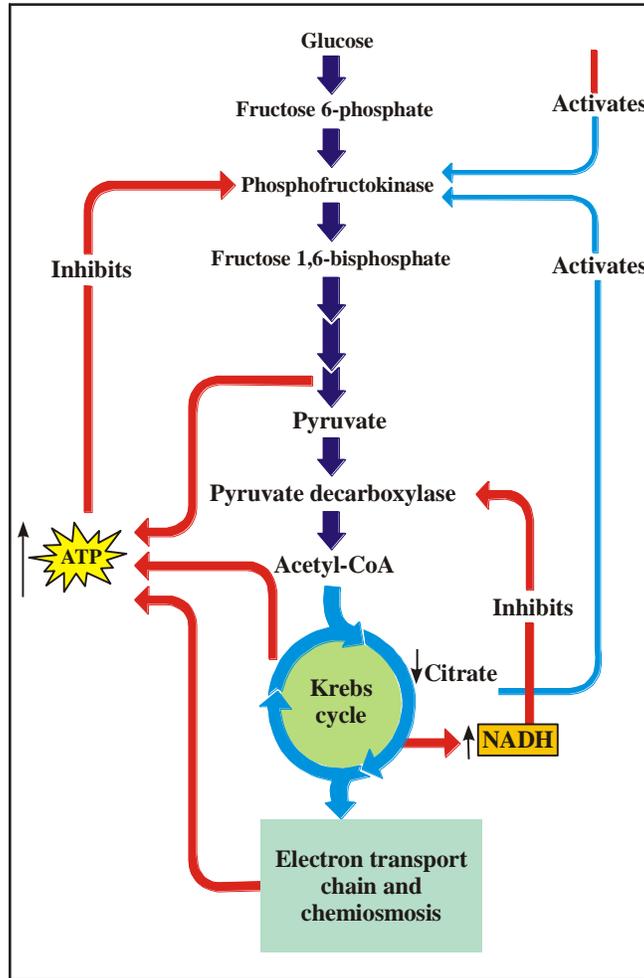
The equation for this process can be expressed as follows:



Where Pi is inorganic phosphate.

Mechanism of Oxidative Phosphorylation

- ◆ The molecular mechanism of oxidative phosphorylation takes place in conjunction with the respiratory chain in the inner membrane of the mitochondrion.
- ◆ Here also, as in photosynthesis, the mechanism involved is chemiosmosis by which electron transport chain is coupled with synthesis of ATP.
- ◆ In this case, however the pumping/movement of protons (H^+) is across the inner membrane of mitochondrion folded into cristae, between matrix of mitochondrion and mitochondrion's intermembrane space.
- ◆ The coupling factors in respiration are also different from those in photosynthesis.



Stages in aerobic respiration. Stage 1: Formation of acetyl-CoA from pyruvate. Stage 2: The Krebs cycle. Stage 3: Respiratory chain and oxidative phosphorylation. Each pair of H atoms entering the respiratory chain as NADH yields 3 ATPs.

Assessment 1

- It is the quantitative study of energy relationships and energy conversions in biological systems.
(a) Bioenergetics (b) Metabolism (c) Thermodynamics (d) Nutrition
- It is a kind of chemical link between catabolism and anabolism.
(a) Glucose (b) ADP (c) ATP (d) Starch
- At dawn and dusk, when light intensity is low, the rate of photosynthesis and respiration may.
(a) Decreased (b) Equal (c) Increased (d) Stop
- When there is no net gas exchange between the leaves and the atmosphere. This is termed as.
(a) Respiration (b) Photosynthesis
(c) Compensation point (d) Metabolism
- Van Neil hypothesized that plants split water as a source of hydrogen, releasing as a by-product, which of the following?
(a) Sulphur (b) Carbon dioxide (c) Sugar (d) Oxygen
- NADPH_2 is the "reducing power" which is along with ATP also formed during.
(a) Dark reaction (b) Light reaction (c) Calvin cycle (d) C_3 – Cycle
- These are the major sites of photosynthesis in most plants.
(a) Leaves (b) Cortex (c) Root (d) Stem
- Thylakoids in chloroplasts are stacked into.
(a) Grana (b) Intergranum (c) Chloroplast (d) None
- Light reactions take place on the.
(a) Chloroplast (b) Stroma (c) Grana (d) Mitochondria
- Where does the dark reaction occur?
(a) Stroma (b) Grana (c) Thylakoid (d) Mitochondria

Assessment 2

- Each mesophyll cell has about how many chloroplasts?
(a) Half a million (b) 1200 (c) 20 – 100 (d) 12000
- Thylakoid membranes are involved in ATP synthesis by.
(a) Z-scheme (b) Reduction (c) Chemiosmosis (d) Photosynthesis
- Photosynthetic prokaryotes have unstacked photosynthetic membranes which work like.
(a) Chloroplast (b) Stroma (c) Thylakoids (d) Matrix
- Pigments are the substances that absorb visible light _____nm in wavelength.
(a) 380 – 750 (b) 380 – 660 (c) 430 – 660 (d) None
- A graph plotting absorption of light of different wavelengths by a pigment is called _____ spectrum of the pigment.
(a) Action (b) Absorption (c) Active (d) Diffraction
- These are the main photosynthetic pigments.
(a) Carotenoid (b) Chlorophyll (c) Xanthophyll (d) Haemoglobin
- Accessory photosynthetic pigments present in the chloroplasts include yellow and red to orange.
(a) Carotenoids (b) Carotenes (c) Xanthophylls (d) Chlorophyll
- Chlorophylls absorb mainly wavelength, except.
(a) Violet blue (b) Orange red (c) Green (d) All
- A chlorophyll molecule has how many main parts.
(a) One (b) Three (c) Two (d) Four
- Chlorophyll head is complex which is made up of 4 joined rings, which are called.
(a) Porphyrin ring (b) Phytol tail (c) Pyrole rings (d) Haem groups

Assessment 3

- It is present in the center of porphyrin ring and is coordinated with the nitrogen of each pyrrole ring.
(a) Mg (b) Fe (c) Ca (d) Ma
- Haem portion of haemoglobin is a porphyrin ring containing which atom in the center.
(a) Fe (b) Ma (c) Ca (d) Mg
- Long hydrocarbon tail which attached to one of the pyrrole rings is phytol, having/
(a) $C_{20}H_{38}$ (b) $C_{39}H_{20}$ (c) $C_{38}H_{29}$ (d) $C_{20}H_{39}$
- Chlorophyll a differs from chlorophyll b due to presence of.
(a) CHO (b) Phytol tail (c) CH_3 (d) Pyrrole ring
- Molecular formulae for _____ is $C_{55}H_{72}O_5N_4Mg$.
(a) Chlorophyll a (b) Chlorophyll c (c) Chlorophyll b (d) Chlorophyll d
- Chlorophyll a is.
(a) Blue green (b) Orange red (c) Yellow green (d) Orange yellow
- Chlorophylls are insoluble in.
(a) Tetrachloride (b) Water (c) Alcohol (d) Acetone
- These are yellow and red to orange pigments.
(a) Carotene (b) Chlorophyll (c) Xanthophylls (d) Carotenoids
- Carotenoid absorbs strongly which of following range.
(a) Blue – Violet (b) Orange – Red (c) Yellow – orange (d) Green
- Which of following is not accessory photosynthetic pigment.
(a) Carotene (b) Chlorophyll a (c) Xanthophylls (d) Chlorophyll b

Assessment 4

- It is generally believed that the order of transfer of energy is.
(a) Chlorophyll a → Chlorophyll b → Carotene
(b) Carotene → Chlorophyll a → Xanthophylls
(c) Carotenoids → Chlorophyll b → Chlorophyll a
(d) Chlorophyll a → Carotene → Chlorophyll b
- Absorption spectrum for chlorophylls indicates two absorption peaks being at around.
(a) 430 – 670 (b) Orange – Red (c) Blue – Green (d) 380 – 730
- Graph showing relative effectiveness of different wavelengths (colours) of light in driving photosynthesis is called.
(a) Absorption spectrum (b) Action spectrum
(c) Atomic spectrum (d) None
- The first action spectrum was obtained by German biologist, T.W. Engelmann in 1883. He worked on.
(a) Chlorella (b) Fungi (c) Hydrilla (d) Spirogyra
- When equal intensities of light are given, there is more photosynthesis in.
(a) Red (b) Green (c) Blue (d) Yellow
- Total photosynthesis is carried out by terrestrial plants.
(a) 90% (b) 50% (c) 10% (d) 30%
- Stomata cover only what percent of the leaf surface.
(a) 1 – 2 (b) 10 (c) 3 – 4 (d) 20
- Which do not use light directly.
(a) Light reactions (b) Z-scheme (c) Dark reactions
(d) Oxidation
- It provides energized electron for the synthesis of sugar.
(a) NADH (b) NADPH₂ (c) NADP⁺ (d) ATP
- Which of the following is reducing power in photosynthesis.
(a) Glucose (b) ATP (c) NADH (d) NADPH₂

Key Assessment 1

1. a

2. c

3. b

4. c

5. d

6. b

7. a

8. a

9. c

10. a

Assessment 2

1. c

2. c

3. c

4. b

5. b

6. b

7. a

8. c

9. c

10. c

Key Assessment 3

1. a
2. a
3. d
4. c
5. a
6. a
7. b
8. d
9. a
10. d

Assessment 4

1. c
2. a
3. b
4. d
5. a
6. c
7. a
8. c
9. b
10. d