Section-IV

FUNCTIONAL BIOLOGY

When a hummingbird sips nectar from a flower, it eats the products of photosynthesis. Photosynthesis in the plant's leaves had converted the energy of sunlight into the chemical energy of organic molecules such as the sugar in nectar. To supply its enormous energy needs— the highest of any animal—the hummingbird must eat its weight in nectar daily. Then its cells must efficiently extract energy from the glucose in the nectar.

Chapter - 11

BIONERGETICS

Energy is defined as the "capacity to do work." It exists in a number of different forms: heat, light, electrical, magnetic, chemical, atomic, mechanical and sound. The laws which apply to energy conversion are the laws of thermodynamics.

11.1 Need for energy in living organisms:

All living cells carry out numerous activities e.g. they generally assemble macromolecules of all types (which are discussed in chapter 3) from raw materials, waste products are produced and excreted, genetic instructions flow from the nucleus to cytoplasm, vesicles are moved fromGolgi bodies to the plasma membrane, ions are pumped across the membranes etc. For these high level of activities, a cell needs energy. The energy is used as fuel for life which is derived from light energy trapped by plant cells and converted into energy rich compounds. Other organisms, which do not have the ability to trap light energy, obtain their energy by eating plants or by eating the organisms that 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. Biological energy transformations obey the laws of thermodynamics.

Nearly all living things break down organic nutrients for energy, only about half a million species can built those nutrient through solar powered carbon fixation, photosynthesis. Those half million support themselves and all other living species. The tempering with environment could lead to disastrous change in the fundamental interdependence of autotrophs and heterotrophs, aerobic respiration and photosynthesis.

11.1.1Role of ATP as energy currency:

Living organisms use organic food as an energy source. These organic molecules especially carbohydrates are degraded to release energy, CO_2 and H_2O. Some of this energy is used to produce ATP. It shows that ATP is the common energy currency of cells. When cells require energy, they spend ATP for that.
As we have already mentioned (chapter 2) that ATP is composed of adenine and ribose sugar with 3-phosphate groups. ATP is also called a "high energy compound because its phosphate groups are easily removed. Under cellular condition it produce 7.3 K.Cal/mole on conversion into ADP.
Wavy lines between the phosphate bonds indicates the high potential energy (the use of the wavy line is for convenience only, it is not an actual means of energy).
ATP acts as a mediator, capable of receiving energy from one reaction and transfer this energy to drive another reaction e.g. oxidation of glucose can provide energy through ATP for the synthesis of a number of cellular materials. ATP plays role in several **endergonic**reaction such as synthesis of protein, lipids,

carbohydrates, active transport etc. In **exergonic** reactions like anaerobic glycolysis and oxidative phosphorylation, it also plays its role and acts as co-enzyme.

11.1.2 Photosynthesis and Respiration: The main energy processing processes:

Most of the energy or ATP of a living organism is processed in two ways. Among them first is the photosynthesis, which occurs in chloroplast. It is the process in which solar energy is converted into ATP. Another process is cellular respiration in which most of the energy producing process occurs in mitochondria during which the chemical energy of carbohydrate is converted to ATP.

11.2 PHOTOSYNTHESIS: (as energy trapping and energy converting process)

The ultimate energy source for most living things is sunlight, and that the organism that transform the light energy into chemical energy are primarily the plants. Algae and some photosynthetic bacteria also perform this transformation. The process by which this transformation is carried out is called **photosynthesis** (photo-light: synthesis-to produce).

On the basis of end product, photosynthesis is called as the formation of carbon containing compound from carbon dioxide and water by illuminated green cells, water and oxygen being the by-products.

In terms of energy we can define that the photosynthesis is a metabolic process during which light energy is converted into chemical/food energy in the presence of chlorophyll and electron carriers. Now photosynthesis may be defined as biochemical anabolic process during which simple carbohydrates are manufactured from CO_2 and water in chlorophyllus cells and in presence of sunlight. O_2 is given out as by-product.

11.2.1 Reactants and Products of photosynthesis:

The reactants of photosynthesis are water, carbon dioxide and light energy. In the vascular plants, water is absorbed by the roots from soil and translocated upto the photosynthetic organs through xylem. The carbon dioxide enters into the plant from the atmosphere through the stomata present on the leaves. The source of light is the sun, when sunlight falls on the green parts of plant, the photosynthetic apparatus captures this energy as solar cells do. In case of unicellular and multicellular organisms living in water, CO_2 is absorbed which is dissolved in the surrounding water. Similarly the oxygen released during this process diffuses into surrounding water.

The important product of photosynthesis is glucose. This is the fundamental material or the 'starter' for complex food molecules. Part of it is converted into complex carbohydrates like starch if remains in chloroplast A part of it is utilised to produce sucrose in the cytosol and other parts are converted into oil and with nitrogen, sulphur, phosphorous it is used in the synthesis of protein and other complex organic compounds.

11.2.2 Role of chlorophyll and other pigments:

As light is flashed on matter, it maybe reflected, transmitted or absorbed. Substances in plants that absorb visible light are called pigments. Different pigments absorb light of different wavelengths. These pigments are most important in the conversion of light energy to chemical energy. The most important pigments required in the process are the chlorophylls, the carotenoid and phycobilin pigments.

Evidences for photosynthetic pigments:
Plants look green, and other pigment can be extracted from a plant by grinding leaves with acetone and filtering. The filtrate looks green, so how it comes to know that there are other five pigments? We can separate these pigments by paper chromatography with suitable solvent these pigment travel up by the paper at different speed due to their structures and size, In this way they are readily separated. Carotene, phaelophytin, xanthophyll, chlorophyll-a, chlorophyll b will give orange, grey, yellow, blue-green and yellow green appearance respectively.

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_5 N_4 Mg and that of Chlorophyll-b molecules is C_{55} H_{70} O_6 N_4 Mg.
Chlorophyll-a is almost identical to chlorophyll-b but the slight structural difference between them is enough to give the two pigments slightly different absorption spectra and hence different colours. Chlorophyll **'a'** is bluish green, whereas chlorophyll-**b** is yellowish green.
Chlorophyll is organised along with other molecules into photosystem, which has light gathering **"antenna complex",** consisting of a cluster of few hundred chlorophyll **'a'**, chlorophyll **'b'** and carotenoid molecules. The number and variety of pigment molecules enable a photosystem to harvest light over a large surface than single pigment molecule. When any antenna molecule absorbs a photon, the energy is transmitted from pigment molecules to pigment molecules until it reaches a particular chlorophyll-**a**, which is structurally same to other chlorophyll molecules but located in the region of photosystem called **"reaction centre",** where the first light driven chemical reaction of photosynthesis occur as shown in Fig. 11.2.
The chloroplast also has a family of carotenoids, which are in various shades of yellow and orange. These are present in the thylakoid membrane along with two kinds of chlorophyll. Carotenoids can absorb wavelength of light that chlorophyll can not absorb and transfer to chlorophyll-**a**. On the other side excessive light can damage chlorophyll. Instead of transmitting energy to chlorophyll, some carotenoids can accept energy from chlorophyll, thus providing a function known as photoreception.

In photosynthetic organisms, chlorophyll is accompanied by carotenoid pigments, which absorb green, blue and violet wave length and reflect red, yellow and orange. They are generally masked by chlorophyll and thus tend to be unnoticed in green leaves, however they give bright and obvious colour to many non photosynthetic plant structures e.g. carrot (root), daffodils (flower), tomatoes (fruit) and com (seed). They give glorious colour to plant in autumn.

11.2.3Role of light:
The plant is capable of using only a very small portion of incident electromagnetic radiation that falls on a leaf or the radiation that is absorbed by the pigment complex of the leaf. Each pigment has its own absorption spectrum.
Light has a dual nature and can be described both as a wave and a particle. It is composed of packets of energy called photon (or quanta). Light energy captured in the light harvesting complexes which is efficiently and rapidly transferred to the chlorophyll molecules present in the photosynthetic reaction centres. When a photon of light hits these chlorophyll-**a** molecules the energy of these photons is absorbed and results in the elevation of an electron from the ground state to an excited state. The excitation state achieved depends upon the energy of the incident photon. A photon of red light has enough energy to raise an electron to

excited state-1 and this energy is sufficient to initiate useful chemical reactions and all other events of photosynthesis. Although a photon of blue light contains more energy than a photon of red light and carries electron to a more energetic excited state-2, the energy transferred by blue or red photons to the photosynthetic electron transport chain is exactly the same, the extra energy delivered by the absorption of a blue photon is rapidly lost by radiationless de-excitation producing an electron in excited state-1.
The movement of energy within the thylakoid membrane is very quick occurring within nanoseconds. During the transfer of electrons some energy is lost. The excitation energy can be used or lost in different ways. It can be used for photochemistry (i.e. it enters the photosynthetic electron transport chain) alternatively it can be dissipated as heat or re-emitted as fluorescence.

11.2.4 Role of water:

Photosynthesis is a redox process. It requires H^+ and electron, to fulfill this requirement H_2O is split and electrons are transferred along with Hydrogen ion (H^+) from H_2O to CO_2, reducing it to sugar.
As water molecules are split, their oxygen atoms combine to form molecules of oxygen (O_2). From this discussion we can conclude that the water thus provides H^+ and e^- necessary for the reduction steps leading to assimilation of CO_2.

11.2.5 Role of CO_2:

Scientists have been studying the diffusion of CO_2 through the stomatal pores of a leaf for more than sixty years. This CO_2 provides the carbon for the basic skeleton to photosynthetic product. The opening and closing of stomata have an important effect on the regulation of photosynthetic activity; particularly in C_3 plants, which incorporate CO_2 directly into phosphorylated sugar intermediate biphospate.

11.3 PROCESS OF PHOTOSYNTHESIS

The process of photosynthesis consists of two main types of reactions (i) light reaction and (ii) dark reaction.

1. In the light-dependent reactions, chlorophyll and other molecules in the membrane of the thylakoids capture light energy and convert some of it into the chemical energy-carrier molecules i.e. ATP and NADPH + H^+.

The overall equation for photosynthesis does not indicate that the process involves the light-dependent reaction and the light independent reactions. The light dependent reactions, located in the thylakoid, capture the energy of sunlight needed by the light independent reactions, located in stroma, to reduce carbon dioxide to carbohydrate.

2. In the dark reactions or light-independent reactions, enzymes in the stroma use the chemical energy of the carrier molecules (ATP and NADPH + H^+) to drive the synthesis of glucose or other organic molecules.

11.3.1 Light reaction (The Light Dependent Reaction):

. In the choroplast, the light capturing chlorophyll molecules, membrane-bound proteins and electron carriers are components which together constitute the electron transfer chain. Four major groups of complexes are present in the membrane. These are photosystem I (PS I), Photosystem II (PS II), the cytochrome b/f complex (cyt b/f) and an ATPase complex. Mobile electron carriers transport the excited electrons between the complexes. These mobile electron carriers are plastoquinone(Pq), plastocyanin(Pc) and ferredoxin(Fd).
These complexes are not evenly distributed throughout the thylakoid membrane which is structurally differentiated into two inter-connected regions, appressed

and non-appressed. The PS I and ATP synthase complexes are located mainly in the non-appressed (non-stacked) stromal lamellae whereas the PS II and associated light harvesting complexes (LHCII) are present in the appressed (stacked) membranes. The Cyt b/f complexes are randomly distributed throughout the membrane.

Photosystem I and II both contain special chlorophyll-a molecules at their centres. These chlorophyll molecules are identical to all other chlorophyll-a molecules if they are isolated away from their binding proteins. Therefore, the changes in these chlorophyll molecules are due to their association with the chlorophyll-bound proteins. The chlorophyll-**a** molecule at the reaction centre of PS I has a maximum absorbance at 700 nm, while those of PS II absorb at 680 nm. Therefore, these reaction centres are called P_{700} and $P_{680}$where P simply stands for pigment.

a) Electron transport:

The 'light' reactions of photosynthesis start from the reaction centre of PS II (P_{680}) which consists of a chlorophyll-a dimer. When a photon of light hits these chlorophyll-a molecules the energy of these photons is absorbed and results in the elevation of an electron from the ground state to an excited state. The excited electron produced within P_{680} is rapidly transferred to the primary electron acceptor phaeophytin and then to plastoquinone molecules which are associated with a ferrous ion.

Photosynthesis seems to have evolved in organisms similar to the green sulphur bacteria, which use an array of chlorophyll molecule (a photocentre) to channel photon excitation energy to one pigment molecules, referred to as P_{840} in green sulphur bacteria and in plant P_{700}. It donates an e^- to e^- transport chain for driving a proton pump and returns the e^- to P_{700} in a process called cyclic photophosphorylation.

The P^+_{680} produced by this primary charge separation and electron transport is re-reduced by an e^- from H_2O. The water-splitting complex is present on the luminal side of the thylakoid membrane and consists of a manganese cluster, Z (the immediate electron donor to P_{680}) and an associated protein. The water splitting complex produces $4e^-$ from two water molecules and releases $4H^+$ and one molecule of O_2, into the lumen. However, the sequence of electron, proton and O_2 release is not yet clear.

Electrons are transferred from PQ, a rapidly turned over plastoquinone (PQ) molecules which accept two electrons and takes up two proton from the stroma. Both electrons and protons are then passed into the plastoquinone pool within the thylakoid membrane. Plastoquinone carries charge from the PS II complex to the Cyt b/f complex. This is thought to be the rate limiting step of electron transport. The electrons from PQ are passed via an FeS centre to cytochrome f within the complex oxidising the PQ and releasing protons into lumen. The second mobile electron carrier plastocyanin (PC) is reduced and is situated in the lumen.

Plastocyanin acts as an electron donor to PS I. PS I has not been studied to such an extent as PS II and therefore its structure and function is less understood. A second excitation event within PS I leads to the eventual transfer of an electron via a series of three FeS centres to Fd. This in turn is used to reduce NADP to $NADPH+H^+$ at the stromal side of the membrane.

b) Formation of ATP (Photophosphorylation):

The energy made available by the passage of electrons down the cytochrome system is coupled to build up ATP in an indirect manner. Some of the carrier of the cytochrome system pump hydrogen ion (H^+) from the stroma into the thylakoid space. This thylakoid space, acts as a reservoir for hydrogen ionsalso because for every water molecule that splits in the beginning, 2 hydrogen ions

stay behind in the thylakoid space. The hydrogen ion taken up by NADP comes from the stroma, not from the thylakoid space.
Because of the large number of hydrogen ions in the thylakoid space compared to the stroma, an extreme electrochemical gradient is present. When these hydrogen ions flow out of the thylakoid space byway of a channel protein present in a particle, called the **ATP synthase complex**, energy is provided for the ATP synthase enzyme to produce ATP from ADP+Pi. This is called **chemosmotic** ATP synthesis because chemical and osmotic events join to permit ATP synthesis. The transport of three protons through the ATPase complex are normally required for the production of one ATPmolecule.
The linear flow of electrons from water to NADP coupled to ATP synthesis is non-cyclic photophosphorylation because the electrons pass on to a terminal acceptor and never back to an initial source. In cyclic photophosphorylation, the electrons are cycled from PS I back to cytochrome complex and from there continue on to the P_{700} chlorophyll. The only product of this process is ATP which can be utilized to meet the ATP demand of CO_2 fixation or other processes such as protein or starch formation.
Finally, four important events take 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 to $NADPH+H^+$
(iv) Synthesis of ATP by photophosphorylation

ATP and $NADPH+H^+$, products of light dependent reaction, play an important role in the light-indepent reaction that follows.

11.3.2Light independent reaction (Dark reaction) or Calvin-Benson Cycle:
The second phase of photosynthesis results in the fixation of atmospheric CO_2 into sugar phosphates. This part of photosynthesis does not require light energy directly, therefore it is generally termed as the 'dark reaction'. These reactions, which require chemical energy in the form of ATP and $NADPH_2$, are collectively known as the Calvin-Benson Cycle (reductive pentose phosphate cycle). During this cycle CO_2 is reduced to triose-phosphate (phosphoglyceraldehyde and di-hydroxyacetone phosphate) and subsequently via other metabolic pathways to carbohydrates. Type of plants in which first stable product is glycerate, 3 phosphate (PGA) contains 3 carbon atom are called C_3 plants and the cycle called C_3 cycle.
The Calvin cycle consists of 13 main reactions catalysed by 11 enzymes as shown in figure 11.5. The C_3 cycle is divide into three distinct phases for the convenience to study.

(i) **Carboxylation** or carbon fixation - during which CO_2 is fixed into organic molecules.

(ii) **Reduction** of synthesis of phosphoglyceraldehyde (PGAL) by the reduction of organic molecules.

(iii) **Regeneration** where the reduced carbon can be utilized either to regenerate the carbon acceptor molecules or for metabolism. These phases are discussed in detail in the following section.

i) Carboxylation: This is the first and key reaction of Calvin cycle where ribulose-1, 5-bisphosphate (RuBP) is combined with atmospheric CO_2 to produce a short lived, six carbon intermediate, which breaks into two molecules ofglycerate-3-phosphate (G3P).

This reaction is catalysed by the enzyme ribulose-1, 5-bisphosphate carboxylase/oxygenase (Rubisco).

Rubisco is an enzyme which function as carboxylase as well as oxygenase. If the supply of CO_2 inside the leaf is inadequate, most of RuBP combines with O_2, giving one molecule of PGA and one molecules of phosphoglycolate, where phosphoglycolate rapidly breaks down to release CO_2.
This process is named as photo-respiration because in the presence of light (photon), oxygen is taken up and CO_2 is evolved (respiration).

ii) Reduction: This phase of the calvin cycle comprises a series of freely reversible reactions. During this phase G3P is reduced to glycerate-1, 3-biphosphate (G1, 3P) and then triose phosphate [3 Phosphoglyceraldehyde (GA3P) and Dihydroxyacetonephosphate (DHAP)] at the cost of ATP and NADPH produced during light reaction.

iii) Regeneration: Many carbon rearrangement takes place during this phase. Three carbon compounds are rearranged to form 5 carbon units including the primary acceptor molecule, RuBP. This stage involves enzymes 5-11.
During this cycle 3 molecules of CO_2fix by 3 molecule of RuBP (3 x C_5), which produces 6 molecules of 3-carbon compounds i.e. triose (6 x C_3). From these 6 molecules five are required to regenerate RuBP (5 x C_3 —-> 3 x C_5). Therefore, only one molecule of 3C is produced (generally called triose-phosphate) which can (a) re-enter the cycle, or (b) be used for starch synthesis within the chloroplast or (c) be exported via a phosphate translocator to cytosol for sucrose synthesis.
For the net synthesis of one G3P molecule, the Calvin cycle consumes a total of nine molecules of ATP and six molecules of $NADPH+H^+$. The light reactions regenerate the ATP and $NADPH+H^+$. The G3P spunoff from the Calvin cycle becomes the starting material for metabolic pathways that synthesize other organic compounds, including glucose and other carbohydrates.

11.3.3 Alternative mechanisms of Carbon fixation in hot, arid climate:

On a hot, dry day, most plants close their stomata, a response that conserve water. This response also reduces photosynthetic yield by limiting access to CO_2, with stomata even partially closed, CO_2 concentration begins to decrease in the air spaces within the leaf, and concentration of O_2 released from photosynthesisbegins to increase. These conditions within the leaf favour a wasteful process called photo-respiration. In certain plant species alternate mode of carbon fixation that minimize photo-respiration even in hot, arid climates have evolved. The two most important of these photosynthetic adaptations are C_4 photosynthesis and CAM.
The **C_4 plants** are so named because they go through the Calvin cycle with an alternate mode of carbon fixation that forms four carbon compound (oxaloacelate) as its first product i.e. oxaloacetate. The four carbon compounds release CO_2, which is reassimilated into organic material by Rubisco and the Calvin cycle. Among the C_4 plants important to agriculture are sugar-cane and corn, members of grass family.
A second photosynthetic adaptation to arid conditions has evolved in succelent plants, many cacti, pineapples and representatives of several other plant families. These plants open their stomata during the night and close them during the day, just reverse of normal behaviour. Closing stomata during the day helps desert

plants conserve water, but it also prevents CO_2 from entering the leaves. 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 fixation is called **crassulacean acid metabolism** or **CAM**. The CAM plants store these organic acids unit moving in their vacuoles. During the day, when the light reactions can supply ATP and NADPH+H for the Calvin cycle. These acids release CO_2 to compete with O_2. In this ratio of CO_2 maintain inside the leaves. This CO_2 is fixed through C_3 cycle.

11.4 CELLULAR RESPIRATION: As energy releasing process

Every living cell requires steady supply of energy to carry out varied functions. This energy comes from fuel molecules such as glucose. In cellular respiration glucose molecule in the presence of oxygen is dismantled. Its bonds break-up. Energy is released in small amounts. Some of the energy is stored by cell in the form of ATP while rest is lost as heat. Thus a cell transfers energy from glucose to ATP through coupled exergonic and endergonic reactions. Thisaerobic breakdown of glucose molecule with accompanying synthesis of ATP is called **cellular respiration**. Carbon dioxide and water are produced as by-products.
Since water molecules appear on both the sides, the equation can be simplified as under.
On hydrolysis of ATP, under the action of enzyme ATPase, the terminal phosphate is removed with the result that ADP and Pi are formed and certain amount of energy is released.

11.4.1 Oxidative phosphorylation:

In the process of respiration glucose loses hydrogen atoms as it is converted to carbon-dioxide. Simultaneously molecular oxygen gains hydrogen atoms and is being converted to water. Each hydrogen atom contains one electron and one proton. Thus transfer of hydrogen atoms is the transfer of electrons and protons. The movement of electrons from one molecule to another is an oxidation and reduction or redox reaction. Redox reaction is coupled reaction and requires both donor and acceptor of electrons. In the process of respiration glucose is oxidized with the loss of electrons and oxygen is reduced by the gain of electrons. During redox reaction, electrons give up energy which is used in synthesis of ATP from (ADP) Adenosine di phosphate and inorganic phosphate (Pi). This synthesis of ATP is called **Oxidative phosphorylation**.

11.4.2 Aerobic and Anaerobic Respiration:

There are two types of cellular respiration.

i) Aerobic (Aero = air, bios = life) respiration.

ii) Anaerobic (An = without Aero = air, bios = life) respiration.

i) Aerobic respiration: Most of the organisms called aerobes, breakdown sugar, involving participation of molecular oxygen and release carbon dioxide, water and sufficient amount of energy. This type of respiration is known as aerobic respiration.

ii) Anaerobic respiration: A small but significant minority of organisms can obtain energy by breaking down sugar in absence of oxygen. This type of respiration is known as anaerobic and organisms are called anaerobe. Many microorganisms including yeasts and some bacteria can respire anaerobically. Certain species of annelids that live in oxygen deficient mud, gut parasites such as tapeworms, roots of plants growing in water logged area and certain tissues under certain conditions respire anaerobically. Two types of anaerobe are recognised a) obligate anaerobe which never need oxygen at all and b) facultative

aerobes which respire aerobically in presence of oxygen and switch over to anaerobic respiration when oxygen is absent or in short supply.
The products of anaerobic respiration are either ethyl alcohol and carbon-dioxide or lactic acid. The process is less efficient in terms of energy production as only a small amount of energy is released. This is because glucose molecule is incompletely oxidized and most of the potential energy is left in end products.
Fermentation: Originally defined by W. Pasteur as respiration in the absence of air, it is an alternative term used for anaerobic respiration, the production of ethyl alcohol from glucose is called Alcoholic fermentation and that of lactic acid as lactic acid fermentation.

Economic importances of fermentation:
Fermentation, though an inefficient method of harvesting biological energy, is an efficient source of many valuable products such as ethyl alcohol, lactic acid, propionic acid and butanol. Thus it has been of great interest to human beings. Brewing and dairy industries rely on fermentation. It is the source of ethyl alcohol in wines and beers. Wines are produced by fermenting fruits particularly grapes. Beers are produced fermenting malted cereals such as barley.
Yeast cells are used to make dough rise before it is baked to make bread. Cheese, yoghurt and other dairy products are produced by microbial fermentation. Lactic acid which is slightly sour, acid imparts flavour to yoghurt and cheese. Dairy products containing lactic acid are more resistant to spoilage. The characteristic flavour of pickles is due to lactic and acetic acid. Acetone and other industrially produced solvents are also by-products of fermentation.

11.4.3Glycolysis: (Glyco = sugar, Lysis = splitting)
The process of aerobic respiration is a continuous one, but for the sake of study it is divided into three main stages.

(i) Glycolysis (ii) Kreb's cycle (iii) Electron transport chain.

In Glycolysis, Glucose; a six carbon molecule is degraded through sequential enzyme dependent reactions into two molecules of pyruvic acid, a three carbon compound.
Glucose is a stable molecule i.e. It has little tendency to breakdown into simpler products. If the energy locked in its molecular configuration is to be released, the glucose must first be made more reactive. A small amount of energy must be invested by the cell to initiate glycolysis. It is adenosine tri phosphate (ATP) that provides the energy for initiating glycolysis.
The first step in glycolysis is the transfer of phosphate group from ATP to No. 6 carbon of glucose. Adenosine di phosphate and glucose 6-phosphate are formed. After an enzyme catalyses, the conversion of glucose 6-phosphate to its isomer fructose-6-phosphate (F-6-P). Another molecule of ATP is invested which transfers its phosphate group this time to No. 1 carbon of F-6-P forming fructose-1, 6-di phosphate and ADP. These reactions are known as **phosphorylation** reactions because phosphate groups are added to glucose and fructose molecules. The next step in glycolysis is enzymatic splitting of fructose 1, 6-di phosphate into two fragments. Each of these two molecules contain three carbon atoms. One is called phosphoglycer aldehyde (PGAL) and other is Dihydroxy acetone phosphate (DHAP). These two sugar molecules are isomers to each other and are interconvertible. This is the reaction from which glycolysis derives its name. Normally both these molecules are converted into pyruvic acid through subsequent enzyme controlled reactions. Since two molecules of ATP are used this part of glycolysis is the energy investment phase. In the remaining part of glycolysis ATP molecules are synthesized hence it is called energy yielding phase.
In the following reaction, an enzyme dehydrogenase and a co-enzyme nicotinamide dinucleonde NAD^+ work together. The enzyme strips off two

hydrogen atoms from PGAL. These electrons are captured by NAD^+. This is a redox reaction where PGAL is oxidized by removal of electrons and NAD is reduced by the addition of electrons. With the loss of two hydrogen atoms PGAL is converted into phosphoglyceric acid (PGA). Now PGA picks up phosphate group (Pi) present in cytoplasm and becomes 1-3 di phosphoglyceric acid (DPGA). In the very next step DPGA loses its phosphate group to ADP forming ATP and 3-phosphoglyceric acid. The phosphate group attached with carbon atom No.3 of PGA changes its position to carbon atom No.2 forming an isomer 2-phosphoglyceric acid. With removal of water molecule 2 PGA is converted into phospho-enol pyruvic acid (PEPA). Finally phosphate group is transferred to ADP forming ATP and pyruvic acid. Synthesis of ATP during glycolysis is known as substrate level phosphorylation because phosphate group is transferred directly to ADP from another molecule.

Glycolysis is the universal energy harvesting process of life. Metabolic machinery of glycolysis is found in all organisms from unicellular bacteria and yeasts to multicellular bodies of plants, animals and human beings. Glycolysis occurs freely in anaerobic environmentwithin cytoplasm without being associated with organelle or membrane structure. Net input and output of glycolysis can be summarized as under.

Looking back over glycolysis for energy yield, 4ATP molecules are produced at substrate level phosphorylation and 2 ATP molecules are consumed to initiate the process. Thus there is net gain of two ATPmolecules. The process also yields two pairs of energized electrons and two NADH.

11.4.4Break down of Pyruvic acid:

The molecular remains of glycolysis are two molecules of pyruvic acid. There are three major pathways by which it is further processed. Under anaerobic conditions it either produces ethyl alcohol (Alcoholic fermentation) or lactic acid (Lactic acid fermentation) or produces carbon dioxide and water via Kreb's Cycle under aerobic conditions.

a) Alcoholic fermentation:

Each pyruvic acid molecule is converted to ethyl alcohol in two steps. In the first step pyruvic acid is decarboxylated under the action of enzyme to produce acetaldehyde, a two carbon molecule. $NADH+H^+$ reduces acetaldehyde to ethyl alcohol.

Ethyl alcohol is toxic. Plants never use it. Neither it can be converted to carbohydrate nor it breaks up in presence of oxygen. Accumulation of ethyl alcohol is tolerable to certain level. Plants must revert to aerobic respiration before the concentration exceeds that tolerable limit, other wise they will be poisoned.

b) Lactic acid fermentation:

When $NADH+H^+$ transfers its hydrogen directly to pyruvic acid, it results in formation of lactic acid.

During extensive exercise such as fast running, muscle cells of animals and human beings respire anaerobically. Due to inadequate supply of oxygen, pyruvic acid is convert into lactic acid. Blood circulation removes lactic acid from muscle cells. When lactic acid cannot be removed as fast as it is produced, it accumulates in the cells and causes muscle fatigue. This forces the person to quit or reduce exercise until normal oxygen levels are restored to deprived cells.

11.4.5Formation of Acetyl Co A:

Aerobes utilize molecular oxygen to extract large amount of energy from two products of glycolysis i.e. Pyruvic acid and $NADH+H^+$. Pyruvic acid diffuses from cytoplasmic fluid (Cytosol) into mitochondrion, the site of Kreb's cycle. Before entering into Kreb's Cycle it undergoes chemical changes. It loses one molecule of

CO_2. The remaining 2 carbon fragment is oxidized to form acetyl group, the ionized form of acetic acid and NAD^+ is reduced to $NADH+H^+$. Finally Coenzyme A (CoA), a sulphur containing compound derived from Vitamin B is attached to acetyl group. The product is Acetyl Coenzyme (Acetyl CoA).
Acetyl CoA links glycolysis with Kreb's cycle. It feeds its acetyl group into Kreb's cycle for further oxidation. For each molecule of glucose that entered glycolysis, two molecules of acetyl CoA enter the Kreb's Cycle.

11.4.6 Kreb's Cycle:

Acetyl coenzyme A, a two carbon compound now participates cyclic series of reactions during which oxidation process is completed. This series of cyclic reactions is called Kreb'scycle or citric acid cycle. The first name honours the biochemist Sir Hans Kreb who worked out these cyclic reactions. The second reflects the first step in the cycle i.e. Citric acid.
An enzyme strips CoAfrom Acetyl CoA. The remaining acetyl fragment reacts with four carbon compound oxalo acetic acid to form 6-carbon compound, citric acid. One molecule of water is used and co-enzyme A is recycled again. Citric acid possesses three carboxyl groups. Hence, Kreb's cycle is also known as tricarboxylic acid cycle or (TCA Cycle).
A molecule of water is removed and another added back so that Citric acid is isomerised to isocitric acid through Cis-aconitic acid.
Isocitric acid undergoes an oxidative decarboxylation reaction. It is first oxidized yielding a pair of electrons (2H) that reduces a molecule of NAD to $NADH+H^+$. The reduced carbohydrate intermediate is decarboxylated. With the removal of CO_2 molecule a 5 carbon compound α-ketoglutaric acid is formed.
α-ketoglutaric acid is again oxidatively decarboxylated. A CO_2 molecule is lost. The remaining four carbon compound is oxidized by transfer of a pair of electron ($2H^+$) reducing NAD^+ to $NADH+H^+$. The four carbon fragment combines with CoA by an unstable bond forming succinyl CoA. Substrate level phosphorylation takes place in the next step. CoA is replaced by phosphate group which is then transferred to Guanosine di phosphate (GDP) to form Guanosine tri phosphate (GTP).
GTP transfers its phosphate group to ADP forming ATP. With addition of water molecule succinic acid is formed.
With loss of two electrons ($2H^+$) Succinic acid is converted to Fumaric acid and $FADH_2$are formed. With addition of one water molecule fumaric acid is converted to malic acid. The last step in kreb's cycle is regeneration of oxalo acetic acid. This is formed by removal of electrons ($2H^+$) from malic acid to NAD^+ forming $NADH+H^+$.
Glucose molecule splits into two molecules of pyruvic acid during glycolysis. Thus two turns of cycle are required for each glucose molecule. For each pyruvic acid molecule, three carbon atoms are removed as CO_2 and five pairs of hydrogen atoms are used to reduce NAD andFAD to $NADH+H^+$ and $FADH_2$, the carrier molecules. The inputs and outputs of kreb's cycle are shown as under.

11.4.7 Electron transport system:

Respiration is an oxidation process in which hydrogen atoms in pairs are removed from oxidizing substrate at various stages during glycolysis and subsequent degradation of pyruvic acid via Kreb's cycle. A pair of hydrogen atom disassociate into a pair of electron and a pair of proton.
In respiration there are six steps at which hydrogen atoms in pairs are released (one in glycolysis and five in kreb's cycle). The electrons thus released at these stages are accepted by Nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) from where they are passed along a chain of electron carriers such as cytochrome "b", cytochrome "c" cytochrome "a" and cytochrome 'a-3' as shown in fig: 11.10. While passing from one carrier to another, these cytochromes are alternately reduced (receive electrons) and oxidized (give up

electrons) with it energy is released which is used in the formation of ATP (adenosine tri phosphate) from ADP and inorganic phosphate. This formation of ATP is called oxidative phosphorylation and takes place in mitochondria. Complete oxidation of a glucose molecule (hexosesugar) results in a net gain of 36 ATP molecules which are released in cytoplasm available for different metabolic reactions.

11.5 ENERGY FLOW THROUGH THE ECOSYSTEM

In an ecosystem, organisms are linked together in energy and nutrient, relationship. The energy can be defined as the capacity to do work. The term work can be used to any energy consuming process such as living cells maintain electrical gradient across membrane and the active transport process which requires expenditure of energy. However, the ecological studies relating food requirement and energy relationship among living components of an ecosystem are referred as bioenergetics. Energy is found in four main forms i.e. radiant energy, heat energy, chemical energy and mechanical energy. Only a small part of solar energy is visible spectrum.

11.5.1Sun as a source of energy:

The ultimate source of energy in an ecosystem is the sun light. It travels as electromagnetic waves and about 40% is reflected back from clouds and other 15% is absorbed by ozone layer and is converted to heat energy by the atmosphere; remaining 45% reaches to earth, of which a small fragment i.e. 2-3% is absorbed by green plants while rest is reflected and dispersed.

11.5.2Unidirectional flow of energy and its subsequent losses:

Energy from sun flows in one way traffic and is not recycled as nutrients, though transforms form one form to another. The producers or green plants directly absorb it from sun and than pass it to organisms.

The plants convert solar energy into chemical energy present in the bonds of chemical substances (mainly ATP molecules). Different forms of energy are interchangeable and they followthe set rules of thermodynamics. According to first law, energy may be transformed from one form into another form but can neither be created nor destroyed. Whereas, second law states that no conversion can be 100 percent accurate and some energy must escape as heat.

Let us consider a simplified energy flow diagram, where one square meter of an ecosystem for example receives 3000 calories of light energy, half of it is absorbed by autotrophic plants i.e. producers of which only about 1 to 5 percent of it is converted to food energy. Thus, only 15 to 75 calories are passed to consumers of various levels. Further loss takes place due to respiration and only 10 percent of iti.e. 1.5 calories reaches to secondary consumers. Thus at each trophic level there is ten time reduction in availability of energy.

11.5.3Trophic Levels: (Trophos = feeding)

In an ecosystem heterotrophs depend upon autotrophic organisms for their food. The autotrophic organisms produce organic substances which are used by heterotrophs. In a food chain a set of organisms is used by other set of organisms, thus eating and being eaten at each stage a particular set of organisms is referred as **trophic level**. In an ecosystem, the first set or 1st trophic level consists of autotrophic plants which take energy from sun and convert it into chemical energy in the form of ATP molecules. The plants are also referred as **producers**. The producer are mainly photosynthetic organisms. Second trophic level consists of herbivores, they feed on producers hence they are known as **primary consumers**. The third trophic level consists of **secondary consumers.** They depend for the food source on primary consumers or herbivores and hence they are carnivores. Similarly the secondary consumers are eaten by tertiary consumers which are also carnivores, hence they form fourth trophic level. The secondary and tertiary consumers may be **predators**. Thus an ecosystem may have 4 to 5 trophic levels. The primary, secondary or tertiary consumers after their death are eaten by decomposers which are saprotrophs (bacteria or fungi) in this way they form 4th or 5th tropic level.

Pyramid of Energy:

The quantitative studies of an ecosystem are carried out by two way i.e. by studying the food chain or food web, and by ecological pyramids. The ecological pyramids are the pyramid of numbers. It is diagrammatic representation of trophic levels i.e. producers, herbivores and carnivores. Pyramid is drawn on the basis of their number. The second way is the use of pyramid of biomass, instead of numbers at each level it involves total mass of the living organisms present at each trophic level. The third way of study is pyramid of energy.

The relationship between different trophic levels is shown by means of pyramid of energy. It provides best picture of ecosystem. It depends upon rate at which food is being produced, however the pyramids of number and biomass provide the picture of existing situation or standing situation. The base of pyramid is represented by primary producers showing the amount of energy they trap during photosynthesis and convert it into chemical energy. Hence, the energy flow from one trophic level to another is calculated and represented diagrammatically in pyramid. Each bar of pyramid represents the amount of energy per unit area in a given period of time. E.P. Odum calculated the energy flow for silver spring, Florida as shown in figure 11.113.

11.5.4The Efficiency of Energy flow and its significance:

The efficiency of energy flow depends upon productivity of an ecosystem which in turn depends upon radiant energy.

Duringphotosynthesis green plants trap sunlight and convert it into food energy. The energy stored in food material by primary producers is said to be **primary productivity.** It depends upon the rate and amount of energy available to an ecosystem. Only a part of it is absorbed by chlorophyll in production of organic molecules. The rate at which this chemical energy is stored by plants is, called **Gross primary productivity (GPP).** About twenty percent of it is used by plants themselves in respiration and other functions, whereas the remaining is stored and is called **net primary productivity (NPP).**

The herbivores feed upon producers and thus the energy is transferred to second trophic level i.e. primary consumers. The production by heterotrophic consumers of various levels is called **secondary production**. The average efficiency of energy transfer from plants to herbivores is about 10 percent and from animal to animal is about 20 percent.

Advantages of short food chains:

Man plays an important role in various food chains, being omnivore, man eats both plants and animals, hence when man eats plants acts as primary consumers, when man eat other primary consumers like cowand sheep he becomes secondary consumers, similarly when man eats carnivorous fishes, he becomes tertiary consumer. So, in ecosystem as it is clear from pyramid of energy, there is great loss of energy at each trophic level, and very short amount of energy is transferred at next trophic level. Most of the energy is lost as heat, this is due to this fact that the total biomass decreases at each level.

The lesson from the pyramid of organic matter was summarized by a popular 1970s phrase "Eat low on the food chain". This refers to the fact that it takes 10 kg of grain to build 1 kg of human tissues if the person eats the grain directly but it takes 100 kg of grain to build 1 kg of human tissue if a cow eats the grain first and the person eats the beefs. Eating lower on the food chain-eating producers, not consumers-save

precious resources on a small planet.

Thus, longer food chains such as in food web consume large amount of energy because loss in form of heat is greater as compared to short food chains. As man is the end source of several food chains, so these large food chains or food webs are nothelpful for solving food problems. Consider a food chain like grass-sheep-man; is a simpler and linear food chain, where loss of energy is very little. So short food chains are helpful in providing food for larger populations while food webs or longer food chains sustained lesser population.

KEY POINTS

- Capturing and conversion of solar energy from one form to another in the living system and its utilization in metabolic activities called **bioenergetics**.
- Plant and other autotrophs are the producers of the biosphere.
- Photo autotrophs use the energy of sunlight to synthesize organic molecule from CO_2 and H_2O.
- Light reaction in grana produces ATP and splits water, releasing oxygen and forming NADPH by transferring electrons from water to NADP.
- Alternative mechanisms of carbon fixation has evolved in hot, arid climate i.e. C_4 plants and CAM plants.
- Cellular respiration and fermentation are catabolic i.e. energy yielding processes.
- Redox reaction release energy for ATP synthesis, this synthesis of ATP is called **oxidative phosphorylation.**
- Respiration is a cumulative function of glycolysis, Kreb's cycle and electron transport.
- Glycolysis harvests chemical energy by oxidizing glucose to pyruvate, occurs in cytosol, produces net two molecules of ATP.
- Pyruvic acid may go to 3 major pathways, i.e. alcoholic fermentation, lactic acid fermentation and Kreb's cycle.
- Krebs cycle completes theenergy yielding oxidation of organic molecule, CO_2 is given off, one ATP is formed and e^- are passed to 3 NAD^+ and one FAD^+.
- Energy from sun absorbed by plant convert it into chemicals, transfer to consumers.
- Energy flow from tropic level to another follows 1st and 2nd law of thermodynamics.
- Each stage in a food chain with a particular set of organisms is called **trophic level.**
- The diagrammatic representation of trophic levels is called **pyramid**.
- Energy stored in food material by primary producers is said to be **primary productivity** and the rate at which this energy is stored called **grossprimary productivity.**

EXERCISE

1. Encircle the correct choice:

(i) Photosynthesis is measured in leaf of a green plant exposed to different wavelength of light:
(a) highest in green light (b) highest in red light
(c) highest in blue light (d) highest in red and blue light

(ii) Where do the light-dependent reaction of photosynthesis occur:
- (a) in the guard cells of stomata
- (b) stroma of chloroplast
- (c) in the thylakoid membrane of chloroplast
- (d) Cytoplasm of leaf

(iii) Oxygen produced during photosynthesis comes from:
- (a) the break down of CO_2 (b) the break down of H_2O
- (c) break down of both CO_2 and H_2O
- (d) Photo respiration

(iv) Where does respiratory electron transport occur:
- (a) cytoplasm (b) matrix of mitochondria
- (c) inner membrane of mitochondria
- (d) outer membrane of mitochondria

(v) What are the economically important products of fermentation of grape juice by yeast.
- (a) Lactic acid and NAD^+ (b) ATP and CO_2
- (c) ATP and ethanol (d) $CO_2$and ethanol

(vi) Process which convert pyruvate in to three molecules of CO_2 is
- (a) C_3Cycle (b) C_4Cycle
- (c) TCA Cycle (d) Banson and calvin cycle

(vii) The generation of ATP by electron transport chain coupled with H^+ ion pump process is called:
- (a) Chemosmosis (b) Endosmosis
- (c) Exosmosis (d) None of them

(viii) The primary electron acceptor in photosystem II is:
- (a) Plastoquinone (b) Plastocyanin
- (c) Pheophytin (d) Ferrodxin

(ix) Flow of energy in an ecosystem is:
- (a) Cyclic (b) Non-cyclic
- (c) Unidirectional (d) Multidirectional

(x) Enzyme responsible for the carboxylation in Banson and Clavin cycle is:
- (a) RUBISCO (b) PEPC
- (c) Pepsin (d) Isomerase

2. Write detailed answers of the following questions:

- (i) Define photosynthesis? Describe the process of photosynthesis?
- (ii) What do you mean by energy producing process during which O_2 is consumed? Describe the aerobic degradation of pyruvic add?
- (iii) What do we mean by energy flow in an ecosystem? What is the role of this flow is the living world?

3. Write short answers of the following questions:

- (i) Why ATP is called currency of energy in living system?
- (ii) Why light independent phase of photosynthesis is called C_3 cycle?

(iii) Why ATP formation during photosynthesis is called non-cyclic photophosphorylation?
(iv) Why kreb's cycle is also called TCA cycle?
(v) Why ATP formation during glycolysis is called substrate level phosphorylation?
(vi) Why photo respiration is called waste full process?
(vii) How plants adopt themselves to avoid from photo respiration?

4. Write short notes on the following:

(i) Chloroplast
(ii) Photosystems of photosynthesis
(iii) Glycolysis
(iv) Kreb's cycle
(v) Significance of energy flow in ecosystem

5. Define the following terms:

(i) Bioenergetics
(ii) Photosynthesis
(iii) Chloroplast
(iv) Antenna complex
(v) reaction centre
(vi) Photophosphorylation
(vii) Chemosmotic
(viii) Photolysis
(ix) Carboxylation
(x) Oxidative phosphorylation
(xi) Fermentation
(xii) Glycolysis
(xiii) Trophic level
(xiv) Ecological pyramids
(xv) Primary productivity

6. Distinguish between:

(i) Photosynthesis and respiration
(ii) Light dependent and independent phase of photosynthesis
(iii) PSI and PSH
(iv) Photophosphorylation and oxidative phosphorylation
(v) Aerobic and anaerobic respiration