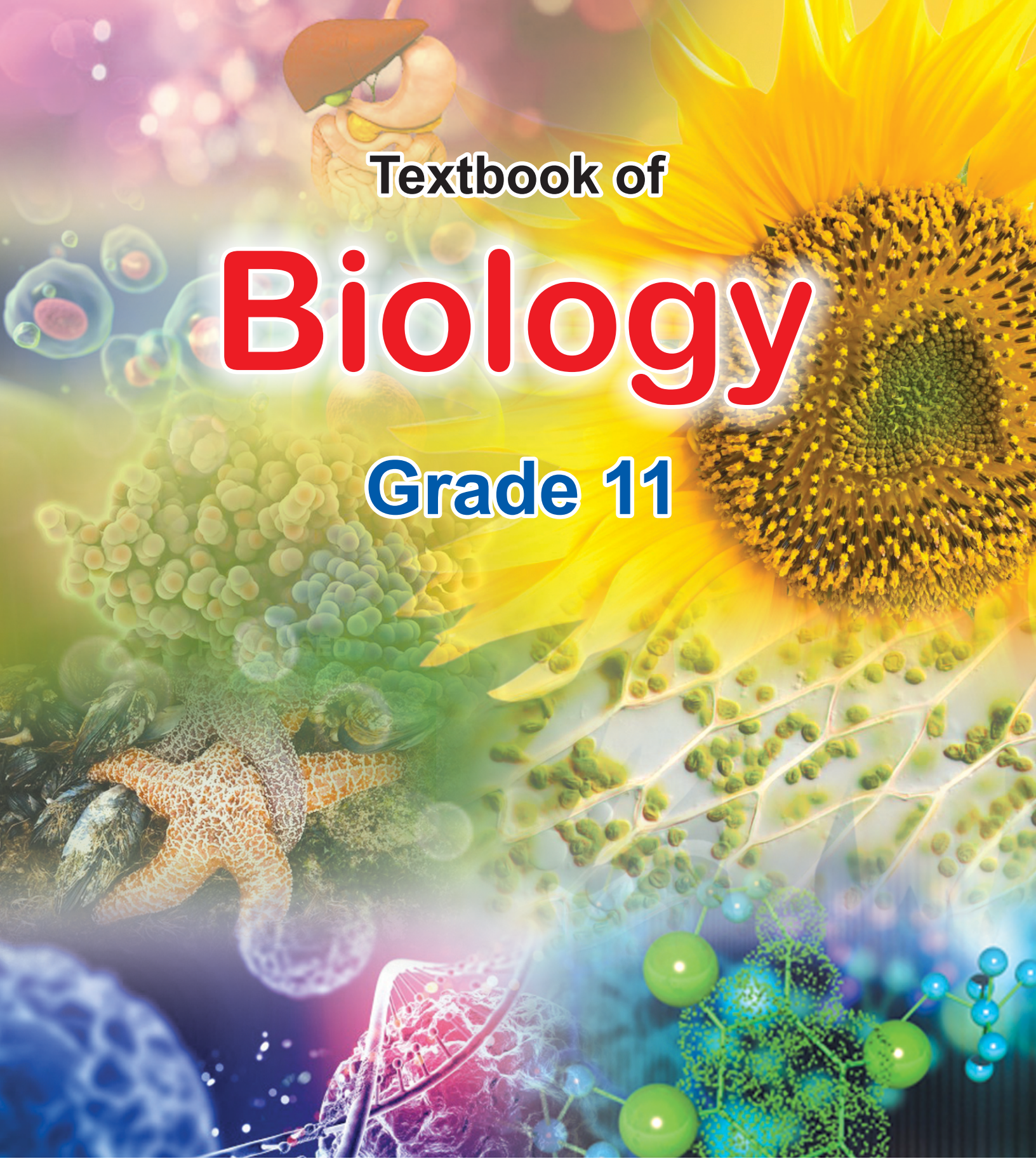

Textbook of Biology

Grade 11

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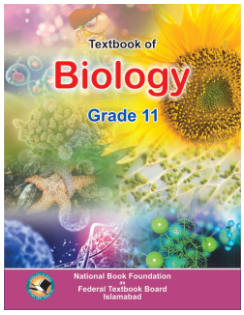
OUR MOTTO

• Standards • Outcomes • Access • Style

Note

The material given in the box (Science titbits, Did you know, Critical thinking, STSC, Activity, Teacher's Point) and parenthesis, are not part of the textor SLO's.

Textbook of
Biology Grade - 11



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Preface

Biology Grade - 11 is developed according to the National Curriculum 2006. It is being published since 2013 and now it is presented under the supervision of textbook development, principles and guidelines with new design and layout.

The standard includes higher thinking, deep knowledge, problem solving substantive conversation and connections to the world beyond the class room and achieve the target set by the curriculum. The special features of the textbook are:

- Each chapter begins with a brief recalling statement i.e., introduction to the chapter. The textbook has coloured illustrations to capture the students' attention. Where necessary, concept mapping has also been incorporated.
- Necessary 'Titbits' and 'Critical Thinking' have been added in each chapter for motivating the students to apply their intelligence and acquire more knowledge.
- The exercises include multiple choice questions, short answer questions and extensive questions. These are given for reinforcement. The teachers should develop assessments questions as per Bloom's Taxonomy.
- At the end of the book a glossary has been annexed.

In each chapter Science, Technology and Society connections are explained in accordance with the curriculum. These interventions will serve as a guide for evaluating the students' skills development through the chapter knowledge and their abilities to apply knowledge to the scientific and social problems. The duration or the number of periods is also allocated to complete each chapter, so that the teachers can develop their teaching strategy and plans in an effective manner accordingly.

Quality of Standards, Pedagogical Outcomes and Actualization of Style is our motto. With these elaborations, this series of new development is presented for use. However there is always room for improvement and suggestions from the teachers and the community will be highly appreciated to make the book more valuable and to make the textbook more interesting, informative and useful for the student. After educational feedback, research and necessary changes, the book is being published again.

May Allah Guides and helps us. (Ameen).

National Book Foundation

Contents

بِسۡمِ اللّٰہِ الرَّحۡمٰنِ الرَّحِیۡمِ ○

In the Name of Allah, the Most Gracious, the Most Merciful

CONTENTS

SECTION 1

Cell Biology

Electron microscope

1

CELL STRUCTURE AND FUNCTIONS

After completing this lesson, you will be able to

- List the principles and identify the apparatus used in the techniques of fractionation, differential staining, centrifugation, micro-dissection, tissue culture, chromatography, electrophoresis and spectrophotometry.
- Describe the terms of resolution and magnification with reference to microscopy.
- Explain the use of graticule and micrometer.
- Describe the locations, chemical compositions and significance of the primary and secondary cell walls and of middle lamella.
- Explain the chemical composition of plasma membrane.
- Rationalize the authenticity of the fluid mosaic model of plasma membrane.
- Relate the lipid foundation and the variety of proteins of the membrane structure with their roles.
- Identify the role of glycolipids and glycoproteins as the cell surface markers.
- Explain the role of plasma membrane in regulating cell's interactions with its environment.
- Describe the chemical nature and metabolic roles of cytoplasm.
- Distinguish between smooth and rough endoplasmic reticulum in terms of their structures and functions.
- Explain the structure, chemical composition and function of ribosome.
- Describe the structure and functions of the Golgi complex.
- State the structure and functions of the peroxysomes and glyoxysomes in animal and plant cells.
- Describe the formation, structure and functions of the lysosomes.
- Interpret the storage diseases with reference to the malfunctioning of lysosomes.
- Explain the external and internal structure of mitochondrion and interlink it with its function.
- Explain the external and internal structure of chloroplast and interlink it with its function.
- Describe the structure, composition and functions of centriole.
- Describe the types, structure, composition and functions of cytoskeleton.
- Explain the structure of cilia and flagella and the mechanisms of their movement.
- Describe the chemical composition and structure of nuclear envelope.
- Compare the chemical composition of nucleoplasm with that of cytoplasm.
- Explain that nucleoli are the areas where ribosomes are assembled.
- Describe the structure, chemical composition and function of chromosome.
- List the structures missing in prokaryotic cells.
- Describe the composition of cell wall in a prokaryotic cell.
- Differentiate between the patterns of cell division in prokaryotic and eukaryotic cells.
- Relate the structure of bacteria as a model prokaryotic cell.

You are quite familiar with the word "cell" i.e., a basic unit of life. By the middle of the nineteenth century, biologists had formulated **cell theory** which is a fundamental concept in biology. The generally accepted portions of the modern cell theory are as follows:

(1) The cell is the fundamental unit of structure and function in living things.

(2) All organisms are made up of one or more cells.

(3) Cells arise from other cells through cellular division.

This chapter will help you to become familiar with the structure of cells and how they work, and also the basic techniques essential for cell study.

1.1 TECHNIQUES USED IN CELL BIOLOGY

To know the structure and functions of cells etc., and cell organelles some of the techniques will be discussed here in brief.

1.1.1 Cell Fractionation

Cell fractionation is the combination of various methods used to separate a cell organelle and components based upon size and density. It is very useful for electron microscopy of cell components. The principle of cell fractionation consists of two steps i.e., homogenization and centrifugation.

Homogenization

It is the formation of a homogenous mass of cells. It involves the grinding of cells in a suitable medium with correct pH, ionic composition and temperature. In plants enzyme pectinase is added to digest middle lamella. This can be done in a blender. This procedure gives rise to a uniform mixture of cells which is then centrifuged.

Centrifugation

Centrifugation is the process to separate substances on the basis of their size and densities under the influence of centrifugal force. It is done by the machine called **centrifuge**. This machine can spin the tubes at very high speed. Spinning the tubes exerts a centrifugal force on the contents. There are two major ways of centrifugation i.e., density gradient centrifugation and differential centrifugation. In **density gradient centrifugation** the cell components of different sizes and densities are separated in different layers. The upper layers are less dense than lower layers.

In **differential centrifugation** the size and shape of particles determines how fast it settles. A series of increasing speeds can be used. At each step, the content which settles in the bottom of the tube are called **pellet** and those that remain suspended above in the form of liquid are called **supernatant**. After each speed, the supernatant can be drawn off and centrifuge again. A series of pellets containing cell organelles of smaller and smaller size can therefore be obtained.

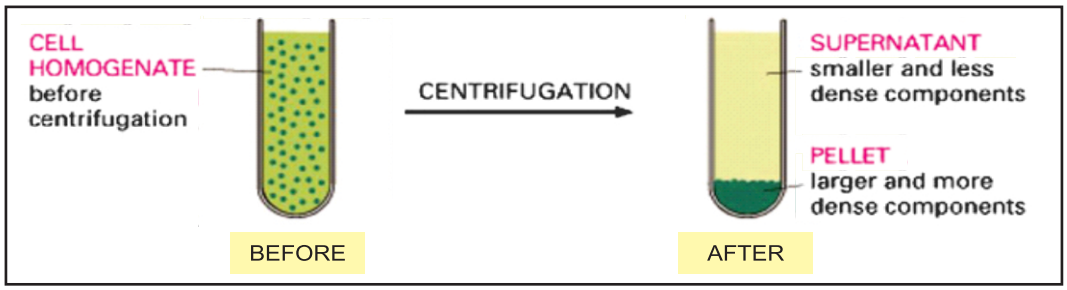


Fig 1.1: Centrifugation of cells

Science Titbits

During centrifugation the bigger particles sediment faster and have higher sedimentation coefficients (Svedberg, or S values). Sedimentation coefficients are, however, not additive. Sedimentation rate does not depend only on the mass or volume of a particle, and when two particles bind together there is inevitably a loss of surface area. Thus when measured separately they will have Svedberg values that may not add up to that of the bound particle. This is notably the case with the ribosome. Ribosomes are most often identified by their sedimentation coefficient. For instance, the 70 S ribosome that comes from bacteria has actually a sedimentation coefficient of 70 Svedberg, although it is composed of a 50 S subunit and a 30 S subunit.

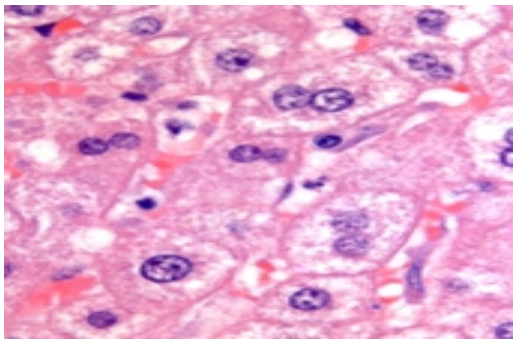


Fig. 1.2: Differential staining

1.1.2 Differential Staining

Most biological structures are transparent. In order to differentiate between these structures various colour dyes are applied. Such techniques are called **staining techniques.** When only one stain, such as borax carmine (that stains nucleus) is used it is called **single staining**. When two stains, one that will stain nucleus e.g., haematoxylin and other that will stain cytoplasm e.g., eosin are used, the process is called **double staining** or **differential staining.**

1.1.3 Microdissections

Microdissection refers to the variety of techniques where a microscope is used to assist in dissection. It is done to remove tumour or granules from delicate tissue or cells like, brain, heart and nerve cells. In this technique, the image is seen on large TV screen or monitor while dissecting

1.1.4 Tissue Culture

Growth of a cell or a tissue on chemically defined nutrient medium under sterile conditions is called **tissue culture**. This technique can be employed for both plants and animals.

Plant tissue culturing is mainly used for plant cloning i.e., production of genetically identical plants (clones). Animal tissue culture is usually set up by growing individual cells to form a single layer of cells over the surface of a glass container. Animal tissue cultures are used to see any abnormality in the cell, e.g., cancer, chromosomal disorder etc.

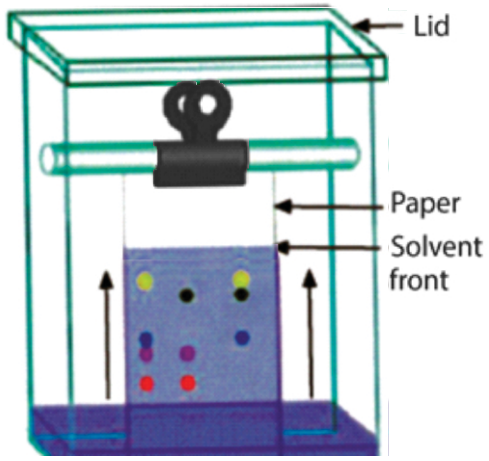


Fig. 1.3: Chromatography chamber

1.1.5 Chromatography

Chromatography is a technique which is used to separate different chemical compounds from a mixtures. It is generally used for the separation of mixtures of proteins, amino acids or photosynthetic pigments. There are different types of chromatographic techniques.

Paper chromatography is a simple and most widely used technique. It involves two phases. **Stationary phase** which is cellulose filter paper and **mobile phase** is solvent in which sample mixture is dissolved. When the solvent travels over the paper, the mixture sample begins to separate as dots at different places on paper according to their affinity. This paper is then called **chromatogram.**

1.1.6 Electrophoresis

It is a technique which is used to separate fragments of a charge bearing polymer molecule according to their size, shape, molecular weight and surface charge whether (+) or (–). Such charge bearing polymer molecules are DNA, RNA, protein etc.

This technique utilizes a gel medium for separation of fragments which is done under the influence of an electric field. Often the gel is sandwiched between glass or plastic plates to form a viscous slab. The two ends of the slabs are suspended in two salt solutions that are connected by electrodes to a power source. At one end of the slab the samples are loaded. When voltage is applied to the apparatus, the molecules present in the gel migrate through the electric field.

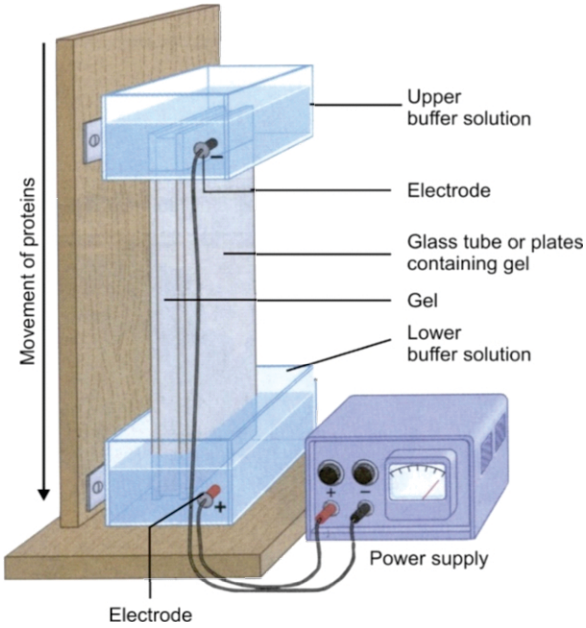


Fig. 1.4: Gel electrophoresis

The negative charged molecule will move towards the positive pole and the molecule having positive charge will move towards the negative pole. The velocity of movement of fragments is inversely proportional to the size. Therefore smaller fragments move faster than larger. In this way all the fragments are separated in the gel after some time. Later on the molecules can be pin pointed by staining the gel.

1.1.7 Spectrophotometry

Spectrophotometry is a technique which is used to determine the absorption of different wavelength of light by a particular chemical compound or a photosynthetic pigment. For this purpose the instrument used is **spectrophotometer.** The amount of light absorbed at each wavelength is plotted in a graph called the **absorption spectrum.**

Fig. 1.5: Spectrophotometer

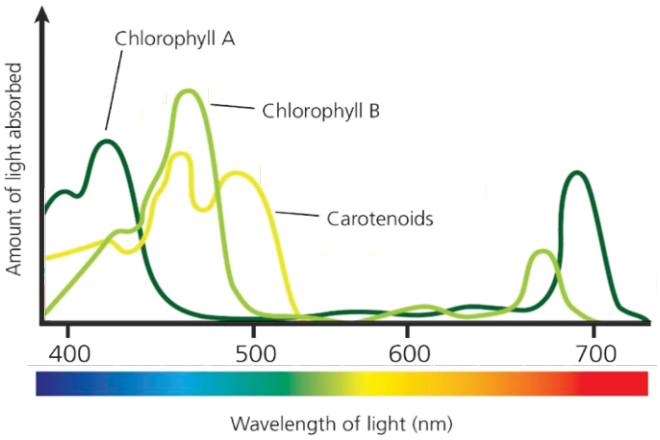


Fig. 1.6: Absorption spectrum

Spectrophotometry can be used to determine the wavelengths of light that take part in photosynthesis. It can also be used to determine the very minute quantity of a substance (such as DNA) in a sample.

1.1.8 Resolution and Magnification in Microscopy

The minimum capacity of a lens to differentiate between two adjacent points is called **resolution.** The resolution of naked eye is 0.1 mm. This resolution can be increased by increasing magnification. The **magnification** is the capacity of an optical instrument to increase the size of an object than its original size. The objects which cannot be seen by naked eye can also be observed by increasing magnification. Different lenses have different magnification powers which are represented by letter "X" that means the number of times than original size. Therefore, a lens of 10X magnification power can increase the size of an object of 1 µm to 10 µm.

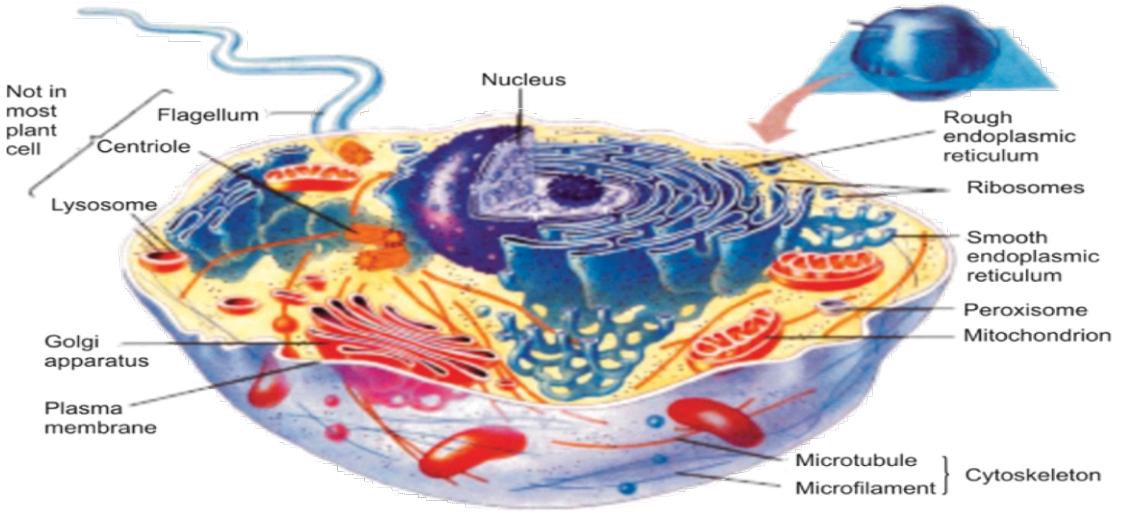


Fig. 1.7: Electron microscopic structure of an animal cell

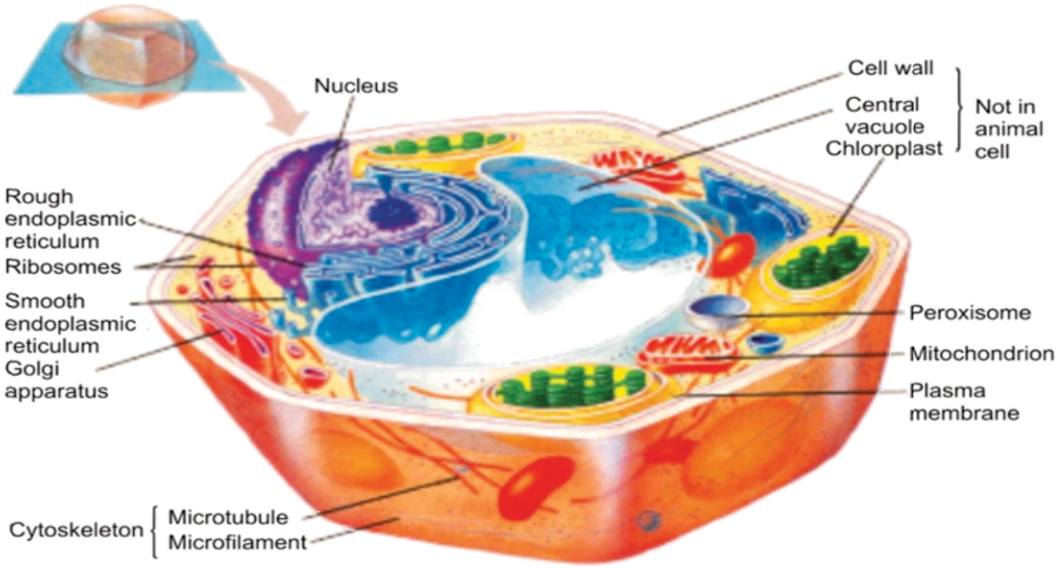


Fig. 1.8: Electron microscopic structure of a plant cell

Microscopy is the technique used to view objects that cannot be seen by the naked eye. The range can be anything between mm and nm. Most animal cells and plant cells are between 10 µm and 30 µm. A common compound microscope consists of ocular lens and objective lens. The overall magnification power of such a microscope is equal to the product of

magnification powers of both lenses. The resolving power of light microscope is 250 nm and its magnification is up to 4000X. The resolving power of electron microscope is 0.2 nm and its magnification is up to 2,000,000X.

1.1.9 Micrometry

Micrometry is the measurement of the size of objects under microscope. It involves two micrometres. The ocular micrometre is a glass disc with 100 equal divisions with no absolute value. It is placed in the eye piece of the microscope. Then it is calibrated by using a **stage micrometre**. This is a glass slide with an exact scale like a miniature transparent ruler. By superimposing the images of the ocular micrometre and stage micrometre scales, it is calibrated so the size of any given object viewed under the microscope can be estimated.

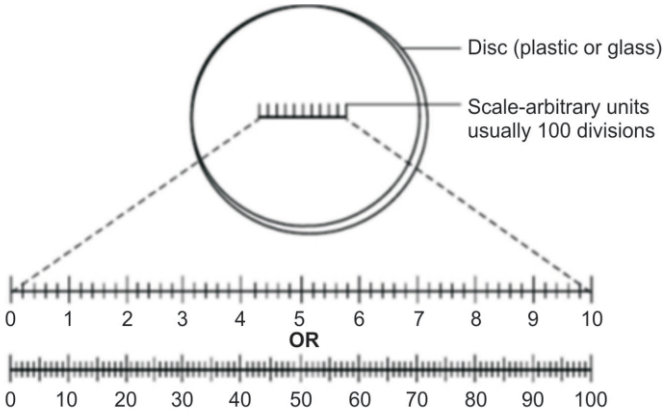


Fig. 1.9: Ocular micrometre

1.2 CELL WALL AND PLASMA MEMBRANE

The plasma membrane is the outer living boundary of the cell. Many cells have an extracellular component that is formed exterior to the membrane, which is called cell wall.

1.2.1 Cell Wall

Critical Thinking

Is plant cell wall permeable, semipermeable or impermeable boundary?

The cell wall is present in plant cells, prokaryotes and fungi but animal cells do not have cell wall. This is probably due to their locomotor mode of life. Plant cell walls (made up of cellulose) differ in chemical composition from those of the prokaryotes (made up of peptidoglycan) and fungi (made up of chitin). We will discuss here only plant cell wall. The cell wall is secreted by the cell. The cell wall is porous and allows free passage of water and dissolved material. The plant cell wall consists of three main layers, primary cell wall, middle lamella and secondary cell wall.

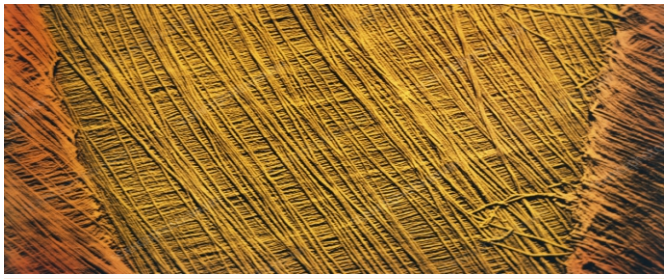


Fig. 1.10 : Crisscross arrangement of cellulose

Science Tidbits

Pectin is a polymer of around 200 galacturonic acid molecules. Majority of its carboxyl groups are methylated ($COOCH_3$). It is less hydrophilic then pectic acid but soluble in hot water. It is another major component of middle lamella but also found in primary walls.

Primary cell wall

Primary cell wall is a true wall and develops in newly growing cell i.e., during cell division. Each cell produces a primary cell wall. The primary cell wall is present inner to the middle lamella. The primary cell wall is thin and slightly flexible. The primary cell wall is composed of cellulose microfibrils (bundles of cellulose chains), running through the matrix of

other polysaccharides like hemicelluloses and pectin. The microfibrils show a crisscross arrangement in layers one above the others. This feature gives the cell great strength. The primary cell wall is adapted to growth. The wall stretches plastically i.e., irreversibly.

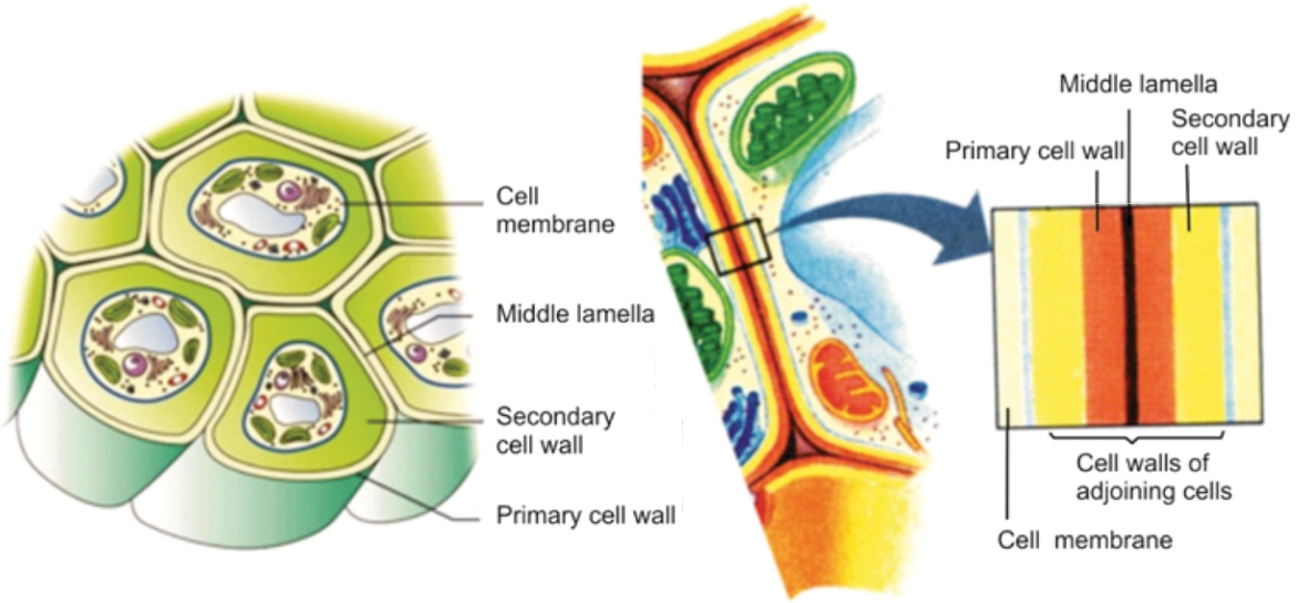


Fig. 1.11: Plant cell wall

Secondary cell wall

Secondary cell wall is formed between the primary cell wall and plasma membrane only in sclerenchyma cells. The plant cells possessing secondary cell wall are generally dead and provide support for the plant. The secondary cell wall develops only when the cell has reached maximum size i.e., completes its growth because it is very much thick and rigid therefore it does not allow further growth. The secondary cell wall consists of cellulose, hemicelluloses, lignin, inorganic salts and waxes. Its cellulose microfibrils also show crisscross arrangement. Lignin cements and anchors cellulose microfibrils together and it is mainly responsible for rigidness. The secondary cell wall provides definite shape and mechanical support to the cell.

Science Titbits

Pectic acids are polymer of around 100 galacturonic acid molecules. These are very hydrophilic and form salts with Ca^{++} and Mg^{++} that are insoluble gels. These are major components of middle lamella but also found in primary cell walls

Middle lamella

Middle lamella is present between primary cell walls of adjacent cells which holds the cells together. It is composed of sticky, gel-like magnesium and calcium salts and pectin.

1.2.2 Plasma Membrane

Plasma membrane is the boundary of protoplasm. It is found in all living prokaryotic and eukaryotic cells. Plasma membrane is also called cell membrane or plasmalemma or cell surface membrane. It controls the passage of materials into and out of the cell.

Composition of plasma membrane

Chemically cell membrane consists of proteins 60-80%, lipids 20-40% and small quantity of carbohydrates.

Critical Thinking

Why the cell surface membrane is described as fluid mosaic?

Structure of plasma membrane

Fluid mosaic model of plasma membrane: The model proposes that the membrane is a phospholipids bilayer in which protein molecules are either partially or wholly embedded. The proteins are scattered throughout the membrane in an irregular pattern just like large ice bergs float in the sea. The pattern of distribution of proteins can vary from membrane to membrane and also vary on both surfaces of membrane. The membrane is about 7 nm thick.

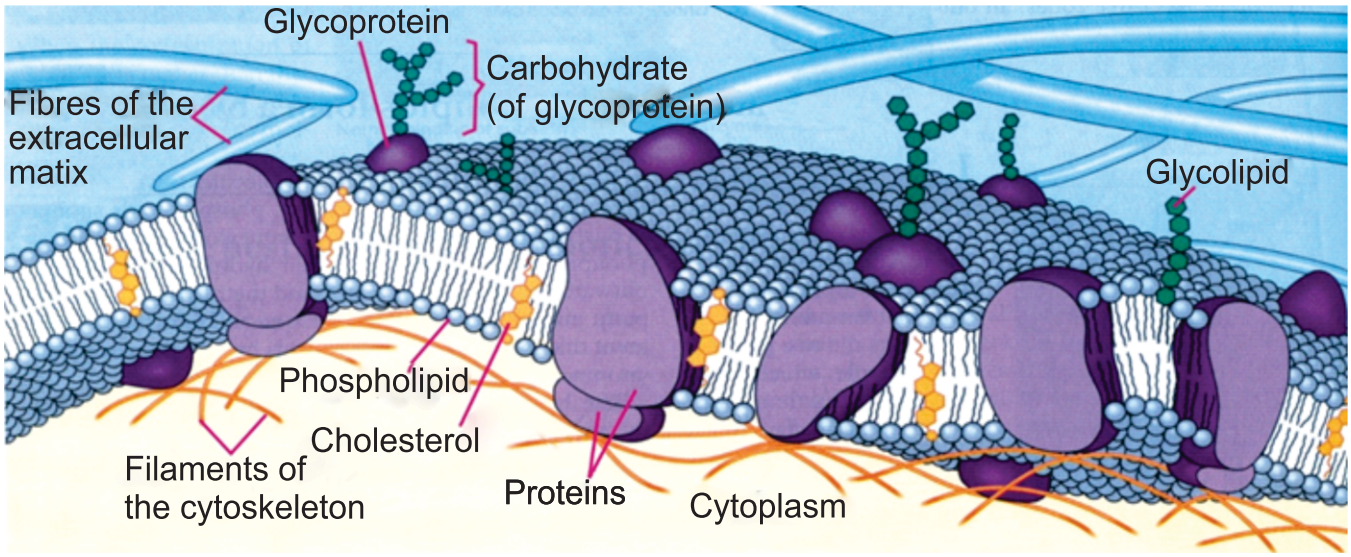


Fig. 1.12: Fluid mosaic model of plasma membrane

The lipid part of plasma membrane consists of two layers (bilayer) of phospholipids which are arranged in such a way that their hydrophobic ends face each other while hydrophilic ends are appeared on the surface. The steroids, cholesterols are wedged into the phospholipid bilayer at some intervals. The plasma membrane is asymmetrical i.e., their two surface and halves are not identical.

Science Titbits

The fluidity of membrane is dependent on its lipid components, including phospholipids, glycolipids and cholesterol.

In general most membrane proteins drift sideways in the fluid bilayer. The proteins within a membrane determine most of the functions. Carbohydrates are either attached to proteins (glycoproteins) or lipids (glycolipids) generally on the outer side of membrane. Filaments of the cytoskeleton are also present on the inner surface of the membrane. These support the plasma membrane.

Functions of plasma membrane lipids

The lipid part of plasma membrane controls the fluidity of the membrane. When the concentration of unsaturated fatty acid in phospholipids becomes greater, the bilayer becomes more fluid that makes cell membrane more flexible. The cholesterol helps to stabilize the lipid bilayer. It also restricts entry and exit of polar molecules and ions.

Functions of plasma membrane proteins

A great variety of proteins are found in plasma membrane which may act as transport channel or carrier, enzyme, receptors or as antigens.

1. **Channel proteins and Carrier proteins:** Certain plasma membrane proteins are involved in the passage of molecules through the membrane. Some of those have a channel through which a substance simply can move across the membrane, other are carriers that combine with a substance and help it to move across the membrane.

2. **Enzymes:** Some plasma membrane proteins have enzymatic functions e.g adenylate cyclase which converts ATP to cyclic AMP (cAMP).

3. **Receptor molecules:** Some proteins in the plasma membrane are receptors that receive signals from other cells. Each type of receptor has a specific shape. The binding of a molecule on receptor can bring about an intracellular response. For example, hormones circulate in the blood, but bind to specific target cells, with specific receptors.

4. **Antigens:** Some proteins are antigens which enable the cells to recognize other cells for example the foreign antigens can be recognized and attacked by immune system.

Roles of glycolipids and glycoproteins as cell surface markers

Mostly glycolipids and glycoproteins act as **cell surface markers.** They are involved in cell to cell recognition and sticking the correct cells together in tissues.

Regulation of cell's interaction with its environment by the plasma membrane

Plasma membrane regulates cell's interaction with its environment by controlling transport of material across the cell. Transport across plasma membrane occurs to: (1) obtain nutrient (2) excrete waste substances (3) secrete useful substances (4) generate ionic gradients essential for nervous and muscular activity (5) maintain a suitable pH and ionic concentration within the cell for enzyme activity.

1.3 CYTOPLASM AND ORGANELLES

The living matter of a cell is called protoplasm. In eukaryotic cells it can be divided into two parts i.e., cytoplasm and nucleus.

1.3.1 Cytoplasm

Cytoplasm is the region between nuclear membrane and plasma membrane. This is also a common component of both prokaryotic and eukaryotic cells. The major difference between the cytoplasm of these two kinds of cells is the presence or absence of cytoskeleton and membrane bounded organelles. These structures are absent in prokaryotic cells.

Physico-chemical nature of cytoplasm

It is about 90% water and forms a solution that contains all the fundamental biochemicals of life. Some of these are ions and small molecules in true solution, such as salts, sugars, amino acids, fatty acids, nucleotides, vitamins and dissolved gases. Others are large molecules, such as proteins, which form the colloidal solutions. The inner portion of cytoplasm i.e., towards the nucleus is less viscous and is called **cytosol** while the peripheral part of cytoplasm i.e., towards the plasma membrane is more viscous and is called **cytogel.** A circular streaming movement can also be observed in cytoplasm due to the contractile activity

of microfilaments. This movement is called **cyclosis** which is responsible for distribution of cell contents in cytoplasm.

Metabolic and storage role of cytoplasm

The cytoplasm acts as a site of metabolism and storehouse of a cell. The metabolic pathways generally occur in the cytosol which includes **protein synthesis**, **glycolysis** etc. The cytogel is usually concerned with storage of useful compounds which are subsequently used in various cellular activities and waste compounds which are eliminated from the cell time to time.

1.3.2 Cell Organelles

In a eukaryotic cell, the cytoplasm contains highly organized discrete structures which are specific for various cellular functions are called **cell organelles**. The cell organelles are generally enclosed by the membrane except few such as ribosome.

The organelles in the cytoplasmic matrix of a cell are: endoplasmic reticulum, ribosomes, Golgi complex, lysosomes, peroxysomes, glyoxysomes, vacuoles, mitochondria, and chloroplasts etc.

Endoplasmic reticulum

An interconnecting network of cisternae (elongated closed sacs) which is generally extended from nuclear membrane to the plasma membrane throughout the cytoplasm of all eukaryotic cells is called **endoplasmic reticulum** (ER). There are two types of ER, rough ER and smooth ER. Most cells contain both types of ER. However, some cells (skeletal muscle cells) have smooth ER more, where these are called **sarcoplasmic reticulum**.

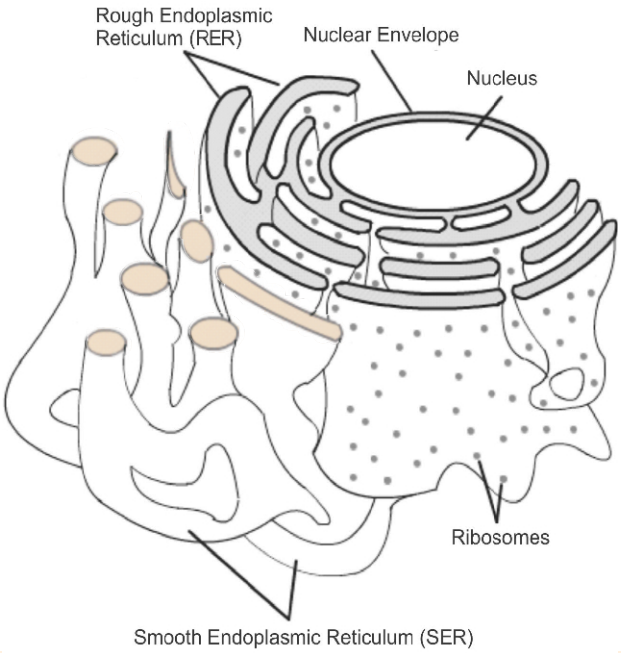


Fig.1.13: Endoplasmic reticulum

Rough ER has ribosomes attached to the sides facing the cytoplasm and has rough appearance under electron microscope. Rough ER is mainly concerned with the events of protein synthesis (translation) due to the association of ribosomes; however, their presence in the cell also provides a mechanical support to the cell.

Smooth ER is continuous with the RER. Since, ribosomes are not attached to it, therefore, it has smooth appearance under electron microscope. The smooth ER functions in various metabolic processes, e.g., metabolism of carbohydrates. The detoxification of drugs and poison especially in the liver cells and synthesis of lipids including oils, phospholipids and steroid take place in smooth ER. It also stores calcium ions, when released calcium ions trigger contraction of the muscle. Smooth ER also transports various cellular products within the cell or out of the cell e.g., proteins from rough ER are also transported to the Golgi complex through smooth ER. Like rough ER, the presence smooth ER in the cell also provides a mechanical support to the cell.

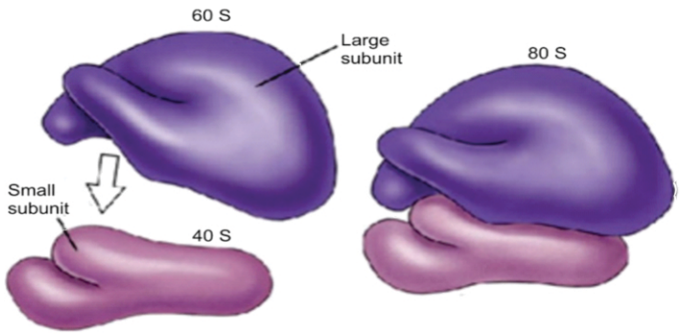


Fig.1.14: Eukaryotic 80S ribosome

Ribosomes

Ribosomes were first observed using electron microscope as dense granules. Ribosomes are roughly spherical, granular, non membranous bodies found in both eukaryotic as well as prokaryotic cells. However, eukaryotic ribosomes are lager and characterized as 80S ribosomes while the prokaryotic ribosomes are slightly smaller and are characterized as 70S ribosomes. They can be seen only under the electron microscope. They are made of almost an equal amount of RNA and protein so they are **ribonucleoprotein**. Ribosomes are formed in the nucleolus. Then these are transported to the cytoplasm through the nuclear pore.

In a eukaryotic cell, the ribosomes may be found as attached with RER or freely dispersed in the cytoplasm. Ribosomes are also found in matrix of mitochondria and stroma of chloroplast but these ribosomes are prokaryotic (70S) in nature.

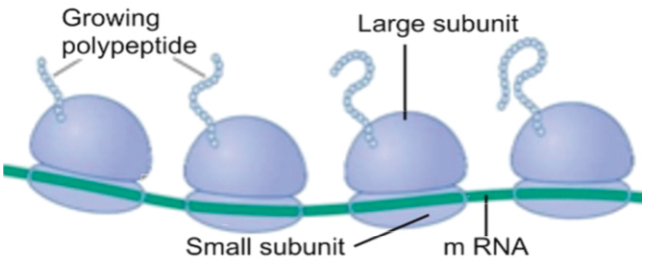


Fig.1.15: Polysome

The eukaryotic ribosomes are composed of two subunits (particles) of different sizes. The larger one is 60S particles and the smaller one is 40S particles. The two subunits on attachment form 80S particles. The attachment is controlled by presence of magnesium ions concentration or forming salt bonds between phosphate group of RNA and amino group of amino acid or both by magnesium ions and salt bonds. Both ribosomal subunits are generally attached together at the time of their function. The ribosomes are involved in the events of protein synthesis. Sometimes, during protein synthesis, several ribosomes are attached to one mRNA molecule. Such a chain of many ribosomes is called **polysome** or **polyribosomes**. In this way several copies of same polypeptide can be produced in very less time.

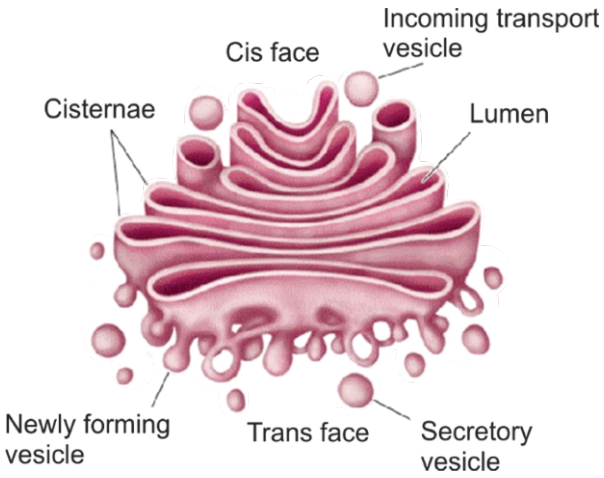


Fig. 1.16: Golgi complex

Golgi complex

It is found in all eukaryotic cells. It was discovered by Italian biologist **Camillo Golgi** in 1898.

Golgi complex consists of a stack of flattened, membrane bound sacs called **cisternae**, together with system of associated vesicles called **Golgi vesicles.** It is a complex system of interconnected tubules formed around the central stack. At one end of the stack a new cisternae are constantly being formed by the fusion of vesicles from the smooth ER. This outer

or **forming face** (cis face) is convex, while the inner end is concave and is called **maturing face** (trans face) where the cisternae breakup into vesicles again.

The most important function of Golgi complex is the processing of cell secretions. Therefore these organelles are abundant in secretory cells. The cell secretions mainly consist of proteins. Golgi complex collects these proteins from RER through SER, modifies them to perform specific function and then exports these modified products in the form of vesicle. Certain organelles, such as lysosomes, peroxisomes and glyoxysomes also originate from Golgi complex. Golgi complex is also involved in the formation of conjugated molecules like glycoprotein, lipoprotein etc. In plant cell during cell division, Golgi complex also gives rise vesicles which contain cell wall synthesizing materials. At cytokinesis, these Golgi vesicles are arranged on the cell equator, fuse together and form a structure, called **phragmoplast**. Later on new cell wall is derived from this structure.

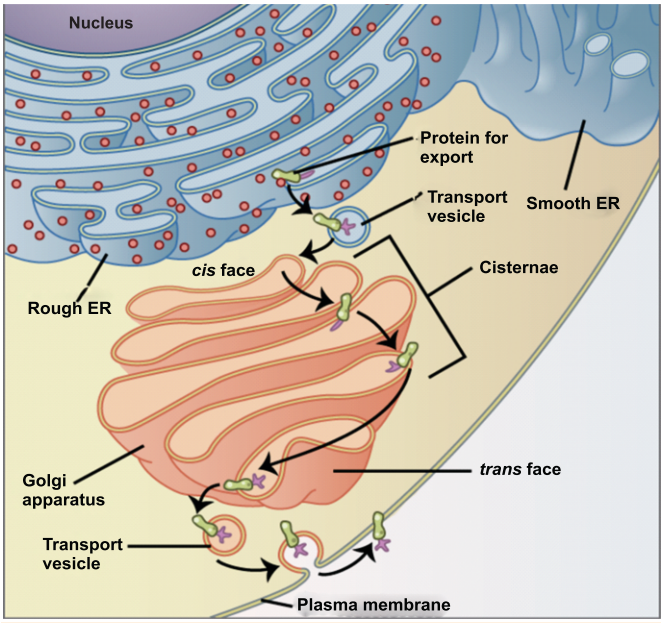


Fig. 1.17: Role of Golgi complex in a glandular cell

Lysosomes

Lyso means splitting and *soma* means body. These are single membranous, spherical vesicles. They contain digestive or hydrolytic enzymes. The lysosomal enzymes are made by the RER and then are transported to Golgi complex through SER. After modification, these enzymes are released from the *trans* face Golgi complex in the form of vesicles. Such vesicles are called lysosomes. The newly formed lysosomes before the start of their functions are usually called **primary lysosomes**. In plants and fungi, certain vacuoles carryout enzymatic hydrolysis, a function shared by lysosomes in animal cells.

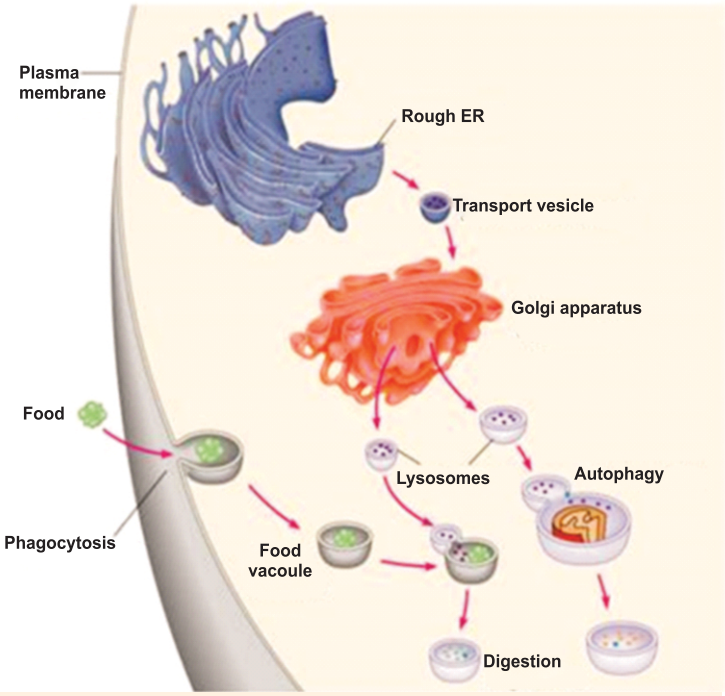


Fig. 1.18: Formation and functions of Lysosomes

Lysosomes contain about 40 different digestive enzymes. These enzymes can breakdown every major macromolecule of the cell. The contents of the **lysosome** are acidic. In

order to perform its function the lysosomes fuses with membrane bound vesicle that arises from any of these pathways **endocytosis, phagocytosis** or **autophagocytosis.** These vesicles are referred to as endosomes, phagosomes and autophagosomes respectively. These endosomes fuses with lysosomes (primary lysosomes) and forms **secondary lysosomes.** The bio-molecules are further broken down into smaller forms like amino acids, monosaccharides, nucleotides and fatty acids which are then recycled in the cell. Major functions of lysosomes include **intracellular digestion**, **autophagy**, **autolysis** and sometimes **release of extra cellular enzymes.**

The ingested food of cell is stored in vesicles, called **food vacuoles**. Once a lysosome has fused with food vacuole, the resulting structure is called **secondary lysosome** in which food begins to digest. The digested products are absorbed by the cytoplasm while the remaining wastes containing vesicle is now called **contractile vacuole**. Later on these vacuoles fuse with cell membrane (exocytosis) to eliminate undigested wastes. This whole process is known as **intracellular digestion.**

The process by which unwanted structures within the cell are engulfed and digested within the lysosomes is called **autophagy**. This is self-eating process of a cell in which a lysosome begins to digest cell's own organelles. Such lysosomes are also called **autophagosomes**. This process either takes place in starvation period in order to obtain energy or it occurs in routine in order to control number of specific organelle. For example: If someone starts to perform heavy muscular exercise, the number of mitochondria begins to increase in his muscle cells, but if he leaves exercise, the number of mitochondria are again decreased by the process of autophagy.

Sometimes, especially during developmental phase, when a particular cell is required to be disintegrated, a type of cell death is committed, called **autolysis.** This is a programmed cell death in which lysosomes burst and their enzyme contents are quickly dispersed throughout the cytoplasm. In this way the cell is disintegrated into fragments which are phagocytosed by other cells. Due to this function lysosomes are also called **suicidal bags.**

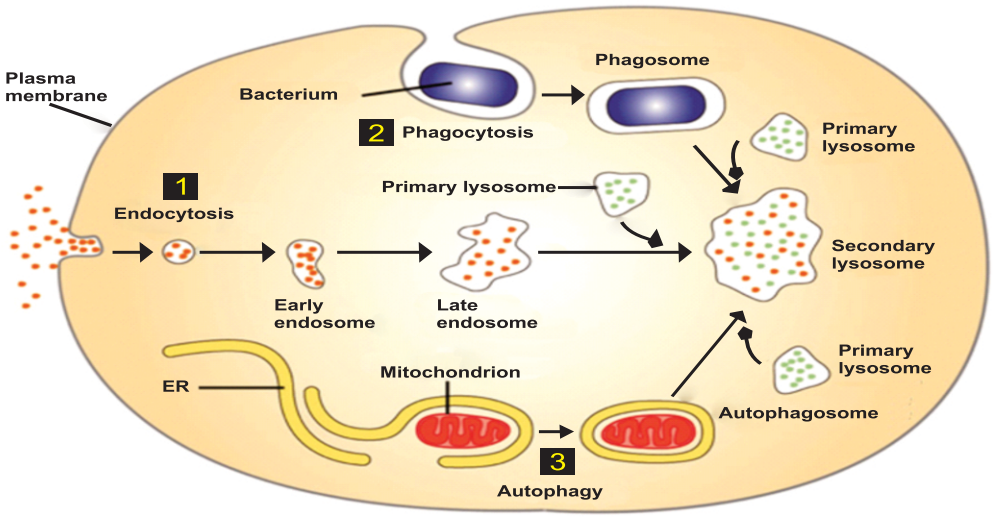


Fig. 1.19: Functions of Lysosomes

Since, lysosomes contain various digestive enzymes, if a particular lysosomal enzyme is missing in an individual, the digestion of that particular substance (for which enzyme was specific) will be affected. As a result, the substance begins to accumulate in the cell and cause different problems. Such complications which are caused by the accumulation of various substances in the cell due to lack of certain lysosomal enzymes are called **lysosomal storage diseases**. These diseases are hereditary and congenital therefore run in particular families and exist by birth in an individual. Most of these diseases are fatal in early childhood. About more than 20 such diseases have been discovered so far. One of the common examples is **Tay-Sachs disease** in which a lipid digesting enzyme is missing or inactive and the brain becomes impaired by an accumulation of lipids in the cell.

Peroxisomes and Glyoxysomes

Peroxisomes and glyoxysomes are collectively called **microbodies.** These are similar to lysosomes in the sense that they are single membranous, vesicular structures. They contain enzymes (although different than lysosome) and originate from Golgi complex but they are smaller than lysosome.

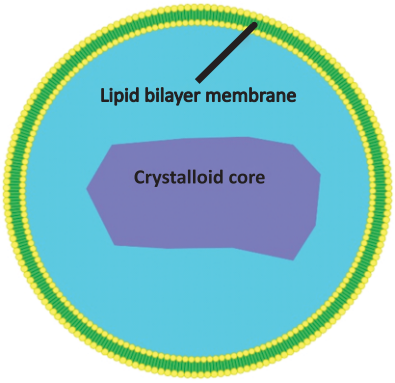


Fig. 1.20: Peroxisomes

Peroxisomes contain some oxidative enzymes like peroxidases, catalases and glycolic acid oxidases. They are abundant in liver cells where they are specifically involved in the formation and decomposition of hydrogen peroxide so they are named **peroxisomes**. They are mainly concerned with the detoxification of alcohol. In this activity alcohol is oxidized into hydrogen peroxide (H_2O_2) with the help of **peroxidase** enzyme. Hydrogen peroxide is itself a toxic molecule, which is immediately broken down to water and oxygen by another enzyme called **catalase**. In plant cell, peroxisomes are involved in **photorespiration**. A step of photorespiration takes place in peroxisomes in which **glycolate** is converted into **glycine** with the help of an enzyme called **glycolic acid oxidase**.

Glyoxysomes are found only at seedling stage in oil seed plants. These organelles have a number of enzymes specific for plant lipid metabolism that are not found in animal cells. The germinating seedlings convert stored fatty acids to carbohydrates. This is achieved through a metabolic pathway called **glyoxylate cycle**, the enzymes of which are located in the glyoxysomes.

Vacuoles

Vacuoles are large vesicles originate from the endoplasmic reticulum and Golgi complex and plasma membrane. Vacuoles perform a variety of functions in different kinds of cells. In animal cells **food vacuoles** are formed by phagocytosis. Many freshwater protists have **contractile vacuoles** that pump excess water out of the cell, thereby maintaining a suitable concentration of ions and molecules inside the cell.

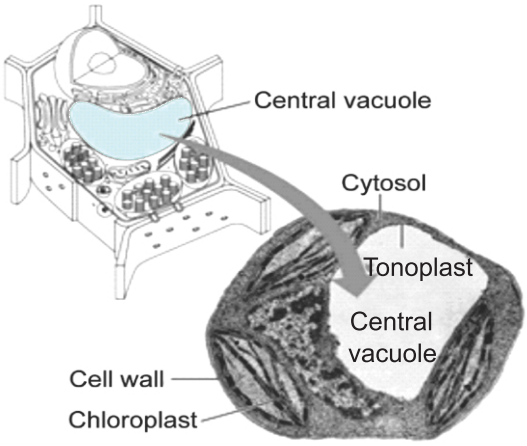


Fig. 1.21: Vacuole of a mature plant cell

In young plant cells, many small vacuoles are present which can hold reserves of important organic

compounds. These vacuoles may also help in protection of plant against herbivores by storing compounds that are poisonous or unpleasant to animals. Mature plant cells generally contain a large **central vacuole** develops by the joining of smaller vacuole. The solution inside the central vacuole, called **cell sap**, is plant cell's main reservoir of inorganic ions, including potassium and chloride. The central vacuole plays a major role in mechanical support by maintaining turgor and also acts a storehouse of the cell. The membrane separating the vacuole from cytoplasm is called **tonoplast.**

Mitochondria

Mitochondria (singular: *mitochondrion*) are present in all eukaryotic cells. Some cells have a single large mitochondrion, but more often a cell has hundreds or even thousands of mitochondria; the number correlates with the cell's level of metabolic activity. For example, cells that move or contract have proportionally more mitochondria per volume than less active cells. Mitochondria are capable to divide themselves (self-replicating) in order to increase their number. They divide by fission.

Mitochondria are cylindrical or rod shaped structures. They are enclosed by double membrane, the outer **membrane** and the **inner membrane**. The outer membrane is smooth and somewhat like a sieve due to presence of **porins.** These are special proteins responsible for the transport of molecules across the membrane. Porins allow free passage of various molecules into the inter-membrane space. The inner membrane is selectively permeable and folded inwards. The folds are called **cristae** which serve to increase the surface area. The inner surface of cristae has granular structures called **F0-F1 particles**. These particles are actually **ATP synthase** (see section 4.2.7) enzymes. In addition, several other complexes are also found in inner mitochondrial membrane, which serve as electron carriers in electron transport chain. The inner membrane divides the mitochondrion into two internal compartments. The first is the **intermembrane space**, the narrow region between the inner and outer membranes. The second compartment, the **mitochondrial matrix**, is enclosed by the inner membrane. Mitochondrial matrix is a jelly like material that contains a small circular DNA, all kinds of RNA, ribosomes (70S) and enzymes. The presence of these components indicates that mitochondria have their own genetic system. It means, the protein, which are required by mitochondria are synthesized by their own metabolic machinery.

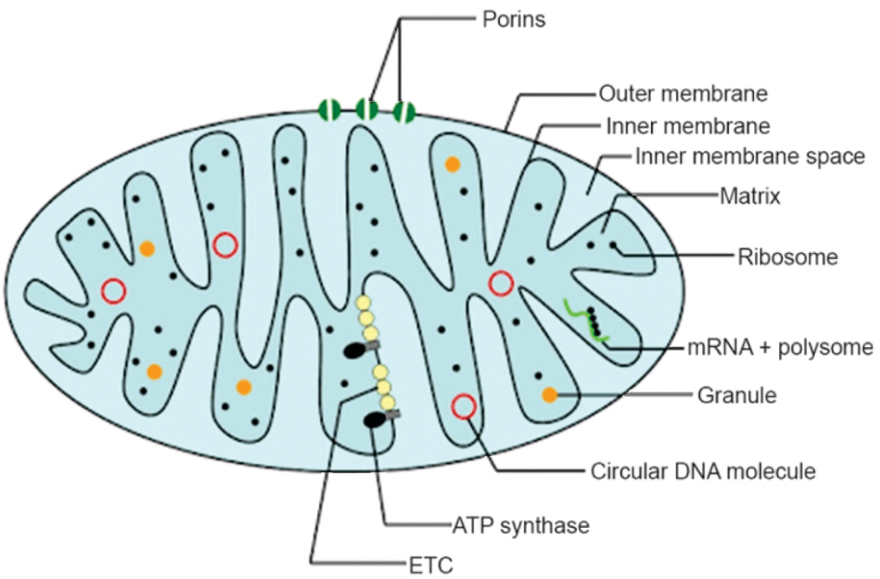


Fig. 1.22: Mitochondrion structure

Mitochondria are the sites of **cellular respiration**, the metabolic process that uses oxygen to generate ATP by extracting energy from sugars, fats, and other organic compounds. Enzymes in the matrix catalyze some of the steps of cellular respiration like Krebs cycle. Other proteins that function in ATP generation through electron transport chain are found into the inner membrane.

Mitochondria (extra reading material)

Mitochondria and chloroplasts display similarities with bacteria like both are self-replicating organelles, both have their own genetic system and metabolic machinery i.e., both has small circular DNA, all kinds of RNA and ribosomes (70S). An interesting fact about them is that they are capable to survive outside the cell in artificial medium if carefully fractionated. Based upon these observations evolutionists believe that they were independent organism and the early ancestor of eukaryotic cells engulfed them. Eventually, the engulfed cells formed a relationship with the host cell in which they were enclosed, becoming an *endosymbiont* (a cell living within another cell). Therefore, they are supposed as organisms within organism.Mitochondria divide and in this way their number doubles before cell division. Lysosomes regulate the number of mitochondria. Excess of mitochondria are digested by Lysosomes. Because mitochondria are contained within ova (egg cells) but not within the heads of the sperm cells, all the mitochondria in a fertilized egg are derived from mother.

Plastids

Plastids are found in plant and algal cells, and they are necessary for essential life processes, like photosynthesis and food storage. On the basis of presence or absence and type of pigments, and the stage of development, plastids have been classified into proplastids, leucoplasts, chromoplasts and chloroplasts.

Proplastids are young, immature and developing plastids. They are self-replicating organelles. They divide and re-divide in meristematic cells and are distributed to different cell types. Depending upon the structures in which they found, the intracellular factors and on exposure to light, they may develop into leucoplast (colourless plastids) or chloroplast (green plastids).

Leucoplasts are found in parenchyma cells of root, stem and seeds. They act as storage organelles. Based on the kind of substance they store they are further classified into **amyloplasts** (store starch), **elaioplast** (store lipids) and **proteinoplast** (store protein). **Chromoplasts** synthesize different coloured pigments other than green. Therefore, they are found in coloured parts of plant such as flower petals and fruit wall where they attract insects and thus help in pollination. **Chloroplasts** are found in green parts of the plants and act as site of photosynthesis.

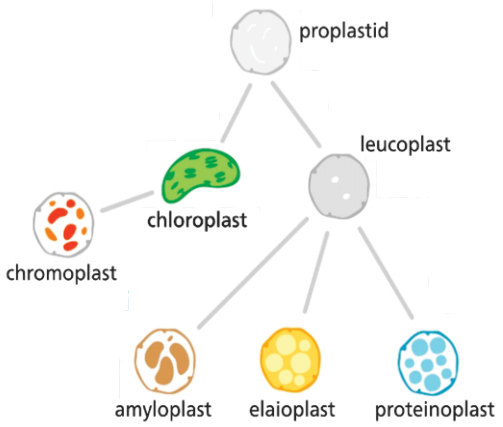


Fig. 1.23: Types of plastids

Structure and functions of chloroplast

Chloroplast is a discoid structure which consists of three parts i.e., envelope, stroma and thylakoids. Each chloroplast is bounded by a smooth double membrane (envelope). The outer membrane like mitochondria contains porins and therefore freely permeable to small molecules. The inner membrane is semipermeable and rich in protein. Between the outer and inner membrane there is intermembrane space.

The ground mass of chloroplast is called **stroma**. It is the colourless proteinaceous substance which like mitochondrial matrix also contains a small circular DNA, all kinds of RNA, ribosomes (70S) and various enzymes. The stroma contains a system of chlorophyll bearing double membrane, flattened sac-like structures called **thylakoids**. There are two types of thylakoids: smaller thylakoids and the larger thylakoids. **Smaller thylakoids** are disc like sacs which are piled over one another like stack of coins. Each stack of smaller thylakoids is called **granum** (plural: *grana*). Each granum consists of 25-50 thylakoids and there are about 40 - 60 grana found in each chloroplast. Photosynthetic pigments are also found in the membranes of smaller thylakoids. **Larger thylakoids** connect the grana with each other and are also called **intergrana**. These membranes are colourless as they do not have pigments.

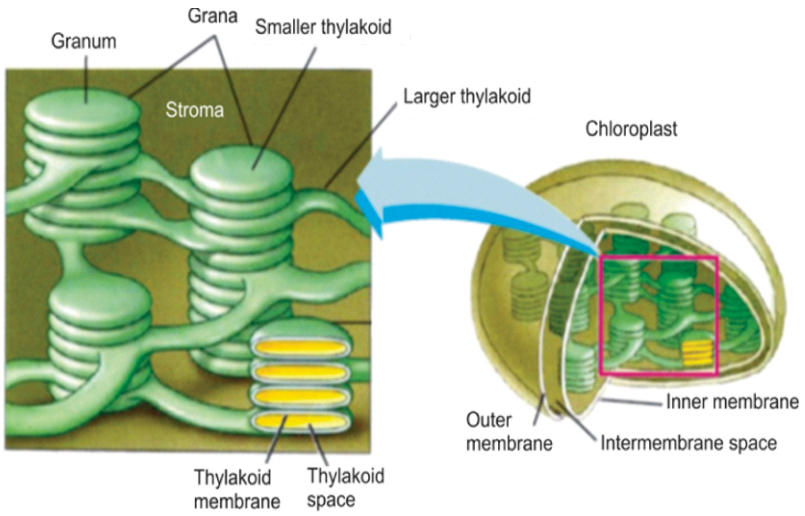


Fig. 1.24: Chloroplast

Chloroplast is the site of photosynthesis in a plant cell. The first phase of photosynthesis is light dependent reaction in which sunlight is captured and transformed into ATP. This phase takes place in grana region of chloroplast. The second phase of photosynthesis is light independent reaction (dark reaction) in which CO_2 is reduced to make carbohydrates. The enzymes for this activity are found in stroma region of chloroplast.

Centrioles

Centrioles are non-membranous cell organelles found mainly in animal cells. They are also found in fungi like protists such as slime molds and water molds. Centrioles are rod shaped structures and usually occur in pairs. These occur at right angle to each other near one pole of the nucleus. Each centriole is composed of nine triplets of microtubule which are circularly arranged around a central axis.

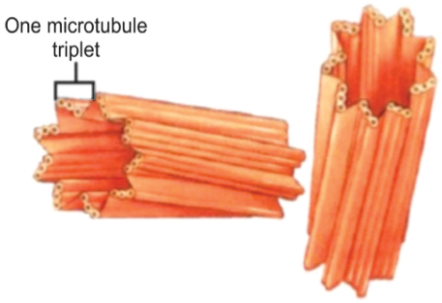


Fig. 1.25: Centrioles

Just before the cell division, the pair of centrioles duplicates and becomes two pairs which later on migrate to the opposite sides of the nucleus. Both centriole pairs give rise microtubules (spindle fibres) during cell division. The whole structure of spindle fibres is known as **mitotic apparatus** which helps in the distribution of chromosomes between the daughter cells during cell division. In addition, centrioles also give rise to **basal bodies** of cilia and flagella.

Cytoskeleton

The term cytoskeleton is generally applied to three different kinds of fibrous structures which are distributed from nucleus to the plasma membrane throughout the cytoplasm of a eukaryotic cell. These fibres include: microfilaments, microtubules, and intermediate filaments.

Microfilaments are also known as **actin filaments**. These are extremely thin contractile fibres about 7 nm in diameter. It consists of four twisted chains. Two chains of **F-actin** and two chains of **tropomyosin** with triplet **troponin** at intervals. They form myofibrils in muscles, involved in muscle contraction and relaxation. They perform **cyclosis** as well.

Microtubules are small hollow cylinders about 25nm in diameter and 0.2-25μm in length. They are composed of a protein, the **tubulin.** Each tubulin is a dimer. In plant cells at the time of cell division freely dispersed microtubules organize themselves to form spindle fibres. In animal cells, the microtubules are involved in the formation of centrioles, cilia, flagella and basal body.

Intermediate filaments are 8 to 10 nm in diameter i.e., intermediate in size between actin filaments and microtubules, this is why they are called intermediate filaments. The basic protein subunit of the filament is **vimentin**. The vimentin subunits also form chains by linear arrangement. Each intermediate filament is composed of three chains of vimentin which are twisted about each other in such a way that no hollow space is left between them. They usually form a network in the cytoplasm which provide a mechanical support to nuclear envelope and plasma membrane.

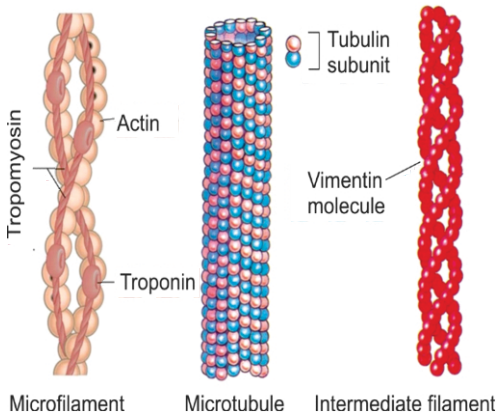


Fig. 1.26: Three types of cytoskeleton

Science Titbits

In muscle cells the microfilaments are called myofilaments which are of two different types i.e., thin and thick myofilaments. The thin filaments are actin filaments while the thick filaments (16μm thick) are composed of another protein, the myosin; therefore, they are also called myosin filaments.

Cilia and Flagella

Cilia and flagella are hair like projection on the surface of the cells. The internal structure of both cilia and flagella is same but they may differ in size, number and pattern of movement. The flagella are longer, few in number, exhibit undulating motion and beat independently. Whereas, cilia are numerous and relatively short and beat perpendicularly in metachronous (cilia of a row beating one after the other) or in synchronous rhythm (all cilia of a row beating simultaneously).

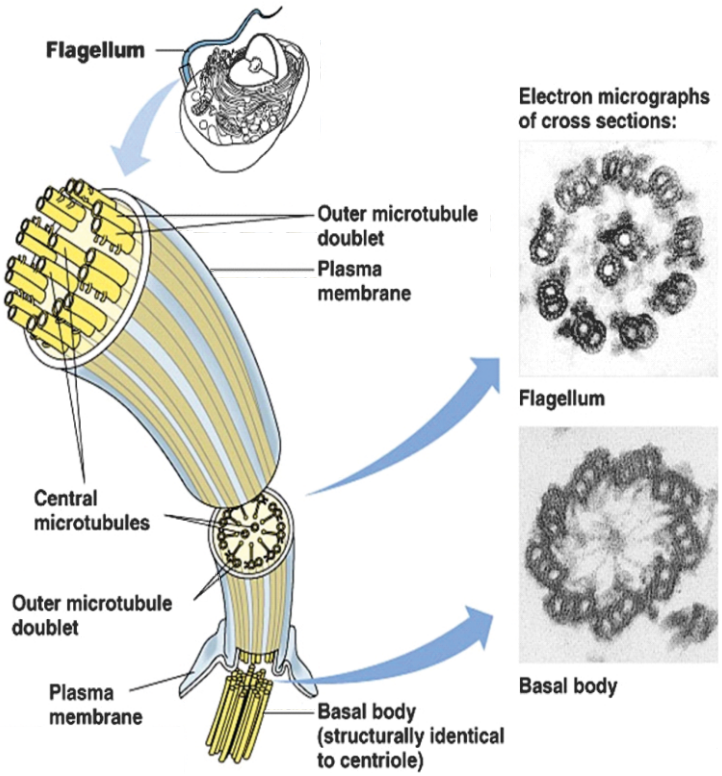


Fig. 1.27: Structure of a eukaryotic flagellum or cilium

Structure of cilia and flagella

Cilia and flagella share a common ultrastructure. Each consists of a longitudinal **axoneme.** The axoneme enclosed is in a spiral sheath of cytoplasm and a plasma membrane. Axoneme is made up of a bundle of eleven longitudinal microtubules. Nine peripheral doublets are arranged in a ring. In the centre of the ring are two single microtubules. This arrangement is called "9 + 2" pattern.

Cilia and flagella originate from their **basal bodies** embedded in the cytoplasm. Basal bodies have the same circular arrangement of microtubule triplets as centrioles.

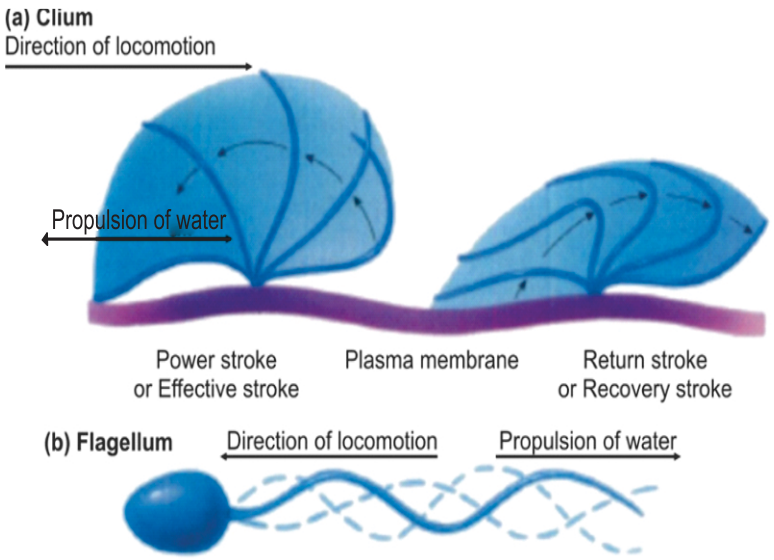


Fig. 1.28: Movement of cilia and flagella

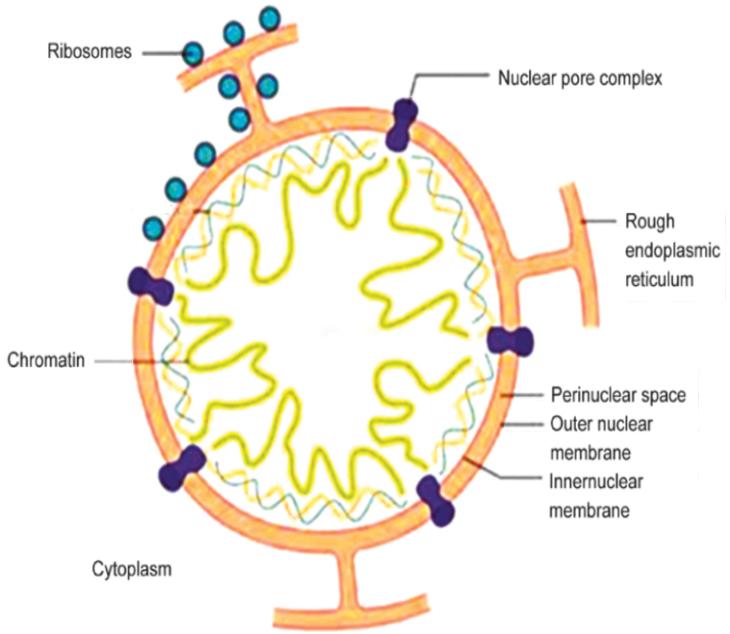


Fig. 1.29: Nucleus

Mechanism of movement of cilia and flagella

Movement of cilia: The movement of cilia is due to sliding of double fibrils in two groups one after the other. Five out of nine double fibrils contract simultaneously. As a result cilium bends or shortens. It is called **effective stroke.** Four out of nine double fibrils contract and cilium becomes straight. It is called **recovery stroke.**

Movement of flagella: A flagellum causes movement by the passage of rapid successive waves of bending from the attached to the free end, as it can be seen in flagellar movement of human sperms, which propel them forward within the fluid medium of the female reproductive tract.

1.3.3 Nucleus

Nucleus is the most prominent and the most important part of a cell. In animal cells it is found in the centre (with exception of muscle fibre cells) but in adult plant cell it is slightly away from the centre due to the presence of a large central vacuole. A typical eukaryotic nucleus consists of nuclear envelope, nucleoplasm, nucleoli and chromatin.

Nuclear envelope

Nuclear envelope (also called nuclear membrane) is a double membrane covering which makes the boundary of nucleus. Both membranes of nuclear envelope are separated by a fluid-filled **perinuclear space**. The membranes are composed of lipid bilayer and proteins. The outer membrane of nuclear envelope is covered with ribosomes and is connected with the membranes of ER. There are numerous pores in nuclear envelope called **nuclear pores** which are composed of a specialized transport protein called **nucleoporin.**

At the point of nuclear pore both the membranes are interconnected. These pores regulate the nucleo-cytoplasmic exchange of materials. This exchange includes RNA and ribosomal proteins moving from nucleus to the cytoplasm and proteins (such as DNA polymerase), carbohydrates, signalling and lipids moving into the nucleus. Although smaller molecules simply diffuse through the pores, larger molecules may be recognized by specific signal sequences and then be diffused with the help of nucleoporin into or out of the nucleus.

Science Titbits

Sieve tube cells in plants and red blood cells in human are exceptional living cells that do not possess nucleus. On the other hand some cells have more than one nuclei i.e., binucleate or dikaryotic cells (cells having two nuclei) and multinucleate or coenocytic cells (cells having many nuclei).

Nucleoplasm

Nucleoplasm is the transparent semifluid ground substance formed of a mixture of proteins, enzymes (DNA and RNA polymerase), free nucleotide and some metal ions (Mg) for the synthesis of DNA and RNAs. It also contains histone and non-histone protein. So the nucleoplasm is slightly different from cytoplasm.

Nucleolus

Nucleolus is a non-membrane bound structure in the nucleoplasm. A cell may have one or more **nucleoli**. Nucleolus appears during interphase and disappears during cell division. A nucleolus consists of a peripheral granular area (contains ribosomal subunits) and a central fibriler area (contains rRNA and rDNA). Therefore, nucleolus is involved in the construction of ribosomes.

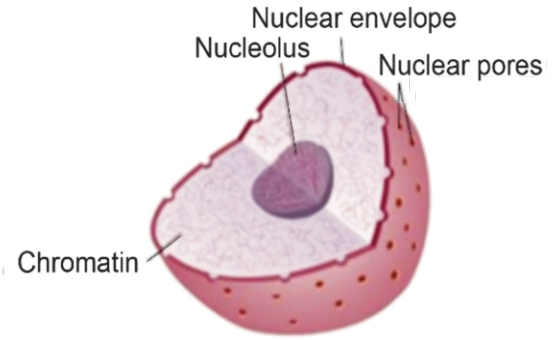


Fig. 1.30: Nucleolus

Chromatin and Chromosomes

Chromatin is a network of thin thread like structures made up of DNA and proteins. During cell division chromatin fibres begin to condense and coil up into separate structures called **chromosomes**, which are thick enough to be seen with a light microscope. A typical chromosome consists of two strands called **chromatids** which are attached with each other at a point known as **centromere.** The centromere lies within a thinner segment of the chromosome called **primary constriction.**

The **centromere** is a constriction functionally related to the movement of chromosomes during cell division. Each centromere has a complex of **kinetochores** protein present on the opposite sides of the constriction. Each kinetochore forms the site of attachment for a single microtubule during cell division. Some chromosomes may have another point of union along the length of chromatids, called **secondary constriction** or **nucleolar organizer**. It gives rise to nucleoli during interphase.

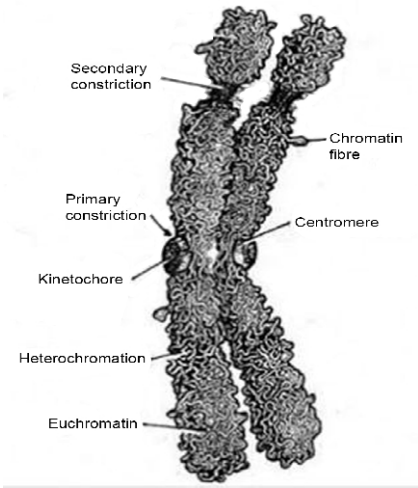


Fig. 1.31: A pair of chromosome

1.4 PROKARYOTIC AND EUKARYOTIC CELLS

Two kinds of structurally different cells have been evolved overtime. Prokaryotic cells include archaea, bacteria and cyanobacteria whereas all other forms of life are composed of eukaryotic cells. A prokaryotic cell lacks definite membrane bounded nucleus and other organelles. Its DNA is dispersed in cytoplasm. On the other hand, a eukaryotic cell contains a nucleus, endoplasmic reticulum, Golgi complex, mitochondrion, lysosomes, nucleolus, chloroplast, cytoskeleton, 80S ribosomes (larger), and flagella or cilia which are made up of microtubules. All these structures are missing in prokaryotic cells. Furthermore, the prokaryotic and eukaryotic flagella have different structure and composition. The prokaryotic cells do not divide by typical mitosis or meiosis like eukaryotic cells, instead their cell division is very simple and is called binary fission. A detailed account on prokaryotic cells is given in chapter 6 of this book.

Skills: Analyzing, Interpreting and Communication

1. Compare and contrast the structure and function of mitochondria with those of chloroplasts.
2. Compare in tabular form, the functions of organelles with the processes occurring in animals and plants.
3. List the structure and molecules, which can cross the nuclear envelope.

Activity

1. Measure the size of *Paramecium*, pollen grains, hair etc., by micrometry.
2. Prepare and examine the slides of animal and plant cells using differential staining.

Exercise

MCQs

1. Select the correct answer

(i) Which of the following is the major advantage of using a light microscope instead of an electron microscope?

(A) superior resolving power
(B) constant depth of focus
(C) observation of living matter
(D) use of very thin sections

(ii) Some cellular organelles are bound by a single membrane, while other organelles have two membranes (envelopes) around them. Which one of the following is correct?

	Single membrane	Double membranes
(A)	peroxysomes, lysosome	nucleus, chloroplast
(B)	chloroplast, lysosome	nucleus, peroxysomes
(C)	nucleus, chloroplast	lysosome, peroxysomes
(D)	nucleus, lysosome	chloroplast, peroxysomes

(iii) Which of the following cell structures contains the highest concentration of RNA?

(A) centriole (B) lysosome (C) chromosome (D) nucleolus

(iv) A tadpole's tail is gradually broken down during metamorphosis into an adult frog. Which organelle increases in number in the cells of the tail at this time?

(A) centriole (B) endoplasmic reticulum

(C) Golgi complex (D) lysosomes

(v) Which of the following organelles always contains DNA?

(A) centriole (B) Golgi complex (C) lysosome (D) mitochondria

(vi) Which distinguishes a prokaryotic cell from a eukaryotic cell?

(A) prokaryotic cell have a cell wall and a nucleus

(B) prokaryotic cells have no membrane bound organelles

(C) prokaryotic cells have a centriole

(D) prokaryotic cells have no ribosomes

(vii) The elasticity of the plasma membrane demonstrates that it is made up in part of

(A) lipids (B) nucleic acids (C) carbohydrates (D) proteins

(viii) Filaments present in flagella and cilia are

(A) microfibrils (B) microtubules (C) microfilaments (D) microvilli

(ix) Which of the following structure is found in all living organisms:

(A) cell membrane (B) nucleus (C) lysosome (D) vacuole

(x) The cell wall of plant cell is different from that of prokaryotes in:

(A) both structure and chemical composition (B) structure only

(C) chemical composition only (D) number of layers only

(xi) Which of the following are present in prokaryotic cells:

(A) chloroplast, DNA, nuclear envelope

(B) chromosomes, mitochondria, nuclear envelope

(C) cytoplasm, DNA, mitochondria

(D) cytoplasm, DNA, ribosome

(xii) Which of the following is present in all eukaryotic cells:

(A) cell wall (B) diploid nucleus

(C) flagellum (D) membrane bounded organelles

(xiii) Which of the following would be more prominent in a secretory cell than non-secretory cell:

(A) lysosome (B) Golgi complex (C) mitochondrion (D) ribosome

(xiv) When a glycoprotein is being synthesized for secretion from a cell, which route is it most likely to take?

(A) Golgi complex → RER→ SER (B) RER→ Golgi complex → SER

(C) RER→ SER→ Golgi complex (D) SER→ Golgi complex → RER

(xv) Which one of the following is responsible for cyclosis?

(A) microtubule (B) microfilament

(C) intermediate filament (D) none of them

Short Questions

2. Name three organelles revealed by an electron microscope.
3. Why cell wall is not present in animal cells?
4. What holds the ribosomes together in a polysome?
5. What would happen if there are no lysosomes in human cells?
6. Why lysosomes are called suicidal bags?
7. Name the structures and organelles which are common in plant cell, animal cell and a prokarytic cell.
8. How is a chloroplast similar to a bacterium?
9. Name the organelles of eukaryotic cell and write their specific functions.
10. What are prokaryotic cells? List the structures missing in prokaryotic cells.
11. Compare microfilaments and microtubules.
12. Which organelles are single membrane bound, double membrane bound and lacking any membrane?
13. How cytoskeletons are important to eukaryotic cells?
14. Compare the chemical composition of nucleoplasm with that of cytoplasm.
15. Explain that nucleoli are the areas where ribosomes are assembled.
16. Draw a labelled diagram of a section through:

    (a) mitochondrion (b) chloroplast
17. Write the difference between:

    (a) resolution and magnification

    (b) cytoplasm of eukaryotic and prokaryotic cell

    (c) rough ER and smooth ER

    (d) chromatin and chromosome

Extensive Questions

18. Describe the principles and uses/applications of the apparatus used in the techniques of:
    (a) Fractionation (b) Microdissection (c) Tissue culture
    (d) Differential staining (e) Centrifugation (f) Chromatography
    (g) Electrophoresis (h) Spectrophotometry
19. What are the locations, chemical compositions and significance of the following in a plant cell wall? (a) Primary cell wall (b) Secondary cell wall (c) Middle lamella.
20. Explain the (a) Chemical composition of plasma membrane (b) Role of plasma membrane in regulating cell's interactions with environment.
21. Describe the lipid composition and variety of proteins of the plasma membrane.
22. What are the functions of the plasma membrane proteins?
23. What is the role of glycolipids and glycoproteins as the cell surface markers?
24. What is the chemical nature of cytoplasm? Explain the metabolic roles of cytoplasm.
25. Describe the structures and functions of smooth and rough endoplasmic reticulum
26. Explain the structure, chemical composition and function of ribosomes.
27. Explain the structure, and functions of Golgi complex.
28. Explain the structure, and functions of the peroxysomes and glyoxisomes in animal and plant cells.
29. Explain the formation, structure and functions of the lysosomes.
30. What are the storage diseases? Explain with reference to the malfunctioning of lysosomes.
31. Describe the external and internal structure of mitochondrion? What are the functions of these structures present in mitochondria?
32. Describe the external and internal structure of chloroplast? What are the functions of these structures present in chloroplast?
33. Compare and contrast the structure and functions of mitochondria and chloroplasts.
34. What are centrioles? Describe the structure, composition and functions of centriole.
35. What are cytoskeletons? Describe the types, structure, composition and functions of cytoskeleton.
36. Describe the structure of cilia and flagella. Explain the mechanism of movement of cilia and flagella.
37. What is nuclear envelope? Describe the chemical composition and structure of nuclear envelope.
38. What are chromosomes? Describe the structure, chemical composition and function of chromosome.
39. What is the relationship of endoplasmic reticulum with Golgi complex, lysosome and plasma membrane?

2

BIOLOGICAL MOLECULES

After completing this lesson, you will be able to

- Introduce biochemistry and describe the approximate chemical composition of protoplasm.
- Distinguish carbohydrates, proteins, lipids and nucleic acids as the four fundamental kinds of biological molecules.
- Describe and draw sketches of the dehydration-synthesis and hydrolysis reactions for the making and breaking of macromolecule polymers.
- Explain the following properties of water that make it the cradle of life.
  high polarity,
  hydrogen bonding,
  high specific heat
  high heat of vaporization
  cohesion,
  hydrophobic exclusion
  ionization
  lower density of ice
- Define carbohydrates and classify them.
- Distinguish the properties and roles of monosaccharides, write their empirical formula and classify them.
- Compare the isomers and stereoisomers of glucose.
- Distinguish the properties and roles of disaccharides and describe glycosidic bond in the transport disaccharides.
- Distinguish the properties and roles of polysaccharides and relate them with the molecular structures of starch, glycogen, cellulose and chitin.
- Justify that the laboratory-manufactured sweeteners are "left-handed" sugars and cannot be metabolized by the "right-handed" enzymes.
- Define proteins and amino acids and draw the structural formula of amino acid.
- Outline the synthesis and breakage of peptide linkages.
- Justify the significance of the sequence of amino acids through the example of sickle cell hemoglobin.
- Classify proteins as globular and fibrous proteins.
- List examples and the roles of structural and functional proteins.
- Define lipids and describe the properties and roles of acylglycerols, phospholipids, terpenes and waxes.
- Illustrate the molecular structure (making and breaking) of an acylglycerol, a phospholipid and a terpene.

- Evaluate steroids and prostaglandins as important groups of lipids and describe their roles in living organisms.
- Define nucleic acids and nucleotides.
- Describe the molecular level structure of nucleotide.
- Distinguish among the nitrogenous bases found in the nucleotides of nucleic acids.
- Outline the examples of a mononucleotide (ATP) and a dinucleotide (NAD).
- Explain the double helical structure of DNA as proposed by Watson and Crick.
- Define gene is a sequence of nucleotides as part of DNA, which codes for the formation of a polypeptide.
- Explain the general structure of RNA.
- Distinguish in term of structures and roles, the three types of RNA.
- Define conjugated molecules and describe the roles of common conjugated molecules i.e. glycolipids, glycoproteins, lipoproteins and nucleoproteins.

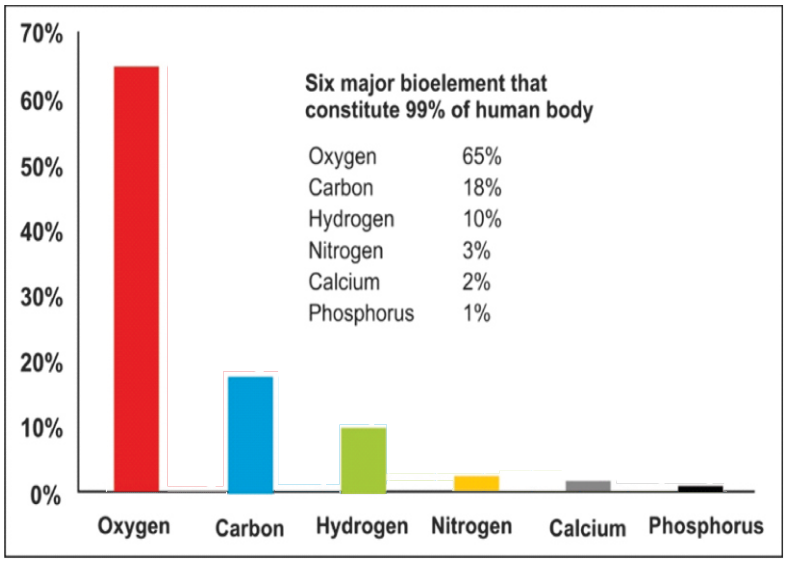
You have got a very brief introduction about biological molecules in IX-X biology course. This chapter caters the detailed study of carbohydrates, proteins, lipids and nucleic acid as well as the importance of water and the role of conjugated molecules.

2.1 BIOLOGICAL MOLECULES IN PROTOPLASM

Biological molecules are different chemical compounds of living beings. **Biochemistry** is the branch of biology that deals with such molecules. It also deals with various chemical reactions (metabolism) of living beings.

2.1.1 Chemical Composition of Protoplasm

Approximately 25 elements out of 92 naturally occurring elements of earth are found in living beings. These are called **bioelements**. However, human body is composed of only 16 of these bioelements. These elements can be classified on the basis of their proportions in organisms. The six commonest bioelements that constitute 99% of protoplasm are called **major** bioelements. **Minor** bioelements are those that are found as less than 1% whereas those that are found as less than 0.01% of the protoplasm are called **trace elements**. The proportions of these



Minor elements include: potassium (0.35%), sulphur (0.25%), chlorine (0.15%), sodium (0.15%) and magnesium (0.05%). **Trace elements** include iron, copper, manganese, zinc

Fig. 2.1: Proportions of various bioelements in human body

elements are given in the fig: 2.1. Some trace elements such as iron are needed by all forms of life. Others are required only by certain species.

The bioelements are combined with each other and can form thousands of different biomolecules which may be **inorganic** (water and minerals) and **organic** (carbohydrates, lipids, proteins and nucleic acids). The proportions of these biomolecules are given in the table.

Table 2.1: Proportions of various biomolecules in bacterial and mammalian cells

Biomolecules	Bacterial cell	Mammalian cell
Water	70%	70%
Protein	15%	18%
Carbohydrates	3%	4%
Lipids	2%	3%
DNA	1%	0.25%
RNA	6%	1.1%
Other organic molecules (enzymes, hormones, metabilites)	2%	2%
Inorganic ions (Na^+, K^+, Ca^{++}, Mg++, Cl^-, $SO4^{--}$)	1%	1%

The four fundamental kinds of biological molecules are carbohydrates, proteins, lipids and nucleic acids. **Carbohydrates** are present in the cytoplasm of the cells and provide fuel for the metabolic activities of the cell. **Proteins** are present in the membranes, ribosomes, cytoskeleton and enzymes of the cell. **Lipids** are present in the membranes and cytoplasm of the cell. Lipids provide a reserved energy source, shape, protect and insulate the cells. The **nucleic acid** DNA is present in the chromosome. It controls the cell activity. The nucleic acid RNA is present in the nucleoplasm and cytoplasm. It takes genetic information from DNA and play role in protein synthesis.

2.1.2 Condensation and Hydrolysis

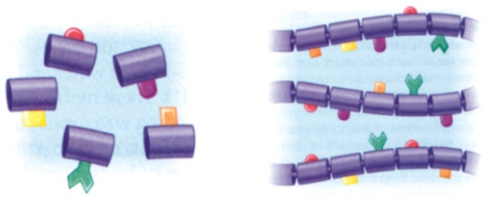


Fig: 2.2: Monomer and polymer

A **macromolecule** is high molecular weight compound which is made from many repeating units. Molecules built like this are also known as **polymers.** The individual units of polymers are **micromolecules** which are also known as **monomers**. The interconversions of these molecules are carried out by condensation and hydrolysis.

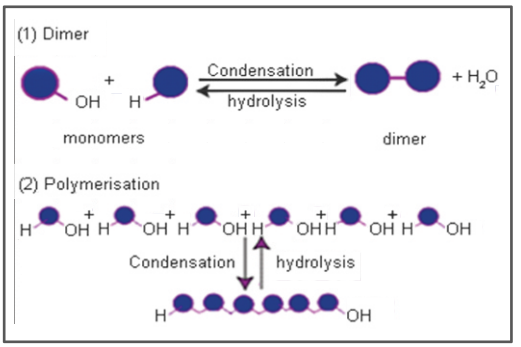


Fig. 2.3: Condensation and Hydrolysis

During **condensation**, when two monomers join, a hydroxyl (–OH) group is removed from one monomer and a hydrogen (–H) is removed from the other to make water and as a result a bond is synthesized between the monomers. The product of such reaction is called a

dimer. If the same reaction is repeated several times the resulting molecule will be a **polymer.** Condensation is also called **dehydration synthesis** because water is removed (dehydration) and bond is made (synthesis). Condensation does not take place unless the proper enzyme is present and the monomers are in an activated energy- rich form.

Science Titbits

Do not confuse involvement of water in hydrolysis with making a solution, in which the role of water is to act as a solvent, rather than taking part in a chemical reaction. Also do not assume that this breakdown releases energy, which is usually produced when the simpler substances are oxidized in respiration. Hydration is yet another completely different process, involving the addition of water, but not breaking of bonds.

The **hydrolysis** is essentially the reverse of condensation i.e., the breakdown of a polymer into its monomers by the addition of water. During hydrolysis, an (–OH) group from water is attached to one monomer and (–H) is attached to the other monomer. Actually all digestion reactions are examples of hydrolysis, which are controlled by enzymes such as carbohydrases, proteases, lipases, nucleases.

2.2 IMPORTANCE OF WATER

Water is one of the main constituents on earth. More than two thirds of the earth is covered by water. Approximately 70 percent of the any organism is formed of water. Water is the most abundant component in any organism, the lowest is 20% in seeds and bones and highest is 85-90% in brain cells. Jellyfish has exceptionally large amount of water i.e., 99% (hence the body shows transparency).

Critical Thinking

When hydrogen gas combines with oxygen gas to form water, is the hydrogen reduced or oxidized?

2.2.1. Properties of water

The properties of water that make it the cradle of life are:

1. High polarity

The bonds which are formed by the mutual sharing of electrons between two atoms are called **covalent bonds**. Normally the sharing of electrons between two atoms is fairly equal and the covalent bond is **nonpolar**. In the case of water, however the sharing of electrons between oxygen and hydrogen is not completely equal so the covalent bond is **polar**. A polar covalent bond is a chemical bond in which shared electrons are pulled closer to the more electronegative atom, making it partially negative and the other atom partially positive. Thus, in H_2O, the O atom actually has a slight negative charge and each H atom has a slight positive charge, even though H_2O as a whole is neutral. Because of its polar covalent bonds, water is a polar molecule i.e., it has a slightly negative pole and two slightly positive ones.

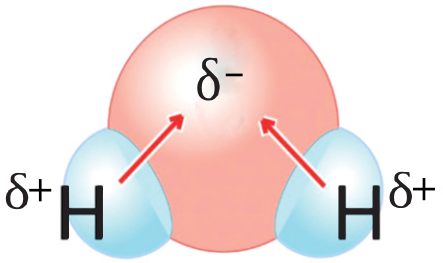


Fig: 2.4: Polarity of water molecule

This is polarity of water molecules that makes it an excellent or **universal solvent** for polar substances. Ionic compound or electrolytes can be easily dissolved in water, non-polar substances having charged groups in their molecules can also be dissolved in water. Such

compounds when dissolved in water, disassociates into positive and negative ions and are in more favourable state to react with other molecules and ions. This is the reason why all chemical reactions in living beings occur in aqueous medium.

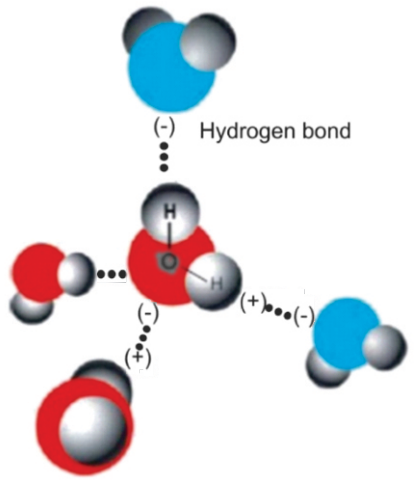


Fig: 2.5 Hydrogen bonds between water molecules

2. Hydrogen bonding

The polarity of water molecules makes them interact with each other. The charged regions on each molecule are attracted to oppositely charged regions on neighbouring molecules, forming weak bonds. Since the positively charged region in this special type of bond is always an H atom, the bond is called a **hydrogen bond**. This bond is often represented by a dotted line because a hydrogen bond is easily broken.

Because of hydrogen bonding, water is a liquid at temperatures suitable for life. The high cohesion and adhesion force of water is due to the presence of hydrogen bonds in water, which in turns makes water as transport medium.

3. Cohesion and adhesion

Cohesion is the attraction among the water molecules which enables the water molecules to stick together. Water flows freely due to cohesion. Water molecules also have attraction to polar surfaces. This attraction is called **adhesion**. Both cohesion and adhesion are due to hydrogen bonds among water molecules. These properties of water enable it to circulate in living bodies and to act as transport medium.

4. High specific heat capacity

Heat capacity can be defined as the amount of heat required for minimum increase in temperature of a substance. The specific heat capacity of water can be represented as number of calories required to raise the temperature of 1g of water up to 1°C i.e., **1 Calorie (4.18 Joules)**. Water has relatively a very high heat capacity than any other substance due to its hydrogen bonding, because much of the heat absorbed by water is utilized in the breakdown of hydrogen bonding therefore it does not manifest itself to raise the temperature of water. Hence, very large amount of heat can increase very little in temperature in water. Due to its high heat capacity water works as **temperature stabilizer** or regulator for organisms in the hot environment and hence protects the living material against sudden thermal changes.

5. High heat of vapourization

Heat of vapourization is the amount of heat required to convert a unit mass of a liquid into gaseous form. Heat of vapourization of water is represented as number of calories absorbed per gram vapourized. Water has high heat of vapourization i.e., **574 calories per gram**. The high heat of vapourization means that a large amount of heat can be lost with minimal loss of water from the body. This is high heat of vapourization of water that gives animals an efficient way to release excess body heat in a hot environment. When an animal

sweats, body heat is used to vapourize the sweat thus cooling the animal. Due to this property of water, evaporation of only 2 ml out of one litter of water lowers the temperature of the remaining 998 ml water by 1°C.

6. Hydrophobic exclusion

Hydrophobic exclusion can be defined as reduction of the contact area between water and hydrophobic substances which are placed in water. For example, if you place few drops of oil on the surface of a water solution, the oil drops will tend to join into a single drop. Biologically, hydrophobic exclusion plays key roles in maintaining the integrity of lipid bilayer membranes.

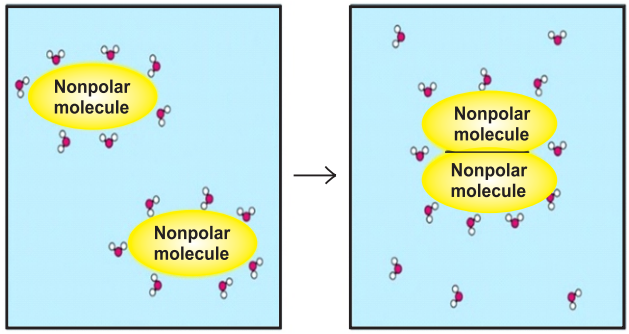


Fig: 2.6: Hydrophobic exclusion

7. Ionization

The dissociation of a molecule into ions is called **ionization**. When water molecule ionizes, it releases an equal number of positive hydrogen and negative hydroxyl ions.

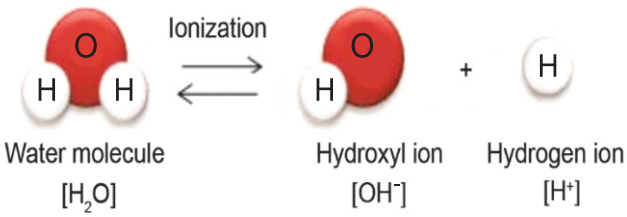


Fig: 2.7: Ionization of water

This reaction is reversible but equilibrium is maintained at 25°C. The H^+ and OH^- ions affect and take part in many of the reactions that occur in cells, e.g., it helps to maintain or change the pH of the medium.

8. Lower density of ice

Ice floats on water. This is because ice is less dense than water. The reason is that ice has a giant structure and show maximum number of hydrogen bonding among water molecules; hence, they are arranged like a lattice. In freezing weather, ice forms on the surface of ponds and lakes forming an insulating layer above the water below. This provides a living environment for some organisms until the ice melts. Organisms can also live under the ice.

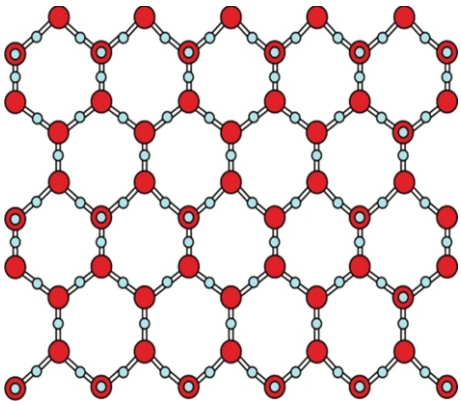


Fig: 2.8: Lattice likes arrangement of water molecules in ice

Skills: Analyzing, Interpreting and Communication

- Draw model diagrams to describe the hydrogen bonding.

2.3 CARBOHYDRATES

Carbohydrates are the compounds of carbon, hydrogen and oxygen. Literally word carbohydrate means “hydrates of carbon” i.e., a carbon associated with water. Chemically carbohydrates are:

"Organic compounds that are polyhydroxy aldehydes or polyhydroxy ketones, or change to such substances on simple chemical transformations, as hydrolysis, oxidation, or reduction."

2.3.1 Classification of Carbohydrates

Carbohydrates are commonly known as **sugars** or **saccharides** because more familiar carbohydrates have sweet taste. Classification of carbohydrates is based upon number of saccharide units. Carbohydrates are generally classified into three group i.e., monosaccharides, oligosaccharides and polysaccharides.

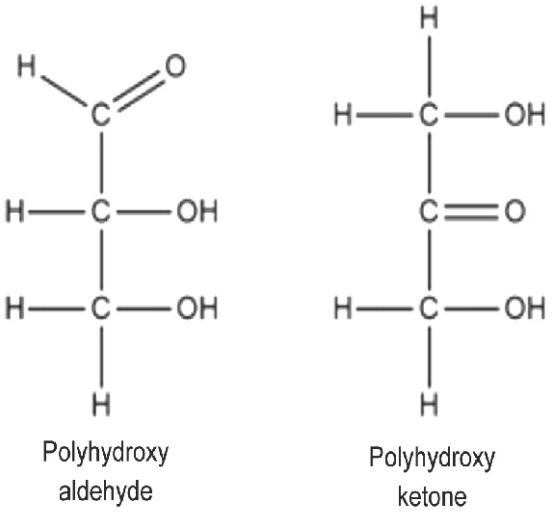


Fig: 2.9: Chemical nature of carbohydrates

Table: 2.2: Comparison of characteristics of carbohydrates

Monosaccharides	Oligosaccharides	Polysaccharides
They consist of single saccharide unit.	They are composed of 2 to 10 saccharide units.	They are composed of more than 10 saccharide units.
They are simplest carbohydrates; therefore, they cannot be further hydrolyzed.	They have less complex structure, so upon hydrolysis they yield at least 2 and maximum 10 monosaccharides.	They have highly complex structure, so upon hydrolysis they yield at least 11 monosaccharides.
They are highly soluble in water.	They are less soluble in water.	They are generally insoluble in water.
They are sweetest among all carbohydrates.	They are less sweet in taste.	They are tasteless.

2.3.2 Monosaccharides

Monosaccharides are true carbohydrates which are either polyhydroxy aldehydes or polyhydroxy ketones. The range of number of carbons in monosaccharides is 3 to 7. All the carbon atoms in a monosaccharide except one, have a hydroxyl group (-OH) while the remaining carbon atom is either the part of aldehyde or ketone. The general formula for the representation of monosaccharides is $C_nH_{2n}O_n$, where, n is the number of carbon atoms in monosaccharides.

Classification of monosaccharides

Classification of monosaccharides is based upon functional group and number of carbon atoms. On the basis of functional group, the monosaccharides containing aldehyde are called **aldoses** while those containing ketone are called **ketoses**. On the other hand monosaccharides are classified into five groups based upon number of carbon atoms i.e., **trioses** (3C), **tetroses** (4C), **pentoses** (5C), **hexoses** (6C) and **heptoses** (7C).

Table: 2.3: Examples and functions of monosaccharides

Class	Formula	Aldoses	Ketoses	Function
Trioses (3C)	$C_3H_6O_3$	Glyceraldehyde	Dihydroxy acetone	Intermediates in photosynthesis and cellular respiration.
Tetroses (4C)	$C_4H_8O_4$	Erythrose	Erythrulose	Intermediates in bacterial photosynthesis.
Pentoses (5C)	$C_5H_{10}O_5$	Ribose, Deoxyribose ($C_5H_{10}O_4$)	Ribulose	Ribose and deoxyribose are components of RNA and DNA respectively. Ribulose is an intermediates in photosynthesis.
Hexoses (6C)	$C_6H_{12}O_6$	Glucose, Galactose	Fructose	Glucose is respiratory fuel (initial substrate) Fructose is an intermediate in respiration. Galactose is the component of milk sugar.
Heptoses (7C)	$C_7H_{14}O_7$	Glucoheptose	Sedoheptulose	Intermediates in photosynthesis.

Chemical structures of monosaccharides

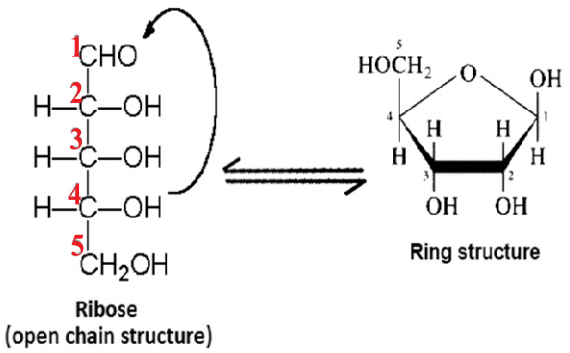


Fig: 2.10: Conversion of open chain into ring chain

Monosaccharides are usually found in open chain structure in crystalline form but when they are dissolved in water most of them (pentoses and hexoses) are converted into ring chain structure.

Let us understand it by taking ribose ($C_5H_{10}O_5$) as an example. It can exist in open chain structure in dried form but it exists in ring structure in aqueous medium. When it is dissolved in water, the oxygen atom from aldehyde group reacts with second last carbon i.e., C4 in case of ribose. In this way oxygen atom forms a link between C1 and C4 while the OH group of C4 is shifted to C1. After this modification ring structure of ribose is formed.

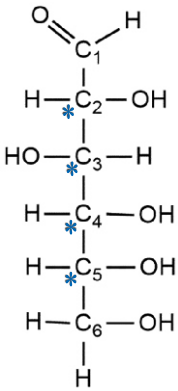


Fig: 2.11: Glucose open chain structure

Each pentose or hexose molecule in ring structure exists in either α or β form depending upon the position of –H and –OH group on C-1. If –OH group is found downward on C-1 then it is called **α sugar** and if –OH is present upward on C-1 then it is known as **β sugar** as shown in the fig: 2.12.

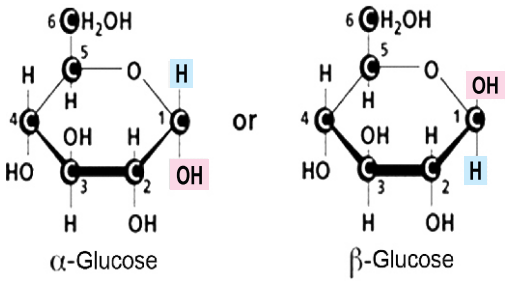


Fig: 2.12: *α* and *β* isomers of glucose

Stereoisomerism in Glucose

Stereoisomers are molecules that have the same molecular formula and differ only in how atoms are arranged in 3D space. Enantiomers is a type of stereoisomers in which molecules

are nonsuperimposable mirror-images. This means that the molecules are mirror image but they cannot be placed on top of one another to give the same molecule. An example of enantiomer is D and L glucose. D sugars are right handed and L sugars are left handed molecules.

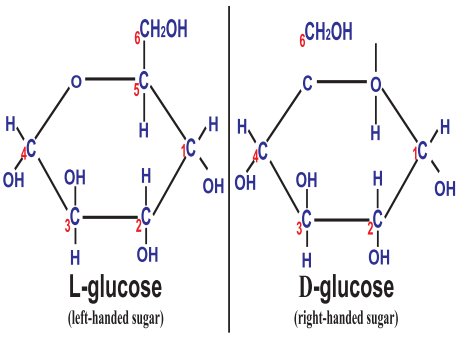


Fig: 2.13: An example of enantiomers

Laboratory Manufactured (Artificial) Sweeteners

Laboratory manufactured sugars are L sugars. On the other hand the naturally occurring sugars in bodies are D sugars. Proteins and cell receptors are designed to react only with D sugars. For example the enzymes in your stomach can digest only right-handed sugars. Likewise left-handed sugars cannot be metabolized by right-handed enzymes. Just as the glove fits only on the proper hand, a right-handed enzyme cannot fit on or react with a left-handed substrate. The substrate must fit on the proper active site of the enzyme. So for the left handed substrate (artificial sweetener) the enzyme must be left-handed.

2.3.3 Oligosaccharides

This group consists of derivatives of monosaccharides. Those carbohydrates which upon hydrolysis yield 2 to 10 saccharide units are called oligosaccharides. On the basis of number of saccharide units, the oligosaccharides are classified into **disaccharides**, **trisaccharides, tetrasaccharides** and so on. The most common among these are disaccharides.

Disaccharides

Two monosaccharides combine to form a disaccharide. It is a kind of oligosaccharides. Disaccharides are less sweet in taste and less soluble in water. These can be hydrolyzed to give monosaccharides. Examples are: maltose, lactose, sucrose. The general formula of disaccharide is: $C_{12}H_{22}O_{11}$. Some common disaccharides are as follows:

Sucrose: It is commonly known as cane sugar. It is widely used as sweetener at homes for making sweet dishes. In plants sucrose is also called **transport disaccharide** as prepared food in plants is transported in the form of sucrose. It is very soluble and can therefore be moved efficiently in high concentration in plants. It is also relatively unreactive chemically. The sucrose is formed by the condensation of glucose and fructose. In this reaction, the –OH group at C-1 of glucose reacts with the –OH group at C-2 of fructose, liberating a water molecule forming **α-1,2-glycosidic linkage**.

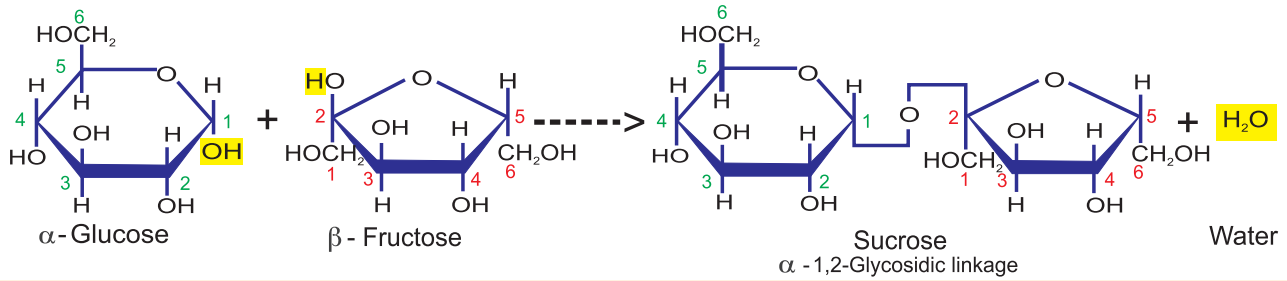


Fig: 2.14: Formation of sucrose

Maltose: It is commonly known as malt sugar. It is an intermediate disaccharide produced during the breakdown of starch and glycogen. Maltose is generally found in germinating seeds. The maltose is formed by the condensation of two α-glucoses. In this reaction, the –OH group at C-1 of one glucose reacts with the –OH group at C-4 of other glucose, liberating a water molecule forming **α-1, 4-glycosidic linkage.**

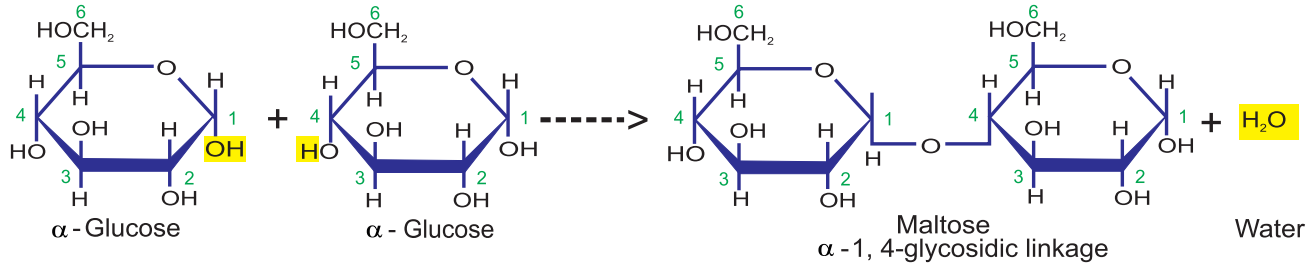


Fig: 2.15: Formation of maltose

Lactose: It is commonly known as milk sugar. The lactose is formed by the condensation of β-galactose and β-glucose. In this reaction, the –OH group at C-1 of galactose reacts with the –OH group at C-4 of glucose, liberating a water molecule forming **β-1, 4-glycosidic linkage.**

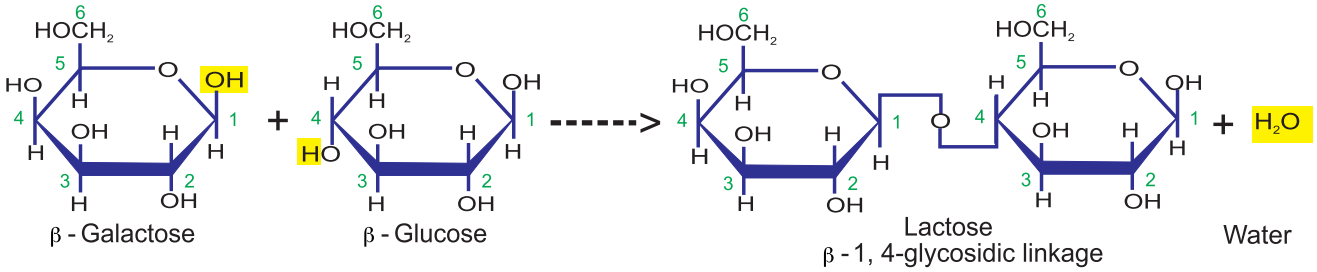


Fig: 2.16: Formation of lactose

Science Titbits

Any carbohydrate which is capable of being oxidized and causes the reduction of other substances without having to be hydrolyzed first is known as **reducing sugar**, but those which are unable to be oxidized and do not reduce the other substances are known as **non-reducing sugars.** All monosaccharides and two of three types of disaccharides (maltose and lactose) have the open chemical structure needed to act as reducing agents. The third type of disaccharides, sucrose, and polysaccharides are non-reducing sugars.

2.3.4 Polysaccharides

Those carbohydrates which upon hydrolysis yield more than ten monosaccharide units are called polysaccharides. This is largest group of carbohydrates. The polysaccharides which are composed by the condensation of only one kind of monosaccharides are called **homopolysaccharides** e.g., starch, glycogen, cellulose, chitin; whereas the polysaccharide which are composed by the condensation of different kind of monosaccharides are called **heteropolysaccharides** e.g., agar, pectin, peptidoglycan. Polysaccharides function chiefly as

food and energy stores, e.g., starch, glycogen, and structural material, e.g., cellulose and chitin. They are convenient storage molecule for several reasons. Their large size makes them more or less insoluble in water, so they exert no osmotic or chemical influence in the cell; they fold into compact shapes and they are easily converted to sugars by hydrolysis when required. Some common polysaccharides e.g., starch, cellulose, and chitin are being discussed here.

Starch

Starch is a homopolysaccharides which is formed by the condensation of hundreds of **α-glucoses**. It is storage carbohydrate of plants. It is mainly stored in root, stem and seeds. Cereal grains and potato tubers are rich sources of starch in human diet. Starch is digested in oral cavity and in small intestine by the enzyme amylase. Upon hydrolysis it yields maltose first and then maltose is further digested by maltase enzyme and yields glucoses. The presence of starch in a given sample can be confirmed by iodine test as it gives blue colour with iodine solution. There are two types of starches i.e., amylose and amylopectin.

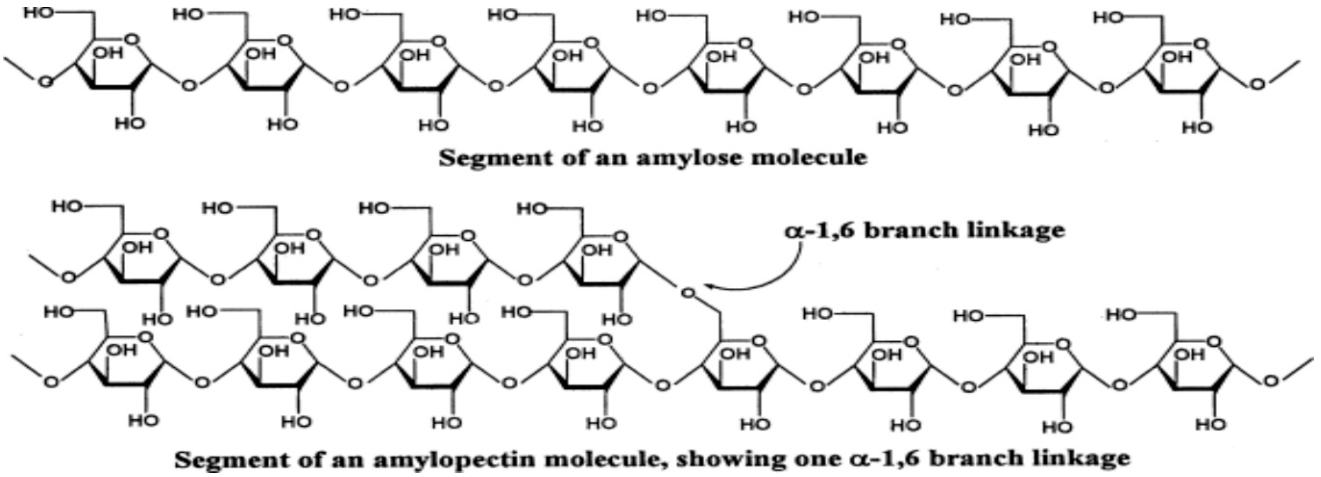


Fig: 2.17: Structure of starches

Amylose is un-branched i.e., a linear chain of glucoses in which glucoses are attached together by **α-1, 4-glycosidic linkages**. It is soluble in hot water only. On the other hand, **amylopectin** has branched structure i.e., a linear chain of glucoses but more chains of glucoses in the form of branches are also attached by **α-1, 6-glycosidic linkages**. It is completely insoluble in water.

Glycogen

Like starch, glycogen is also a homopolysaccharides composed of **α-glucoses**. It is storage carbohydrate of animals. It is mainly stored in liver and muscles. Therefore it is also known as **animal's starch**. The digestion of glycogen is also quite similar to that of starch. The presence of glycogen in a given sample can

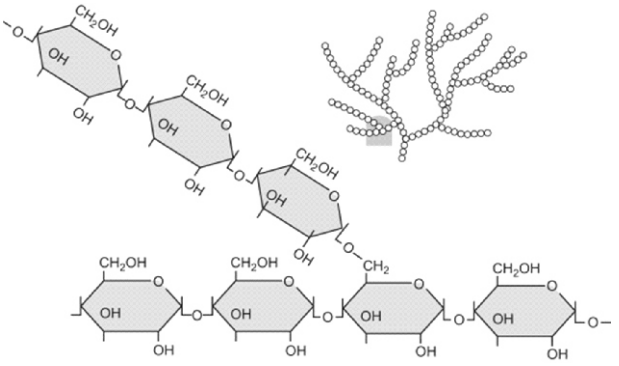


Fig: 2.18: Structure of glycogen

also be confirmed by iodine test as it gives red colour with iodine solution. Structure of glycogen resembles with amylopectin starch but glycogen has much more branching than amylopectin.

Cellulose

Cellulose is most abundant carbohydrate on earth. It is also a homopolysaccharides but unlike starch and glycogen it is formed by the condensation of hundreds of **β-glucoses**. It is structural carbohydrate of plants as it is major constituent of plant cell wall. Cotton and paper are the pure forms of cellulose.

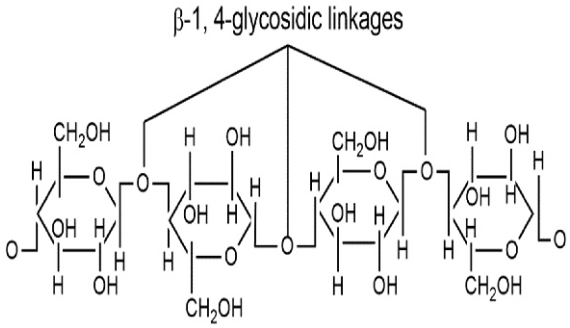


Fig: 2.19: Structure of cellulose

Cellulose shows no colour with iodine solution. Structure of cellulose resembles with amylose starch in such a way that it has un-branched structure but it has **β-1, 4-glycosidic linkages** between glucose residues.

Science Titbits

Cellulose cannot be digested by human body but it has to be taken into diet because it works as roughage or fibre so it prevents abnormal absorption of food in intestine. However, herbivore animals have some symbiotic bacteria that secrete **cellulase** enzyme for its digestion. Upon hydrolysis it first yields a disaccharide, the **cellubiose** and then cellubiose is further digested into glucoses.

Chitin

Chitin is the second most abundant organic molecule on earth. It is also a homopolysaccharides. It is a structural carbohydrate found in the cell walls of fungi and in the exoskeleton of arthropods. Due to the occurrence of chitin in fungal cell wall, it is also known as **fungal cellulose**. Chitin is the derivative of **N-acetyl glucosamine** monomers which is a modified form of glucose. It has an un-branched structure and its monomers are linked together by **β-1, 4-glycosidic linkages.**

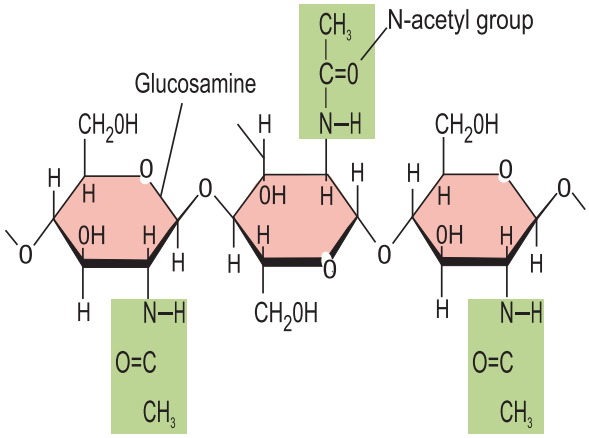


Fig: 2.20: Structure of chitin

2.4. PROTEINS

Proteins are the main structural components of the cell. All proteins contain C, H, O and N, while some contains P, S. Few proteins have Fe, I and Mg incorporated into the molecule.

2.4.1 Structure of Proteins

Chemically proteins can be defined as **polymers of amino acids** or **polypeptide chains**. A protein may consist of a single polypeptide or more than one polypeptide.

Amino acids

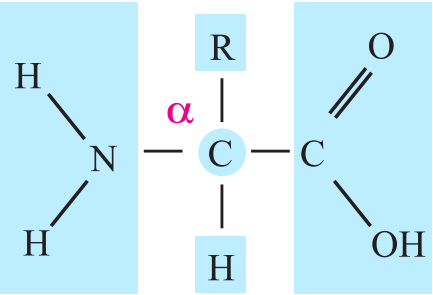


Fig: 2.21 General structure of an amino acid

Amino acids are the building blocks of proteins. There are many amino acids known to occur, but only 20 are commonly found in proteins. The amino acids are built on a common plan. Each contains a carbon atom. It is called α (alpha) carbon to this a hydrogen atom, an amino group (–NH2), a carboxyl group (–COOH) and a variable group known as –R group are attached. The R group has a different structure in each of the 20 biologically important amino acids and determines their individual chemical properties. Two simplest amino acids i.e., glycine and alanine are shown in figure 2.21.

Dipeptides and Polypeptides

Dipeptides and polypeptides are formed by the condensation of amino acids on the ribosome under the instructions of mRNA which takes these instructions from DNA. This process is known as **translation**. During this process, when an amino acid reacts with another amino acid, the –OH from carboxylic acid group of one amino acid and –H from amino group of other amino acid are liberated and form a water molecule, as a result a bond is established between C of carboxylic acid group and N of amino group of two amino acids called **peptide bond**. Hence, a product of two amino acids is formed which is known as **dipeptide.**

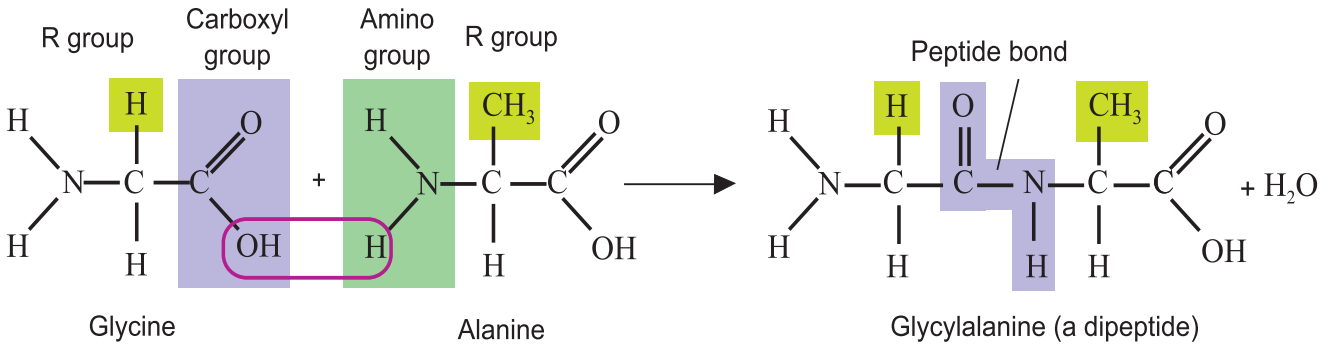


Fig: 2.22: Formation of a dipeptide and peptide bond

A dipeptide has two ends; one is called amino or **–N terminal** end while other is called carboxylic acid or **–C terminal** end. A new amino acid can be added in this chain from its carboxylic acid or –C terminal end in the same way. Thus, a **tripeptide** (a product of three amino acids) is formed and another water molecule is also released. Similarly, when several amino acids are linked together by many peptide bonds, the **polypeptide** chain is formed.

Structural conformations in proteins

A linear polypeptide with a specific sequence and number of amino acids is called **primary structure**. It is shown by all proteins at the time of their synthesis on ribosomal surface. After synthesis a protein does not remain in its primary structure but can be changed into some other structural conformations (particular form, shape or structure).

A helical **(α-helix)** or flattened sheets **(β-pleated sheet)** like structures which are established by **H-bonding** between opposite charge bearing groups of different amino acids are called **secondary structures**. In some proteins the linear polypeptide is changed into α-helix, then α-helix fold again and again by **ionic bonds** and **disulfide bridges** to form a globular shaped structure, the **tertiary structure**. Some proteins exist in very complex structure in which more than one globule is attached together by **hydrophobic interaction**. Such structures are called **quaternary structures**.

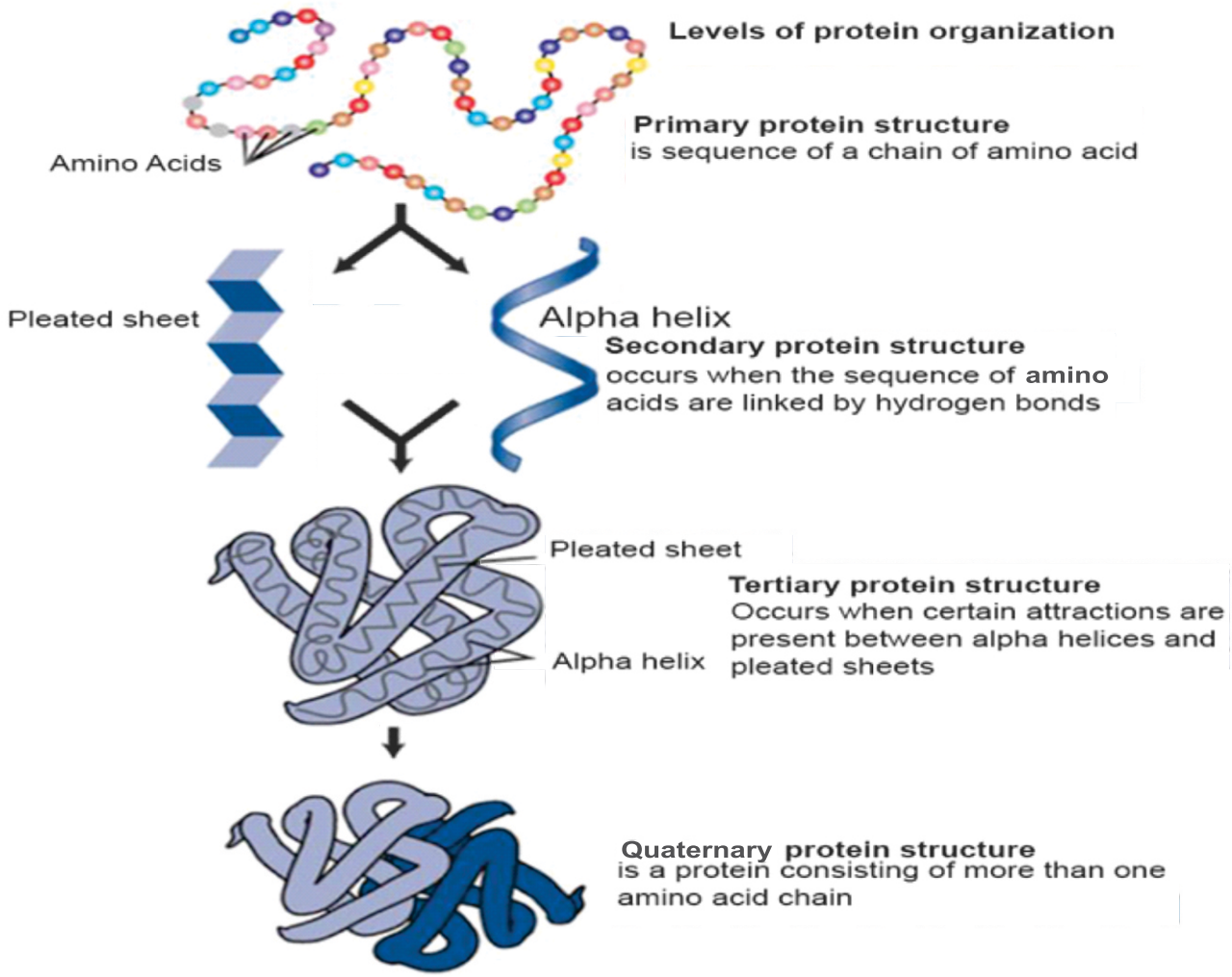


Fig: 2.23: Structural conformations in proteins

2.4.2 Significance of Amino Acid Sequence

Sequence of amino acid in a polypeptide is a characteristic feature of primary structure of protein which is responsible for proper functioning of protein. It is determined by the sequence of nucleotide in DNA. Even due to **point mutation** (change of single or few nucleotides in DNA) the sequence of amino acid in a particular protein (polypeptide) may be disturbed which causes severe defects in the body as it happens in sickle cell anemia, a hereditary disease.

Normal red blood cells are disc-shaped and look like doughnuts without holes in the centre. They move easily through your blood vessels. Red blood cells contain an iron-rich protein called haemoglobin. This protein carries oxygen from the lungs to the rest of the body. **Normal haemoglobin (Hb^A)** contains four polypeptides i.e. two α-chains which consist of 141 amino acids each and two β-chains which consist of 146 amino acids each.

Sickle cell anemia is a serious disorder in which the body makes sickle or crescent shaped red blood cells. Sickle cells contain abnormal hemoglobin called **sickle haemoglobin (Hb^S)**. Sickle haemoglobin causes the cells to develop a sickle, or crescent, shape. Sickle cells are stiff and sticky. They tend to block blood flow in the blood vessels of the limbs and organs. Blocked blood flow can cause pain and organ damage. Sickle cell anemia is caused by a point mutation in β-globin gene in which only one nucleotide is replaced by another which causes a change in amino acid sequence of β-chain of haemoglobin. Sickle cell haemoglobin (Hb^S) shows only one difference from Hb^A i.e., **glutamic acid** is replaced by **valine** at position number six in β-chain.

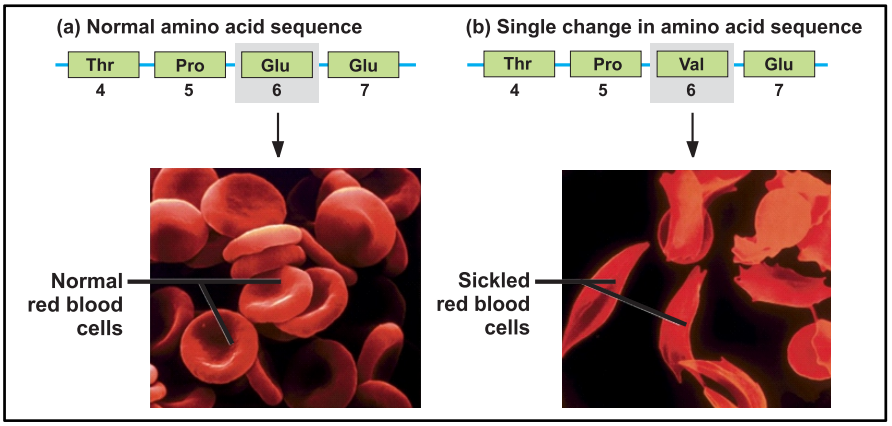


Fig: 2.24: Difference in *β*-chain of Hb^A and Hb^S

2.4.3 Classification of Proteins

Based upon structure and shape proteins can be classified into two groups i.e., fibrous and globular.

Fibrous proteins

These proteins have fibre or filament like shape. Therefore, they exist in secondary structure during function. These proteins are insoluble in aqueous medium, elastic in nature and cannot be crystalized. Examples are: collagen, fibrinogen, actin, myosin and keratin.

Globular proteins

These proteins have spherical or globules like shape. Therefore, they exist in tertiary or quaternary structure during function. These proteins are soluble in aqueous medium, inelastic in nature and can be crystalized. Examples are: enzymes, hormones, antibodies, channel proteins.

2.4.4 Role of Proteins

Proteins are very important molecules in our cells. They are involved in virtually all cell functions. Each protein within the body has a specific function. Some proteins are involved in support or composition of body parts i.e., structural roles, while others are involved in various physiological activities like bodily movement or in defence against germs i.e., functional roles. A list of several types of proteins and their functions is given in table 2.4 and 2.5.

Table: 2.4: List of structural proteins	
Types	**Roles of proteins**
Collagen	It establishes the matrix of bone and cartilages.
Elastin	Elastin provides support for connective tissues such as tendons and ligaments.
Keratin	It strengthens protective coverings such as hair, nails, quills, feathers, horns, and beaks.
Histone	It arranges the DNA into the chromosome.

Table: 2.5 List of functional proteins	
Types	**Roles of proteins**
Enzymes	The most of enzymes are protein which control metabolism i.e., they speed up the biochemical reactions.
Hormones	Some hormones are protein in nature which are involved in the regulation of physiological activities such as regulation of glucose level, calcium level, digestion, blood pressure etc.
Antibodies	These proteins are produced by WBCs in response to antigen (a foreign particle) and provide immunity.
Haemoglobin	It is found in RBCs and is involved in the transport of oxygen mainly and carbon dioxide to some extent.
Fibrinogen	It is found in blood plasma and is involved in blood clotting process.
Ovalbumin and Casein	Ovalbumin is found in egg whites and casein is a milk-based protein. Both of them are involved in the storage of amino acids.

Skills: Analyzing, Interpreting and Communication

- Draw table to illustrate different structural and functional proteins with roles of each.

2.5 LIPIDS

Lipid is the collective name for variety of organic compounds such as fats, oils, waxes and fat-like molecules (steroids) found in the body. Therefore, it is defined as a heterogeneous group of organic compounds which are insoluble in water (hydrophobic) but soluble in organic solvent such as acetone, alcohol, and ether etc. Lipids are composed of carbon, hydrogen and oxygen as carbohydrates. However, they have relatively less oxygen in proportion to carbon and hydrogen than do carbohydrates. For instance, **tristearin** is a simple lipid which shows molecular formula as $C_{57}H_{110}O_6$. Due to high contents of carbon and hydrogen, they contain double amount of energy than carbohydrates.

In general lipids are components of cell membranes (phospholipids and cholesterol), act as energy stores (triglycerides), steroid hormones and are also involved in protection, waterproofing, insulation and buoyancy.

Some common lipids are acylglycerol, waxes, phospholipids, terpenes, prostaglandin and steroids.

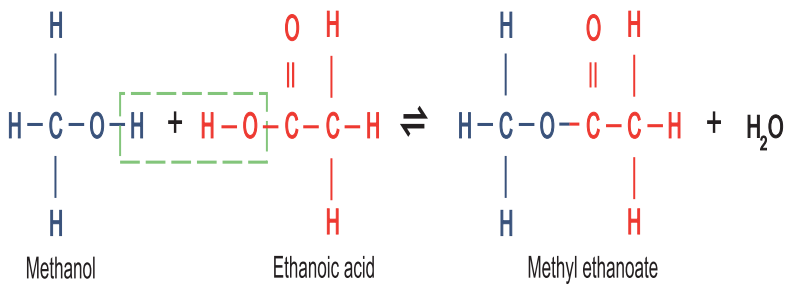


Fig: 2.25: Esterification

Acylglycerol

The most abundant lipids in living things are acylglycerol. Chemically, acylglycerols can be defined as esters of glycerol and fatty acids. An **ester** is the compound produced as the result of a chemical reaction of an alcohol with acid and a water molecule is released such a reaction is called **esterification**.

Glycerol is a trihydroxy alcohol which contains three carbons, each bears an OH group. A **fatty acid** is a type of organic acid containing one carboxylic acid group attached to a hydrocarbon. Fatty acids contain even number of carbons from 2 to 30. Each fatty acid is represented as R-COOH, where R is a hydrocarbon tail. When a glycerol molecule combines chemically with one fatty acid, a **monoacylglycerol** (monoglyceride) is formed. When two fatty acids combine with a glycerol a **diacylglycerol** (diglyceride) is formed and when three fatty acids combine with one glycerol molecule a **triacylglycerol** (triglyceride) is formed. Triacylglycerols are also called **neutral lipid** as all three OH groups of glycerol are occupied by fatty acids and no charge bearing OH group is left.

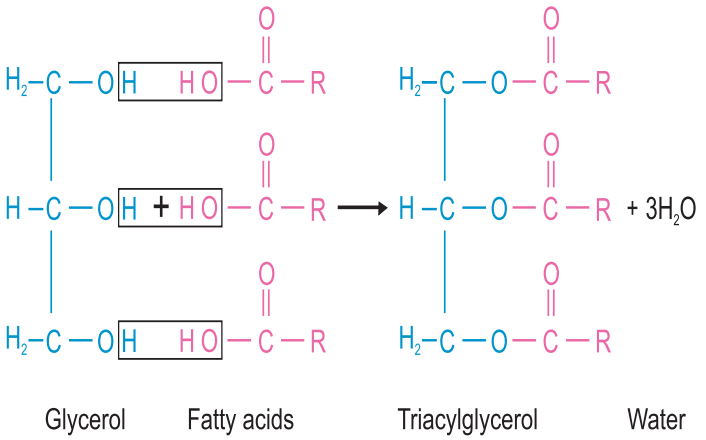


Fig: 2.26: Formation of a triacylglycerol (neutral lipid)

Properties and types of fatty acids

About 30 different fatty acids are found. Fatty acids vary in length. Acetic acid (2C) and butyric acid (4C) are simplest fatty acid, whereas palmitic acid (16C) and stearic acid (18C) are most common fatty acids. Some properties of fatty acid are increased with an increase in number of carbon atoms, such as melting point, solubility in organic solvent and hydrophobic nature. Some common fatty acids are given in the table 2.6. Fatty acids are either saturated or unsaturated. Fatty acids in which all of the internal carbon atoms possess hydrogen side groups are said to be **saturated fatty acids** because they contain the maximum number of hydrogen atoms that are possible, e.g., palmitic acid. Saturated fatty acids tend to be solid at room temperature (higher melting point) and are more common in animal lipids (fats).

Unsaturated fatty acids have one or more pairs of carbon atoms joined by a double bond. They therefore are not fully saturated with hydrogen, e.g., oleic acid. Unsaturated fatty acids are liquid at room temperature (lower melting point) and are more common in plant lipids (oils). Triglycerides containing hydrocarbon chains melt at a low temperature. This is useful for living things.

Table: 2.6: Common types of fatty acids

Name	Typical source	No. of Carbon	Condensed Formula	Melting point (°C)
Saturated				
1.Palmitic	**Most fats and oils**	**16**	$CH_3\text{-}(CH_2)_{14}\text{-}COOH$	**63**
2.Stearic	**Most fats and oils**	**18**	$CH_3\ (CH_2)_{16}\ COOH$	**70**
Unsaturated				
3.Oleic	**Olive oil**	**18**	$CH_3\text{-}(CH_2)_7\text{-}CH{=}CH\text{-}(CH_2)_7\text{-}COOH$	**4**
4.Linoleic	**Vegetable oils**	**18**	$CH_3\text{-}(CH_2)_4CH{=}CHCH_2CH{=}CH\text{-}(CH_2)_7\text{-}COOH$	**-5**

Waxes

Waxes are highly hydrophobic compounds. There are two types of waxes. **Natural waxes** are simple lipids. They are typically esters of long chain fatty acids and long chain alcohols, such as bee's wax (found in honeycomb) and cutin (on leaf surfaces of plants). These are chemically inert and resistant to atmospheric oxidation. Waxes have protective functions in plants and animals.

Synthetic waxes are generally derived from petroleum or polyethylene e.g. paraffin wax which is used to make candles.

Phospholipids

Phospholipids are derived from **phosphatidic acid**. A phospholipid is formed when phosphatidic acid combines with one of the four organic compounds such as **choline** (a nitrogenous base), **ethanolamine** (an amino alcohol), **inositol** (an amino alcohol) and **serine** (an amino acid). A phosphatidic acid molecule is most similar to diglyceride that it contains a glycerol, two fatty acids esterified with first and second OH groups of glycerol and a phosphate group esterified with third OH group of glycerol. Most common type of phospholipid is **phosphatidylcholine** also called **lecithin** in which choline is attached to phosphate group of phosphatidic acid. One end of the phospholipid molecule, containing the phosphate group and additional compound is hydrophilic i.e., polar and readily soluble in water. The other end, containing the fatty acid side

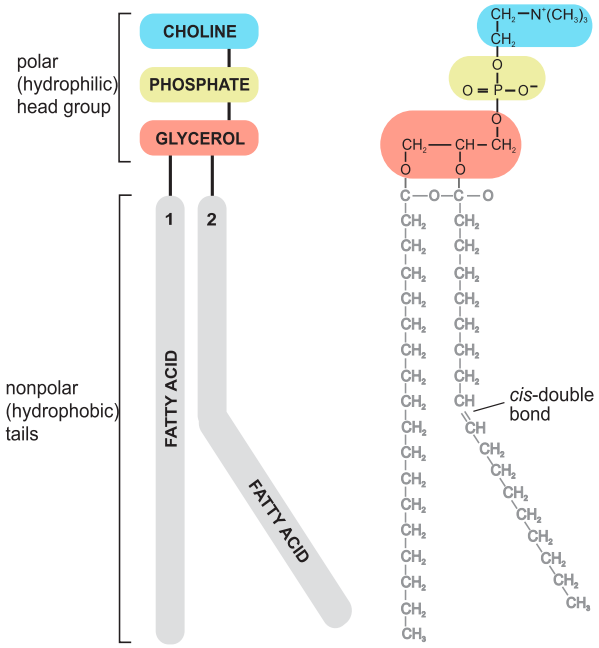


Fig. 2.27: Phosphatidylcholine (Lecithin)

chains, is hydrophobic i.e., non-polar and insoluble in water. These phospholipids are major constituents of lipid bilayer of cell membrane.

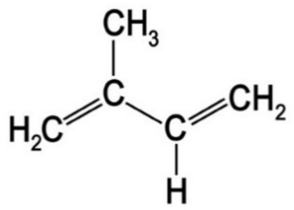


Fig. 2.28 Isoprene unit

Terpenes

All the terpenes are synthesized from a five-carbon building block known as **isoprene unit**. This unit condenses in different ways to form many compounds. Two isoprene units form a **monoterpene** e.g., menthol, four form a **diterpene** e.g., vitamin A, phytol (chlorophyll tail) and six form a **triterpene** e.g., ambrein. Natural rubber is a **polyterpene.**

Steroids

Steroids are lipids of high molecular weight which can be crystalline. A steroid nucleus consists of 17 carbon atoms arranged in four attached rings, three of the rings contain six carbon atoms, and the fourth contains five. The length and structure of the side chains that extend from these rings distinguish one steroid from other steroids. These structures are synthesized from isoprene units.

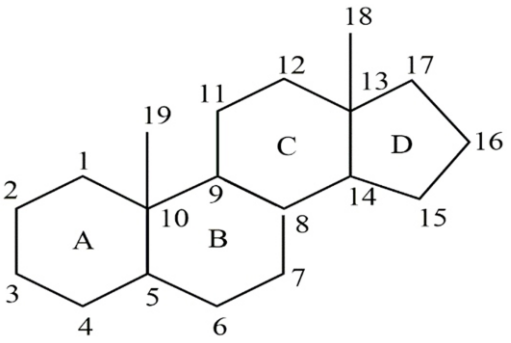


Fig. 2.29 Steroid nucleus

Cholesterol is a structural component of cell membrane. Cholesterol is the precursor of a large number of equally important steroids which include the bile acids, male sex hormone testosterone, female sex hormone progesterone and estrogen etc. Bile salts which emulsify fats and Vitamin D, which helps to regulate calcium metabolism are also steroid.

Prostaglandins

Prostaglandins exist in virtually every mammalian tissue, acting as local hormones. Prostaglandins are derived from **arachidonic acid.** Their functions vary widely depending on the tissue. Some reduce blood pressure, whereas others raise it. In the immune system, various prostaglandins help to induce fever and inflammation and also intensify the sensation of pain. They also help to regulate the aggregation of platelets an early step in the formation of blood clots. In fact, the ability of **aspirin** to reduce fever and decrease pain depends on the inhibition of prostaglandin synthesis.

Science, Technology and Society Connections

- **Relate the role of prostaglandin in inflammation with the inhibition of prostaglandin synthesis through aspirin.**

Prostaglandins play a pivotal role in inflammation a process characterized by redness (*rubor*), heat (*calor*), pain (*dolor*), and swelling (*tumor*). The changes associated with inflammation are due to dilation of local blood vessels that permits increased blood flow to the affected area. The blood vessels also become more permeable, leading to the escape of white blood cells (leukocytes) from the blood into the inflamed tissues.

Aspirin is anti-inflammatory, analgesic, and antipyretic. Aspirin inhibits prostaglandin synthetase salicylate. This drug affects the metabolism of arachidonate via the lipoxygenase pathway by inhibiting the conversion of 12-hydroperoxy- to 12-hydroxy-5, 8, 10, 14-eicosatetraenoic acid.

2.6 NUCLEIC ACID

Nucleic acids were first reported (in 1869) by a Swiss physician when he isolated a new compound from the nuclei of pus cells (white blood cells). This compound was neither a protein nor lipid nor a carbohydrate; therefore, it was a novel type of biological molecule. He named this molecule as **nuclein**, because it was located in the nucleus. The basic structure and chemical nature of nuclein was determined (in 1920) and was renamed as **nucleic acid** because of its acidic nature.

2.6.1 Chemical Structure of Nucleic Acids

Now it has been cleared that nucleic acids are of two types i.e., **deoxyribo nucleic acid (DNA)** and **ribo nucleic acid (RNA)**. Both nucleic acids are linear un-branched polymers. The monomers of the nucleic acid are called **nucleotides.**

Composition of a nucleotide

Nucleotides of DNA are called **deoxyribonucleotides** and of RNA are known as **ribonucleotides**. Each nucleotide consists of pentose sugar, a phosphate and a nitrogen containing ring structure called base. The **pentose sugar** in deoxyribonucleotides is

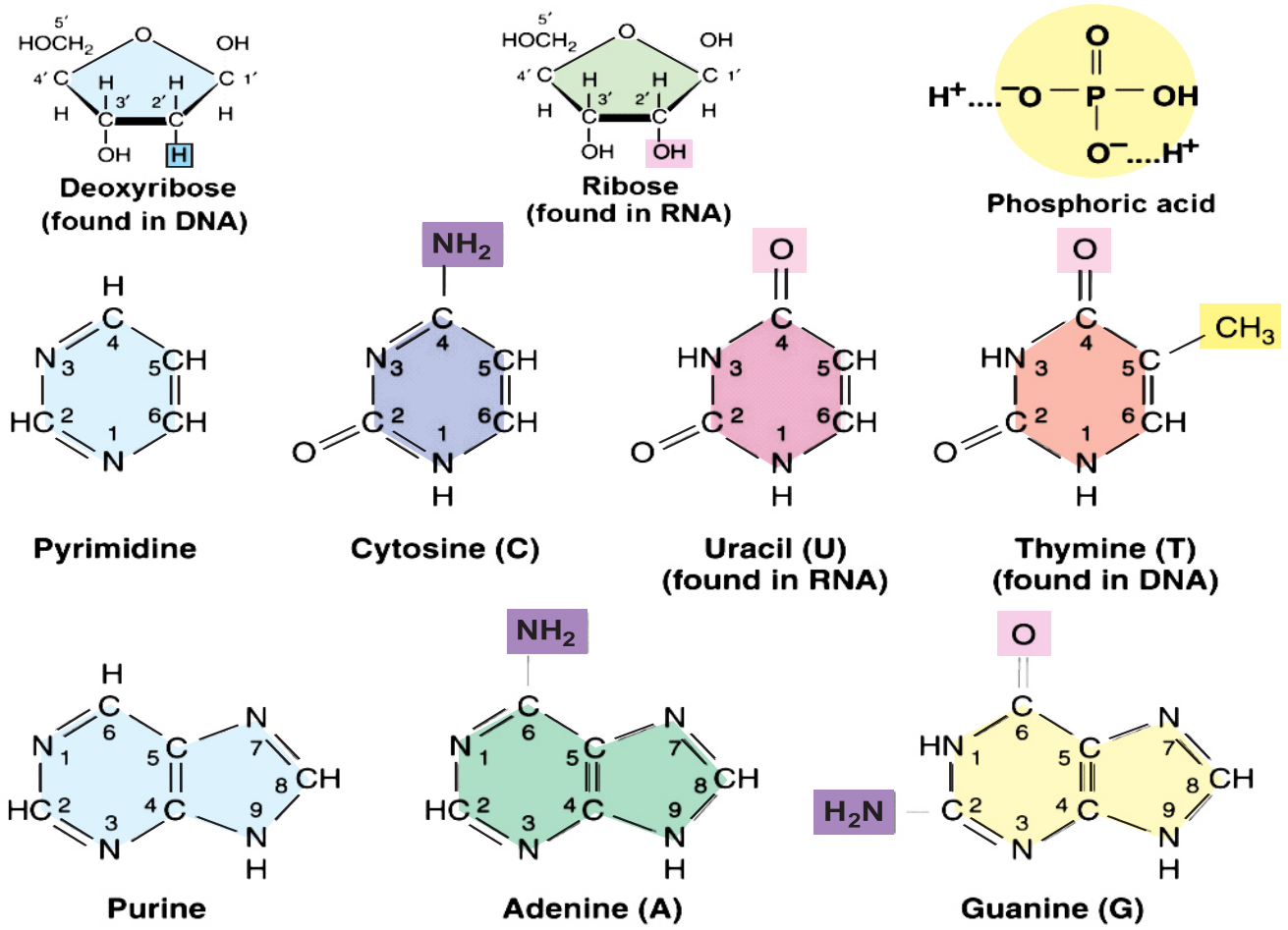


Fig. 2.30: Components of nucleotides

deoxyribose and in ribonucleotides is ribose. **Phosphoric acid** is a common component of both nucleotides which provides acidic properties to DNA and RNA. The nitrogen containing ring structures are called **bases** because of unshared pair of electron on nitrogen atoms, which can thus acquire a proton.

There are two major classes of nitrogenous bases i.e., single ring **pyrimidine** and double ring **purines**. Pyrimidine bases are of three types i.e., cytosine (C), thymine (T) and uracil (U). Thymine is only found in DNA while the uracil is only found in RNA. On the other hand, the purine bases are also of two types i.e., adenine (A) and guanine (G).

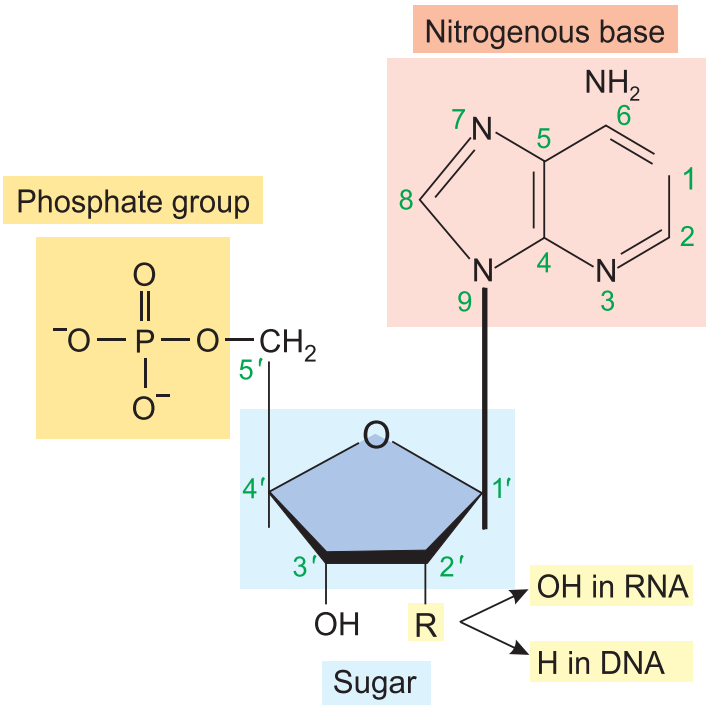


Fig. 2.31: Structure of a nucleotide

During the formation of a nucleotide, first nitrogenous base is linked with 1′ carbon of pentose sugar. Such combination is called **nucleoside**. When a phosphoric acid is linked with 5′ carbon of pentose sugar of a nucleoside, the nucleotide is formed. A nucleotide with one phosphoric acid is called **nucleoside monophosphate** with two phosphoric acids is called **nucleoside diphosphate** and with three phosphoric acids is called **nucleoside triphosphate.**

The nucleotides which take part in the formation of DNA or RNA must contain three phosphates but during their incorporation into DNA or RNA polymer each nucleotide losses its two terminal phosphates. Different terms used for nucleosides and nucleotides are given in the table 2.7.

Table: 2.7: Different types of nucleosides and nucleotides of RNA and DNA

Nitrogenous base	RNA		DNA	
	Ribonucleosides (Ribose + Base)	Ribonucleotides (Ribose+Base+ Phosphate)	Deoxyribonucleosides (Deoxyribose + Base)	Deoxyribonucleotides (Deoxyribose+Base+ Phosphate)
Adenine	Adenosine	AMP, ADP, ATP	d-Adenosine	dAMP, dADP, dATP
Guanine	Guanosine	GMP, GDP, GTP	d-Guanosine	dGMP, dGDP, dGTP
Cytosine	Cytidine	CMP, CDP, CTP	d-Cytidine	dCMP, dCDP, dCTP
Uracil/ Thymine	Uredine	UMP, UDP, UTP	d-Thymidine	dTMP, dTDP, dTTP

Polymerization of nucleotides (Formation of polynucleotide)

Nucleotides are also joined together by a condensation reaction like other biomolecules. Unlike proteins, carbohydrates, and lipids, however, the molecule that is released is not water but pyrophosphate (two phosphate groups bound together). When pyrophosphate is cleaved by the addition of water, a great deal of free energy is released which derives the process. In this way nucleotides begin to link by phosphodiester bonds and a polymer of nucleotides (polynucleotide) is formed. Polynucleotides have a free 5' phosphate group at one end and a free 3' hydroxyl group at the other end. By convention, these sequences are named from 5' to 3'.

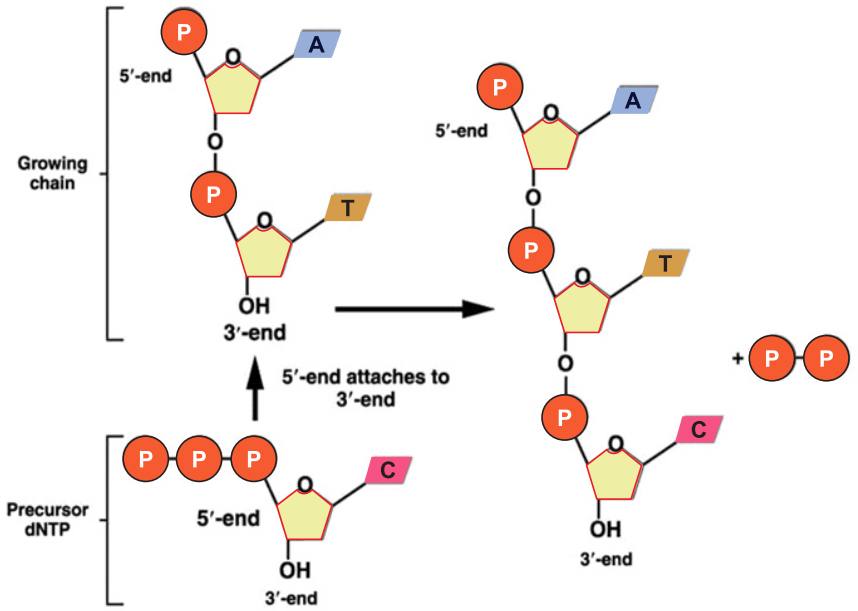


Fig. 2.32 Polymerization of nucleotides

2.6.2 Chemical Nature and Role of ATP and NAD

Adenosine triphosphate (ATP) is a mononucleotide. As shown in fig. 2.32 ATP has three parts, connected by covalent bonds: (a) adenine, a nitrogen base, (b) ribose, a five carbon sugar, (c) three phosphates. The two covalent bonds linking the three phosphates together are called **high-energy bonds**. ATP can be converted to ADP and inorganic phosphate (iP) by hydrolysis. ATP is known as the energy currency of cells.

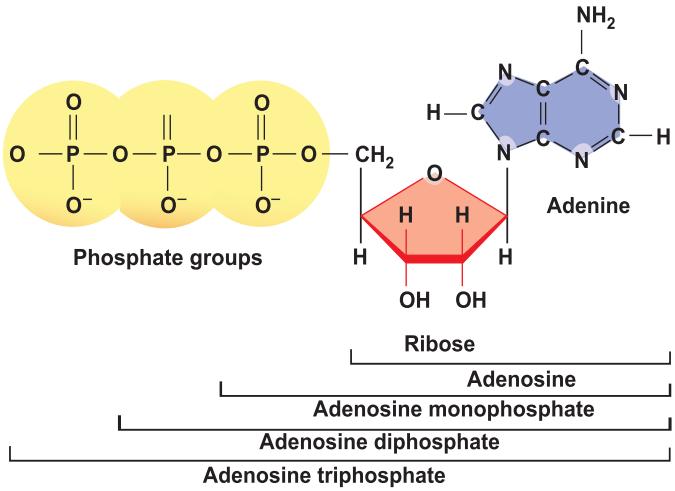


Fig. 2.33 Structure of ATP

Nicotinamide adenine dinucleotide (NAD) consists of two nucleotides. One

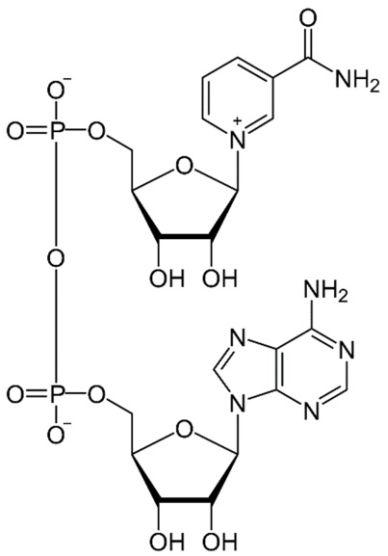


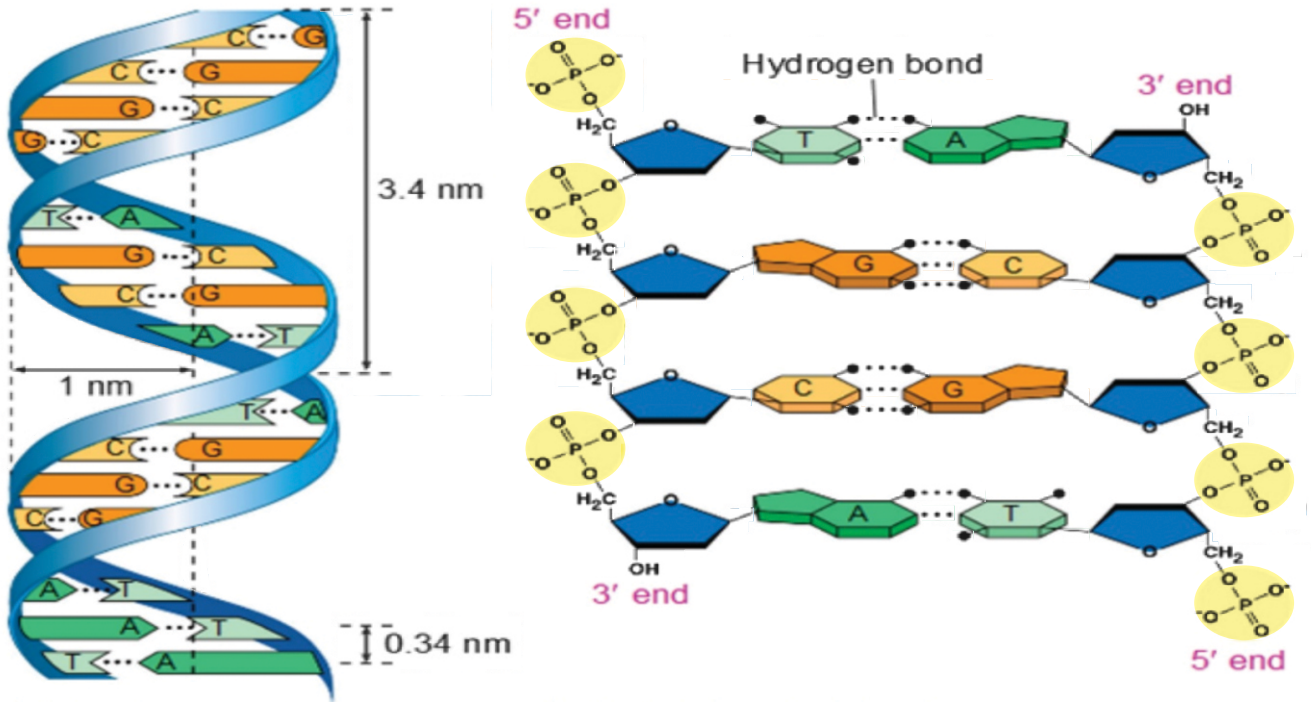
Fig. 2.34 Structure of NAD

nucleotide consists of nicotinamide, sugar and phosphate. Other nucleotide consists of adenine-sugar and phosphate. The two nucleotides are joined by their phosphate group forming a dinucleotide. NAD is a coenzyme.

2.6.3 Watson and Crick Model of DNA

In 1951, **Erwin Chargaff** found that the nitrogenous bases in a DNA show specific ratios. He observed that amount of adenine is always equal to the amount of thymine and amount of guanine is always equal to the amount of cytosine in DNA. This implies that the total purines and total pyrimidines are in 1:1 in any DNA. This conclusion is known as **Chargaff's rule**. In those days the **X-ray diffraction analysis** of DNA by **Maurice Wilkins** and **Rosalind Franklin** was published. They first time claimed that DNA is a duplex (double helix) molecule. The width of duplex is 2ηm while the length of each turn is 3.4ηm. In 1953, on the basis of these observations a graduate student **Francis Crick** and a research fellow **James Watson** of Cambridge University proposed a physical model of DNA which is now called **Watson and Crick Model of DNA.**

According to this model a DNA is made up of two polynucleotide chains which are attached together by base pairs. In order to make base pairing the two polynucleotide chains are opposite in direction i.e., one chain runs from 5′ to 3′ downward and the other chain runs



(a) Key features of double helix model **(b) Partial chemical structure**

Fig. 2.35 Watson and Crick model of DNA

from 5′ to 3′ upward. Both chains show a constant width of 2 ηm. Therefore, both chains are supposed be antiparallel to each other. The base pairing is very specific i.e., Adenine makes the pair with Thymine and Guanine with Cytosine. The base pairs are held together by the hydrogen bond. There are three hydrogen bonds between Guanine and Cytosine and two hydrogen bonds between Adenine and Thymine. Each turn of the duplex consist of 10 base pairs. Both polynucleotide chains are complementary to each other. There is no restriction of the sequence of nucleotides along the length of a DNA strand. The sequence can vary in countless ways. The sequence is specific for different species, organisms and even individuals.

Science Titbits

Watson and Crick assembled the molecular model and published their two-page article on their molecular model of DNA in the journal *"Nature"* in April 1953. Few milestones in the history of biology have as broad an impact as their double helix. They were awarded Nobel Prize in 1962 for their model of DNA.

2.6.4 Concept of Gene

A gene is region of DNA which is made up of nucleotides. It is the physical and functional unit of heredity. Each gene contains the information required to build specific proteins needed in an organism, such as they contain the instructions for our individual characteristics – like eye and hair colour. In order to make proteins, the gene from the DNA is copied into messenger RNA. The mRNA moves out of the nucleus and uses ribosomes to form the polypeptide that finally folds and configures to form the protein.

2.6.5 Ribonucleic Acid (RNA)

RNA is also a polymer of nucleotides. Its detailed chemical nature has already been discussed in previous topics. Unlike DNA, the RNA is generally single stranded and does not form a double helix like DNA. However, some regions of RNA shows a secondary double stranded structure in their complementary regions. There are three major classes of RNA each with a special function in protein synthesis. These RNA are transcribed from DNA template.

Messenger RNA (mRNA)

mRNA consists of a single strand of variable length. Its length depends upon the size of the gene, as well as the protein for which it is taking message. For example, for a protein molecule consisting of 100 amino acids, the mRNA will have the length of 300 nucleotides. Actually every three nucleotides in mRNA encode a specific amino acid, such triplets of nucleotides along the length of mRNA are called **codons** of **genetic codes**. mRNA is about 3 to 4% of the total RNA in the cell. mRNA takes the genetic message from the nucleus to the ribosome in the cytoplasm to form particular protein. This process is known as **translation.**

Ribosomal RNA (rRNA)

Ribosome consists of rRNA and protein. rRNA is transcribed by the genes present on the DNA of the several chromosomes. It is called rRNA because it eventually becomes part of ribosome. The rRNA is packaged with a variety of proteins into ribosomal subunits. The base sequence of rRNA is similar from bacteria to higher plants and animals. rRNA have largest size among the RNA. Approximately, 80% of total RNA contents of a cell are rRNA. It is a part of ribosome where protein synthesis takes place. In other words rRNA provides a platform for protein synthesis.

Transfer RNA (tRNA)

It is the smallest of the RNA molecules and it consists of 75 to 90 nucleotides. A tRNA is a single stranded molecule but it shows a duplex appearance at its some regions where complementary bases are bonded to one another. It shows a flat cloverleaf shape in two dimensional views. Its 5′ end always terminates in Guanine base while the 3′ end is always terminated with base sequence of CCA. Amino acid is attached to tRNA at this end. The nucleotide sequence of the rest of the molecule is variable.

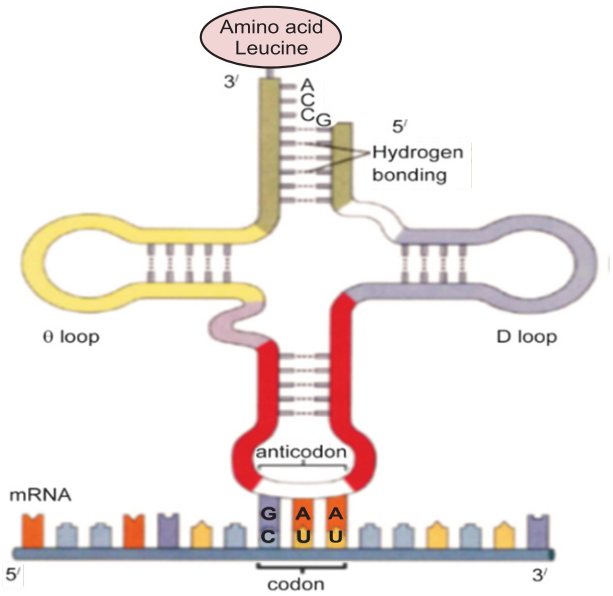


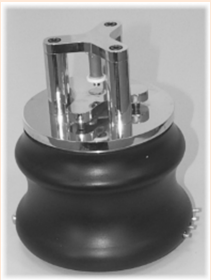
Fig: 2.36: Cloverleaf model of tRNA

tRNA has three loops. The middle loop in all the tRNA is composed of 7 bases, the middle three of which form the **anticodon**; it is complementary to specific **codon** of mRNA. The D loop recognizes the activation enzyme. Theta (θ) loop recognizes the specific place on the ribosome for binding during protein synthesis. There is at least one tRNA molecule for each of the 20 amino acids found in proteins. Sixty tRNA have been identified. However, human cells contain about 45 different kinds of tRNA molecules, each transports a specific amino acid from cytoplasm to the surface of ribosome for protein synthesis.

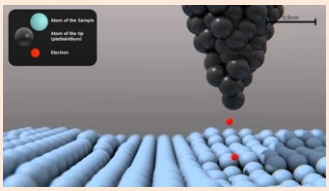
Science, Technology and Society Connections

- **Correlate the scanning tunnelling microscope as the latest advancement for seeing the atoms of DNA.**

The Scanning tunneling microscope was invented in 1980. It can allow scientists to view atoms on the surface of a solid. It is a very powerful tool that can be used to resolve features less than a nanometer. The microscope's inventors, Gerd Binnig and Heinrich Rohrer were awarded Nobel Prize in Physics in 1986. Seeman's group worked on the DNA nanotechnology. They constructed molecular building blocks of DNA.



Scanning tunneling microscope



Atoms seen on the surface of a solid

2.7 CONJUGATED MOLECUELS

Molecules when joined by other kinds of molecules are called conjugated molecules. The examples are glyocolipids, glycoproteins, lipoproteins and nucleoproteins.

Glycolipids are complex lipids containing one or more simple sugars in connection with long fatty acids or alcohol. Glycolipids are present in white matter of brain and myelin sheath of nerve fibres and chloroplast membrane.

Glycoproteins are formed when proteins are covalently attached to carbohydrates. Glycoproteins are widely distributed in the cells. They function as hormones, transport proteins, structured proteins and receptors. The blood group antigens contain glycoproteins, which also play an important role in blood grouping.

Lipoproteins are formed by the combination of protein with phospholipids. Phospholipid protein complexes are widely distributed in plant and animal material. They occur in milk, blood, cell nucleus, egg yolk membrane and chloroplasts of plants.

Nucleoproteins consist of simple basic protein and nucleic acid. They are found in chromosomes and ribosomes.

Science Titbits

Why do the nucleotides in DNA have a hydrogen atom at the 2' carbon instead of the hydroxyl group in ribose? The answer is that a hydroxyl group at the 2' position can participate in a reaction that cleaves the phosphodiester bond. Thus, DNA can act as a stable long-term repository for genetic information. RNA is usually degraded within your cells in 30 minutes.

Skills: Analyzing, Interpreting, and Communication

- Draw the Watson—Crick model of DNA
- Illustrate the formation of phosphodiester linkage

Science Technology and Society Connections

- **List the career opportunities in the field of biochemistry.**

Biochemistry, the study of chemical processes that take place in living organisms, is a broad field that offers a wide range of career options. Biochemists can pursue stem cell or genetic research that has the potential to result in dramatic medical or scientific breakthroughs. Some biochemists study the body's immune response to germs and allergens or the effectiveness of drugs in treating a wide array of afflictions. Other biochemists work in the commercial food or agricultural field looking for ways to improve products and crops. The many and diverse applications of biochemistry include pharmacology, genetics, immunology, bioinformatics, environmental science, forensics, toxicological studies and food science. The career options are nearly endless, and still unfolding, as new applications for this exciting field of study continue to evolve.

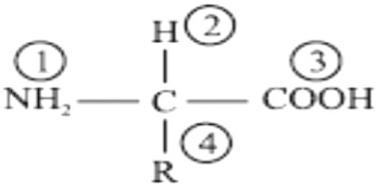
Activity

1. Performing Benedict's test for reducing sugars and confirmation of the presence of starch through Iodine test
2. Confirmation of the presence of proteins through Biuret test
3. Confirmation of the presence of lipids through Emulsion test
4. Demonstration of the presence of nucleic acids in biological materials e.g., onion

Exercise

MCQs

1. Select the correct answer



(i) An amino acid molecule has the following structure:

Which two of the groups combine to form a peptide link between two amino acids?

(A) 1 and 2 (B) 1 and 3 (C) 2 and 3 (D) 2 and 4

(ii) Which class of molecule is the major component of cell membrane

(A) phospholipid (B) cellulose (C) wax (D) triglyceride

(iii) Glycerol is the backbone molecule for

(A) ATP (B) terpenes (C) neutral lipids (D) steroids

(iv) A fatty acid is unsaturated if it

(A) contains hydrogen (B) contains double bonds

(C) contains an acid group (D) all of them

(v) In RNA the nitrogen base that takes the place of thymine is

(A) adenine (B) cytosine (C) guanine (D) uracil

(vi) The ending—ose means a substance is a

(A) sugar (B) lipid (C) protein (D) nucleic acid

(vii) Glycolipids and lipoprotein are important components of

(A) cellular membrane (B) cell wall (C) both of them (D) none of them

(viii) When two amino acids are linked to form peptide linkage ..... is removed

(A) hydroxyl (B) water (C) carbon (D) nitrogen

(ix) What is the theoretical number of chemically different dipeptides that may be assembled from two amino acids?

(A) one (B) two (C) three (D) four

(x) A polar molecule is …….. in water

(A) soluble (B) insoluble (C) reactive (D) innert

(xi) Which statement correctly describes a property of water?

(A) a relatively large amount of heat is needed to increase its temperature

(B) at normal room temperature, its molecules are bound together by ionic bonds

(C) the highest density of water occurs below its freezing point

(D) water acts as solvent for nonpolar molecules

(xii) Estrogen, vitamin-D and cholesterol are all examples of

(A) glycolipids (B) lipoproteins (C) terpenes (D) steroids

(xiii) Which term includes all others?

(A) carbohydrate (B) starch (C) monosaccharide (D) polysaccharide

(xiv) Choose the pair of terms that correctly completes this sentence: Nucleotide are to ------as --------are to proteins.

(A) nucleic acids; amino acids (B) amino acids; polypeptides

(C) glycosidic linkages; polypeptide linkages (D) polymers; polypeptides

(xv) The enantiomer of D-glucose is

(A) D-galactose (B) L-galactose (C) both of them (D) none of them

Short Questions

2. How would you describe biochemistry?
3. What are bioelements?
4. Describe the chemical composition of protoplasm.
5. What are the four fundamental kinds of biological molecules? Explain.
6. Why is the covalent bond in water polar?
7. Why water is regarded as universal solvent?
8. What is the importance of hydrogen bonding?
9. Why very large amount of heat can increase very little temperature in water?
10. How water protects living things against sudden thermal change?
11. What is the importance of high heat of vapourization of water to animals?
12. Describe classification of carbohydrates.
13. Describe the classification of monosaccharides?
14. Describe the conversion of open chain of ribose into ring chain.
15. Draw and label the ring forms of alpha and beta glucose.
16. Justify that the laboratory-manufactured sweeteners are “left handed” sugars and cannot be metabolized by the “right handed” enzymes.

17. Illustrate the formation and breakage of (a) sucrose (b) maltose (c) lactose.
18. Draw the structural formula of amino acid.
19. Describe the synthesis of peptide bond
20. Describe the four types of structure of proteins.
21. Describe (a) globular proteins (b) fibrous proteins.
22. Describe the classification of lipids
23. What role do lipids play in living organisms?
24. Why phospholipids form a thin layer on the surface of an aqueous solution?
25. What is isoprene unit? Explain.
26. Describe a steroid nucleus.
27. How might an error in the DNA of an organism effect protein function?
28. Define gene is a sequence of nucleotides as part of DNA, which codes for the formation of a polypeptide.
29. Write the differences between:

(a) major and minor bioelements
(b) dimer and polymer
(c) polar and nonpolar covalent bond
(d) polyhydroxy aldehyde and polyhydroxy ketone
(e) alpha and beta glucose
(f) D-glucose and L-glucose
(g) amylase and amylopectin
(h) amylopectin and glycogen
(i) primary and secondary structure of proteins
(j) tertiary and quaternary structure of proteins
(k) purine and pyrimidine
(l) saturated and unsaturated fatty acids
(m) DNA and RNA

Extensive Questions

30. Describe the chemical composition of protoplasm.
31. Distinguish carbohydrates, proteins, lipids and nucleic acids as the four fundamental kinds of biological molecules.
32. Describe and draw sketches of dehydration synthesis and hydrolysis reactions for making and breaking of macromolecule polymers.

33. How the properties of water make it the cradle of life?
34. Distinguish the properties and role of monosaccharides.
35. Write the emperical formula of monosaccharides and classify them.
36. Compare the stereoisomers of glucose.
37. Distinguish the properties and role of disaccharides.
38. Describe glycoside bond in the transport of disaccharides.
39. Distinguish the properties and role of polysaccharides.
40. Describe the properties and roles of starch, glycogen, cellulose and chitin.
41. Justify the significance of the sequence of amino acids through the example of sickle cell haemoglobin.
42. List examples and the roles of structural and functional proteins.
43. Describe the properties and roles of:
    (a) acylglycerol
    (b) phospholipids
    (c) terpenes
    (d) waxes
44. Evaluate the role of the following as important groups of lipids and describe their roles in living organism:
    (a) steroid
    (b) prostaglandins
45. Describe the molecular level structure of nucleotides.
46. Distinguish among the nitrogenous bases found in the nucleotides of nucleic acids.
47. Describe the structure of a mononucleotide (ATP) and a dinucleotide (NAD).
48. Explain the formation of phosphodiester bond.
49. Explain the double helical strucutre of DNA as proposed by Watson and Crick.
50. What is a gene? How gene codes for the formation of a polypeptide?
51. Explain general strucutre of RNA.
52. Explain the structure and role of three types of RNA.
53. Describe the roles of the following conjugated molecules:
    (a) glycolipids
    (b) glycoproteins
    (c) lipoproteins
    (d) nucleoproteins

3

ENZYMES

After completing this lesson, you will be able to

- Describe the structure of enzyme.
- Explain the role and component parts of the active site of an enzyme.
- Differentiate among the three types of co-factors i.e. in organic ions, prosthetic group and co-enzymes, by giving examples.
- Explain the mechanism of enzyme action through Induced Fit Model, comparing it with Lock and Key Model.
- Explain how an enzyme catalyzes specific reactions.
- Define energy of activation and explain through graph how an enzyme speeds up a reaction by lowering the energy of activation.
- Describe the effect of temperature on the rate of enzyme action
- Compare the optimum temperatures of enzymes of human and thermophilic bacteria.
- Describe the range of pH at which human enzymes function
- Compare the optimum pH of different enzymes like trypsin, pepsin, pepane.
- Describe how the concentration of enzyme affects the rate of enzyme action.
- Explain the effect of substrate concentration on the rate of enzyme action.
- Construct and interpret graphs based on data about the effect of temperature, enzyme concentration and substrate concentration on the rate of enzyme action.
- Describe enzymatic inhibition, its types and its significance.
- Name the molecules which act as inhibitors.
- Categorize inhibitors into competitive and non-competitive inhibitors.
- Explain feedback inhibition.
- Classify enzymes on the basis of the reactions catalyzed (oxido-reductases, transferases, hydrolases, hydrolyases, isomerases, and ligases).
- Classify enzymes on the basis of the substrates they use (lipases, diastase, amylase, proteases etc).

You got a brief introduction about enzymes in IX-X biology course. There is complete check and balance on the chemistry of cell, which is exhibited through various enzymatic reactions going on within a cell. The concepts developed in this chapter will construct knowledge where you will be able to analyze comprehend and apply that knowledge.

The sum of all the chemical reactions going on in a cell is known as **metabolism.** These reactions have to be carried out very quickly so that their products can be utilized in various life activities in the cells. **Enzymes** are biological catalysts and therefore they speed up the biochemical reaction without being consumed.

Some common properties of enzymes are:

(i) Increase the speed of chemical reaction.

(ii) Required in very small quantity for the reaction.

(iii) Highly sensitive to pH and temperature.

(iv) Either highly specific or slightly less specific.

(v) Can work in *vivo* (living cells) as well as in *vitro* (glassware).

(vi) Some require co-factor for proper activity.

(vii) Lower the need of activation energy.

(viii) Only speed up a reaction and do not affect the equilibrium of the reaction.

Science Titbits

During the early nineteenth century, two French chemists, **Payen** and **Persoz** grounded up barley seeds in water to make a crude mixture that would digest starch. They gave the name **diastase** whatever it was that digested the starch.

3.1 ENZYME STRUCTURE

With exception of ribozymes, all the enzymes are globular proteins which are made up of one or more polypeptides. **Ribozymes** are the enzymes which consist of RNA and are found in ribosomes. For example, peptidyl transferase is a ribozyme which forms peptide bond during protein synthesis.

3.1.1 Shape of Enzymes and Components of an Active Site

Majority of enzymes which are protein in nature can have molecular weights ranging from about 10,000 to over 1 million. Such enzymes have tertiary or quaternary structures. The catalytic activity of an enzyme is located in its **active site** which is a specific charge bearing, three dimensional cavity. The substrate (the reactant which is to be converted into product) molecule is attached to the active site by non-covalent interactions like hydrogen bonding and hydrophobic interactions. Active site consists of 3-12 amino acids which may be scattered in the polypeptide but are brought together in a particular fashion due to secondary and tertiary folding of the protein molecule, e.g., the active site for aldolase consists of glycine, histidine, and alanine amino acids. An active site consists of two functional regions, i.e., binding site and catalytic site. Some amino acids have active site which makes bonds with substrate constitute the **binding site** while the other amino acids which cause conversion of substrate

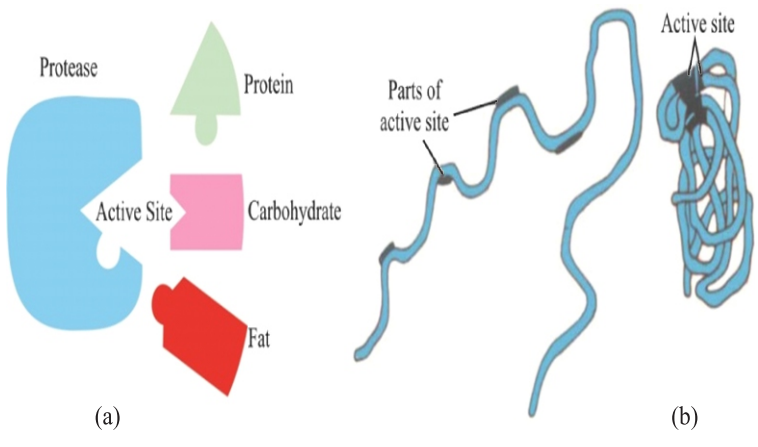


Fig: 3.1: Active site: (a) Which substrate fits the active site? (b) Grouping of amino acids of a polypeptide during the formation of tertiary structure to produce an active site.

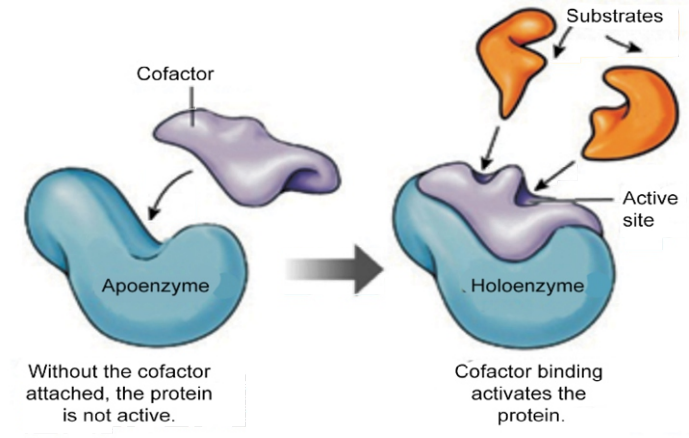


Fig. 3.2 Structure of enzyme

into product (catalysis) constitute the **catalytic site**. The shape of active site is designed according to the substrate therefore only a particular substrate can attach to the active site, however, sometime related substrate can also bind to the active site.

Some enzymes also require a non-protein part, the **cofactor** which is not only responsible for the attachment of substrate to the active site but also participate in catalytic process. The final shape of active site is actually established after the attachment of cofactor. An enzyme which requires a cofactor becomes active only if the cofactor is combined with it. Such an active enzyme is called **holoenzyme**. If the cofactor is not available the remaining protein part of enzyme becomes catalytically inactive and is called **apoenzyme**. On the other hand, the enzymes which do not require cofactor can also show active and inactive states. Pepsin is an example of such enzyme. It is secreted by gastric gland from stomach wall in an inactive state, the **pepsinogen**. In this state, it has an additional polypeptide fragment attached to its active site which does not allow the binding of substrate, hence it remains inactive. When pepsinogen is exposed in HCl (as in stomach cavity) the additional polypeptide fragment is removed and as a result inactive (apoenzyme) pepsinogen is changed into its active (holoenzyme) form, the **pepsin.**

Science Titbits

How are enzymes formed? Enzymes are proteins, so they are formed as per message or base sequence in DNA. Enzymes are synthesized by living cells but they retain their catalytic action even when extracted from cells, i.e., they can act in vitro. These days' enzymes are also being produced by recombinant DNA technology.

3.1.2 Types of Cofactors

The cofactor may be inorganic or organic molecules. The inorganic cofactors are different metallic ions such as Fe^{++}, Mg^{++}, Cu^{++}, Zn^{++}, etc. These are only attached to the enzymes when substrate gets bind i.e., they are detachable cofactors. Such cofactors are also called **activators**.

$$\textbf{Glucose + ATP} \xrightarrow{\text{Hexokinase + } Mg^{+2}} \textbf{Glucose-6-phosphate + ADP}$$

The organic cofactors are either co-enzymes or prosthetic groups. The **coenzymes** are the derivatives of vitamins. For example ATP, NAD^+, FAD^+ are common coenzymes. Like inorganic cofactors they are also attached to the enzymes when substrate gets bind i.e., they are also detachable cofactors.

$$\textbf{Ethyl alcohol} \xrightarrow{\text{Alcohol dehydrogenase + } NAD^+} \textbf{Acetaldehyde + } NADH_2$$

On the other hand a **prosthetic group** is covalently bonded part of an enzyme which is permanently attached to enzyme and does not detach after the completion of reaction. An iron containing porphyrin ring attached to some enzymes like cytochromes is the example of prosthetic group.

3.2 MECHANISM OF ENZYME ACTION

In an enzyme-catalysed reaction, the substrate first binds to the active site of the enzyme to form an **enzyme-substrate (ES) complex**, then the substrate is converted into **product** while it is attached to the enzyme **(EP complex)**, and finally the product is released, thus allowing the enzyme to start all over again.

$$\underset{\text{enzyme}}{E} + \underset{\text{substrate}}{S} \longrightarrow \underset{\text{enzyme-substrate complex}}{ES} \longrightarrow \underset{\text{enzyme-product complex}}{EP} \longrightarrow \underset{\text{enzyme}}{E} + \underset{\text{product}}{P}$$

Actually, the enzyme can make the local conditions inside the active site quite different from those outside (such as pH, water concentration, charge), so that the reaction is more likely to happen. For example, if a substrate is to be split, a bond might be stretched by the enzyme, making it more likely to break.

3.2.1 Models of Enzyme Action

The mechanism of enzyme action can be explained with the help of two different models. **Emil Fischer** proposed **Lock and key model** (in 1894). According to this model the active site of the enzyme has definite shape and rigid structure. Shape of active site is complementary to the shape of substrate. Therefore, a particular substrate can only bind to the active site. The active site remains unchanged during or after the reaction. Lock and key model assumes that like a particular key opens a particular lock, a specific **enzyme (key)** acts upon a particular **substrate (lock).** Actually, the notched portion of the key is equivalent to the active site on the enzyme. It reflects that enzymes are highly specific in their action and each enzyme can carry out only one particular reaction. The enzymes,

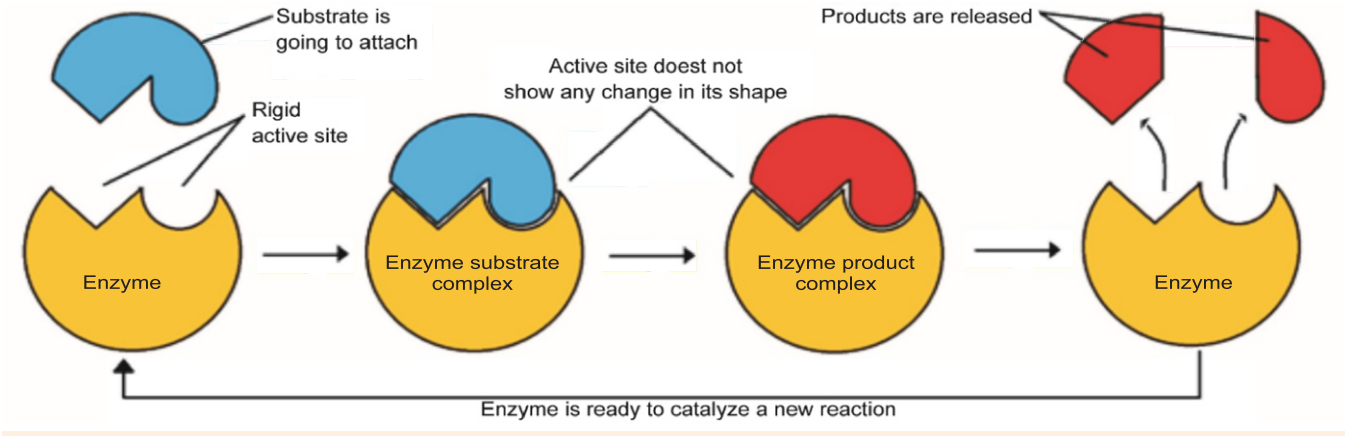


Fig: 3.3: Fischer's "Lock and Key" hypothesis of enzyme action

which work according to this model, are called **non-regulatory enzymes**. However, this model is exercised by a very small number of enzymes, for example sucrase, maltase etc. The ability of enzyme to catalyze one specific reaction is perhaps its most significant

property. Although, many enzymes show a broad range of specificity towards the substrate they catalyze. When one enzyme can catalyze only one substrate and essentially no others it is called **absolute specificity** e.g., urease.

$$\textbf{Urea + Water} \xrightarrow{\text{Urease}} \textbf{Ammonia + Carbon dioxide}$$

Koshland proposed **Induced fit model** (in 1959). According to this model the active site is flexible; therefore, it is modified as the substrate interacts with enzyme. The amino acids, which makeup the active site are molded into a precise shape which enables the enzyme to perform its catalytic function more effectively. The change which is induced in the shape of active site is responsible for the conversion of substrate into product. As the reaction is completed the active site regains its original shape. This is the flexibility of active site which allows more than one type of related substrates to be attached on active site and therefore, an enzyme can carry out more than one type of related reactions. The example is carbonic anhydrase which can add O_2 to haemoglobin as well as can control the formation of carbonic acid and bicarbonates in blood.

Enzymes, which follow the induced fit mechanism, are called **regulatory** or **allosteric enzymes** for example hexokinase.

$$\textbf{Hb + 4O}_2 \xrightarrow{\text{Carbonic anhydrase}} \textbf{Hb4O}_2\textbf{ (Oxyhaemoglobin)}$$

$$\textbf{CO}_2\textbf{ + H}_2\textbf{O} \xrightarrow{\text{Carbonic anhydrase}} \textbf{H}_2\textbf{CO}_3 \xrightarrow{\text{Carbonic anhydrase}} \textbf{H}^+\textbf{ + HCO}^-$$

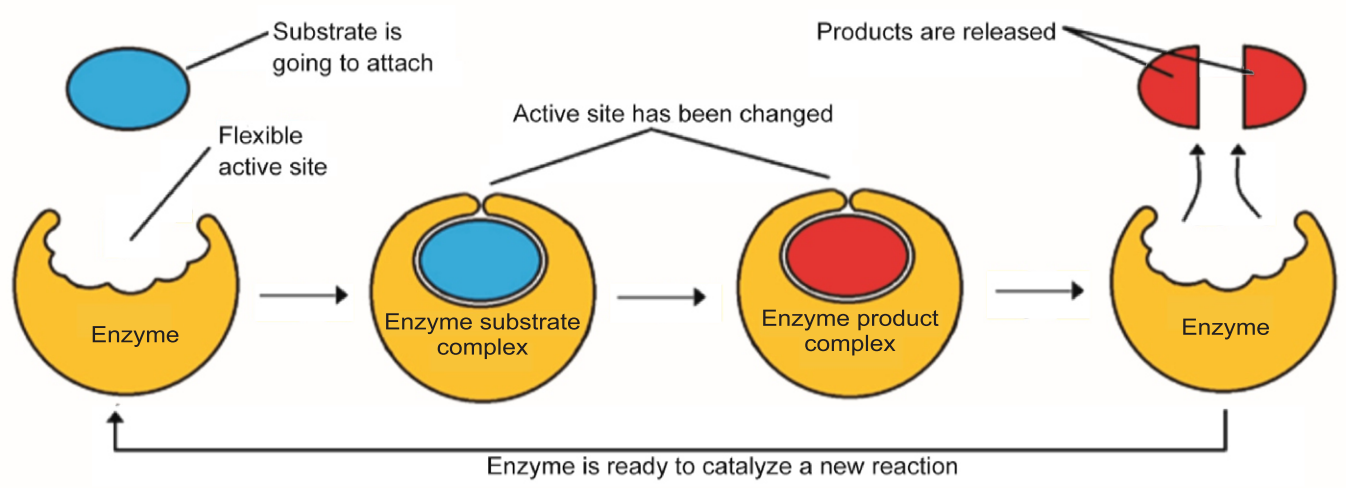


Fig: 3.4: Koshland's "Induced Fit" model of enzyme action

3.2.2 Energy of Activation

Molecules do not react with one another unless they are activated in some way. The energy that must be added to cause molecules to react with one another is called the **energy of activation**. In nonliving system we use heat as energy of activation to increase the number of effective collision between molecules. In living systems large amount of heat cannot be used as energy of activation. Why? All living cells and organisms are

mainly composed of temperature sensitive protein molecules. About 1,000 chemical reactions are being carried out in a cell at any time. Energy of activation required for such a large number of reactions cannot be provided by living system.

The living system works in isothermal condition. The excited state of molecules or reactants is achieved by biochemical process. Enzyme (E) reacts with reactant (A) to form an AE transitional complex. The energy level of AE complex reaches to the energy level of reactant B. AE complex then reacts with reactant B to form AB and enzyme (E) is released.

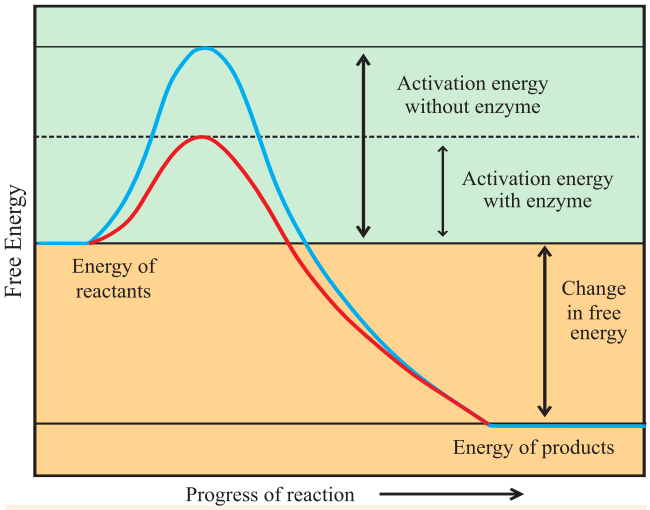


Fig: 3.5: Energy of activation: Enzymes speed the rate of chemical reactions because they lower the amount of energy required to activate the reactants and lower the need of activation energy

A + E ⟶ AE Complex + B ⟶ AB + E

Enzyme does decrease the energy of activation by changing energy dependent process to energy independent process. Thus the energy of activation is "energy required to break the existing bonds and begin the reaction". An enzyme greatly reduces the activation energy necessary to initiate a chemical reaction.

3.3 FACTORS AFFECTING THE RATE OF ENZYMATIC ACTION

The rate of enzymatic reaction is measured by the amount of substrate changed or amount of product formed, during a period of time. The external conditions which affect rate of enzyme reactions are: temperature, pH, concentration of enzyme and substrate concentration.

3.3.1 Temperature

Heating increases molecular motion. Thus the molecules of the substrate and enzyme move more quickly, so probability of a reaction to occur is increased. Increasing temperature affect the rate of reaction in such a way that an increase of just 10°C in the existing temperature doubles the rate of reaction but this effect remains up to a certain limit. The temperature that promotes maximum activity is called an **optimum temperature**. If the temperature is increased above this level, then a decrease in the rate of the reaction occurs despite the increasing frequencies of collision. This is because the secondary and tertiary structures of the enzyme have been disrupted

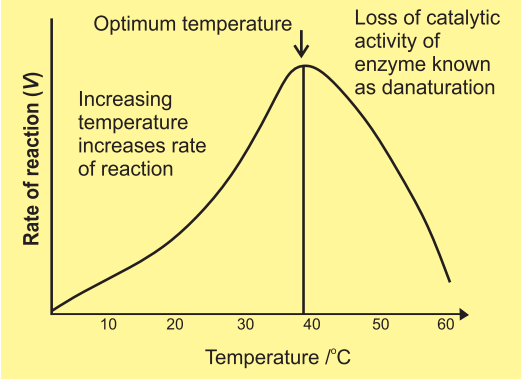


Fig: 3.6 (a): Effect of temperature on the rate of an enzyme controlled reaction

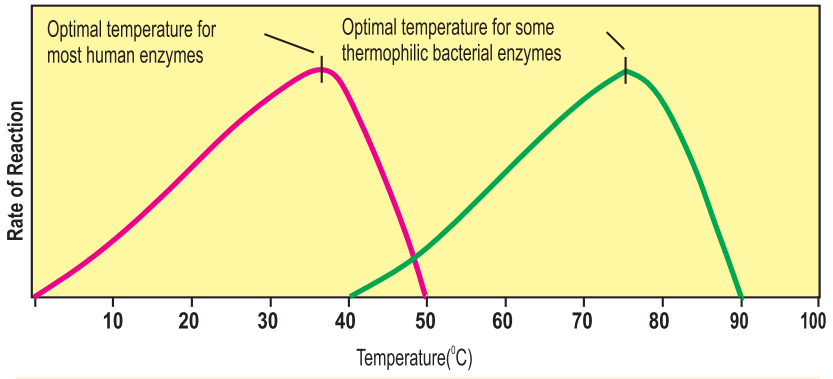


Fig: 3.6 (b): Optimum temperature for human enzymes and thermophilic bacteria

and the enzyme is said to be denatured. The enzyme unfolds and the precise structure of the active site is gradually lost. This temperature which causes denaturation of enzyme is called **maximum temperature**. The bonds which are most sensitive to temperature change are hydrogen bonds. All human enzymes have a optimum temperature of about 37-38°C, but bacteria living in hot springs may have an optimum temperature of 70°C or higher. Such enzymes have been used in biological washing powders for high temperature washes. If temperature is reduced to near or below freezing point, enzymes are inactivated, not denatured. They will regain their catalytic influence when higher temperatures are restored. This temperature where an inactive enzyme becomes active again is called **minimum temperature.**

3.3.2 pH

Every enzyme functions most effectively over a particular pH range. This narrow range of pH at which the maximum rate of reaction is achieved is called **optimum pH.** Enzyme conformation is sensitive to pH changes because pH influences the charges on the amino acid side chains that are involved in maintaining tertiary and quaternary structure of enzyme. Slight change in optimum pH of an enzyme causes ionization of amino acid of the enzyme therefore, they become inactive temporarily. On the other hand, extreme changes in optimum pH alter the ionic charge of the acidic and basic groups of enzyme and therefore disrupts the ionic bonding (denaturation) that helps to maintain the specific shape of the enzyme.

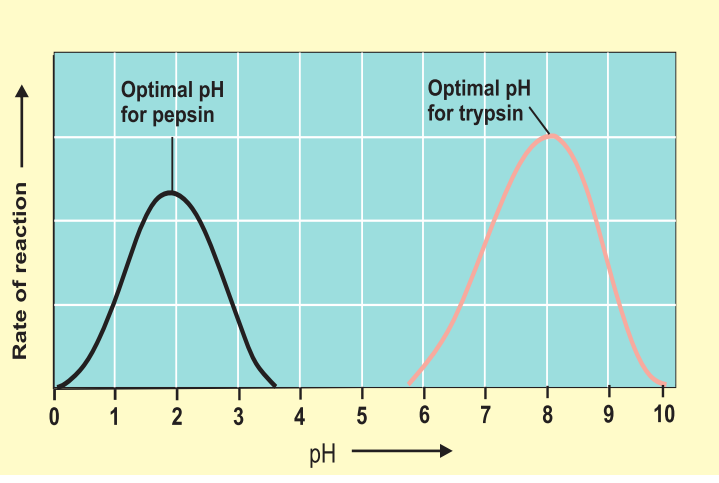


Fig: 3.7: Effect of pH on the rate of enzyme-controlled reaction

The optimum pH values for most enzymes fall in the range of pH 6-8, but there are exceptions. Some enzymes like papain from green papaya act both in acidic and alkaline media. Protein digesting enzyme pepsin is active in acidic medium at pH 2 and trypsin is inactive at this pH but shows maximum activity in alkaline medium at pH 8.

Critical Thinking

Industrial pollution can change the pH of a pond, lake or river to make the water more acidic. How can this affect the metabolic pathways of the plants that live in water?

3.3.3 Enzyme Concentration

Provided that the substrate concentration is maintained at a high level (unlimited availability), and other conditions such as pH and temperature are kept constant, the rate of reaction becomes directly proportional to the enzyme concentration. If there is only one enzyme in the system it can convert hundreds of substrates into products but it takes more time. By increasing concentration of enzyme, numbers of active sites become more available and the rate of conversion of substrate into product becomes fast. Such effect persists till the equilibrium state (when concentration of enzyme and substrate becomes equal), after that further increase in enzyme concentration will have no effect upon rate of reaction.

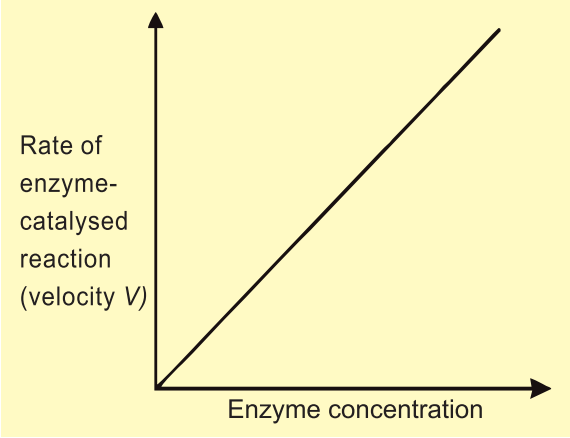


Fig: 3.8: Relationship between Enzyme concentration and the rate of an Enzyme-controlled reaction

3.3.4 Substrate Concentration

When other conditions such as pH and temperature are kept constant and the enzyme concentration is maintained at a higher level (unlimited availability), the increase in substrate concentration (S) increases the velocity (V) of the enzymatic reaction at first. The reaction ultimately reaches a maximum velocity at equilibrium state. The rise in V is decreased progressively with further increase in S. The reaction does not increase by any further rise in substrate concentration. This happens because all the active sites of enzyme molecules are occupied by the substrates (saturation) and no enzyme is left free to bind with additional molecules of the substrate.

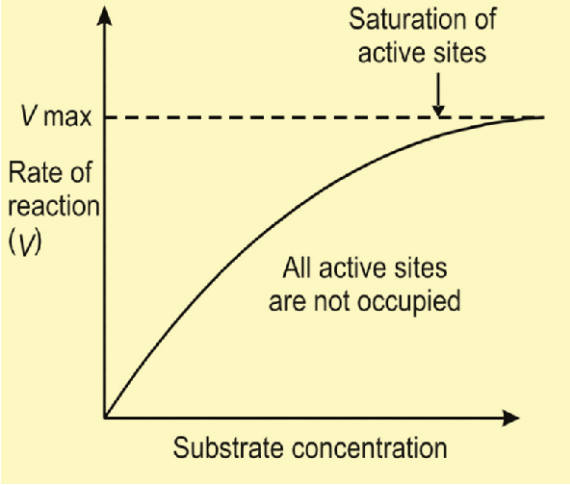


Fig: 3.9: Effect of Substrate concentration on the rate of Enzyme-controlled reaction

3.4 ENZYME INHIBITION

The phenomenon in which an enzyme fails to catalyze a reaction is called **enzyme inhibition** and the molecules which react with enzyme but are not converted into desired products are called **enzyme inhibitors**. In general, the enzyme inhibition is a normal part of the regulation of enzyme activity within cells but sometimes when external factors cause enzyme inhibition; it may become dangerous for life. The molecules which act as inhibitors include poisons, cyanides, antibodies, anti-metabolites, penicillin, sulpha drugs etc. Inhibition may be competitive or noncompetitive.

Science Titbits

Penicillin blocks the active site of an enzyme unique to bacteria. When penicillin is taken, bacteria die but human are unaffected.

3.4.1 Competitive Inhibition

A type of enzyme inhibition in which enzyme activity is blocked by the presence of a chemical that compete with the substrate for binding to the active site is called **competitive inhibition**. Usually a competitive inhibitor is structurally similar to the normal substrate and so fits into the active site of the enzyme. However, it is not similar enough to substitute fully for the normal substrate in the chemical reaction and the enzyme cannot catalyze it to form reaction products. Competitive inhibition is usually temporary, and the inhibitor eventually leaves the enzyme hence it is also called **reversible inhibition.** This means that the level of inhibition depends on the relative concentrations of substrate and i nhibitor, since they are competing for places in enzyme active sites. Therefore, if the concentration of the substrate is increased relative to the concentration of the inhibitor, the active site will usually be occupied by the substrate. An example of inhibitor is **malonate.** Succinate dehydrogenase that catalyzes the formation of fumarate from succinate is competitively inhibited by malonate.

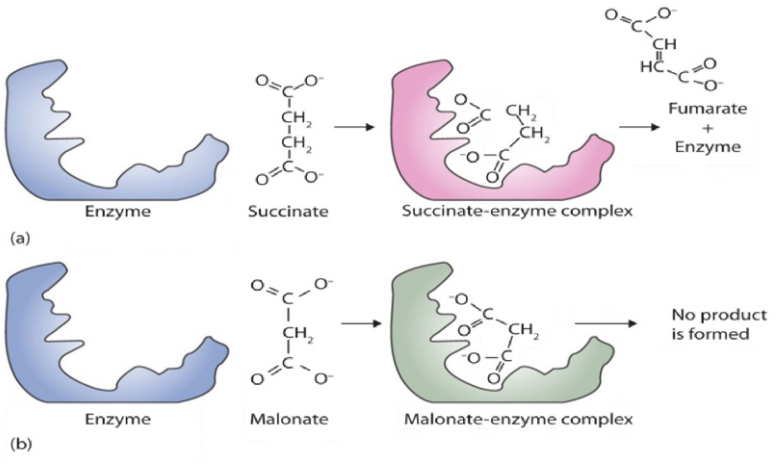


Fig: 3.10: Effect of malonate as competitive inhibitors

The **importance** of competitive inhibitors is: (a) It supports lock and key hypothesis. (b) It shows that substances which are similar to substrate are not acted upon by enzymes. (c) Competitive inhibitors are used as drugs in the control of bacterial pathogens. Antibiotics known as sulphonamides are used to combat bacterial infection.

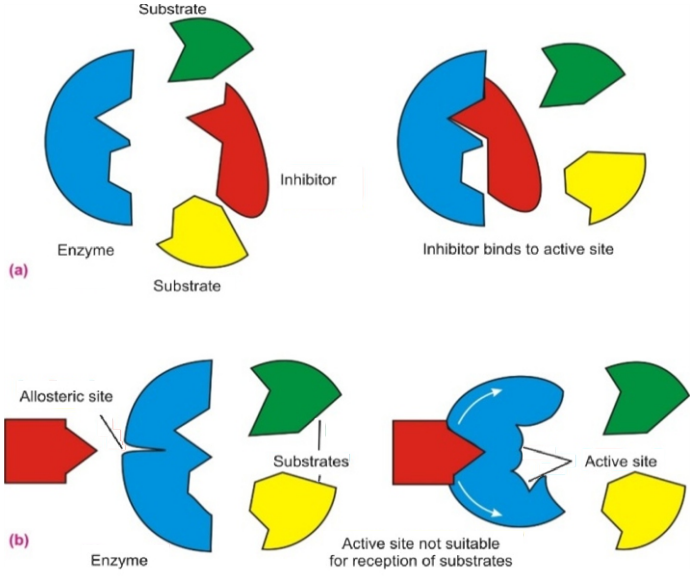


Fig: 3.11: (a) Competitive inhibition (b) Non-competitive inhibition

3.4.2 Non-Competitive Inhibitors

In non-competitive inhibition the inhibitor molecule binds to an enzyme other than active site. The other binding site of enzyme is called **allosteric site.** The non-competitive inhibitors inactivate the enzyme temporarily (reversible inhibition) or they denature the enzyme permanently (irreversible inhibition). **Reversible non-competitive** enzyme inhibitors work not by preventing the

formation of enzyme-substrate complexes, but by preventing the formation of enzyme-product complexes. So they prevent the substrate to be converted into product. Feedback inhibition is an example of reversible non-competitive enzyme inhibition

On the other hand, an **irreversible non-competitive** enzyme inhibitor destroys enzyme by altering its shape so that the substrate cannot bind to the active site. The examples of irreversible non-competitive inhibitors include cyanides and salts of heavy metals. **Cyanides** are potent poisons of living organism because they can kill an organism by inhibiting cytochrome oxidase essential for cellular respiration. They block the action of these enzymes by combining with iron which may be present in the prosthetic group. **Ions of heavy metals** such as mercury, silver and copper (Hg^{++}, Ag^{+}, and Cu^{++}) combine with thiol (-SH) groups in the enzyme breaking the disulphide bridges. These bridges are important in maintaining tertiary structure. When these bridges are broken, the enzyme becomes denatured and inactive.

Critical Thinking

Suggest why substrate concentration has no effect on non-competitive inhibition?

3.4.3 Feedback Inhibition

The activity of almost every enzyme in a cell can be regulated by its product. When the activity of an enzyme is inhibited by its own product, it is called feedback inhibition. This is a type of reversible non-competitive inhibition. This phenomenon is a part of normal regulatory mechanism and usually happens during the regulation of metabolic pathways. For example, the amino acid aspartate becomes the amino acid threonine by a sequence of five enzymatic reactions. When threonine, the end product of this pathway, is present in excess, it binds to an allosteric site on enzyme 1 on this pathway and then the active site is no longer able to bind aspartate. When all the threonine is consumed in cellular events, the threonine molecule which is attached to the allosteric site is also removed; the pathway resumes its activity once again.

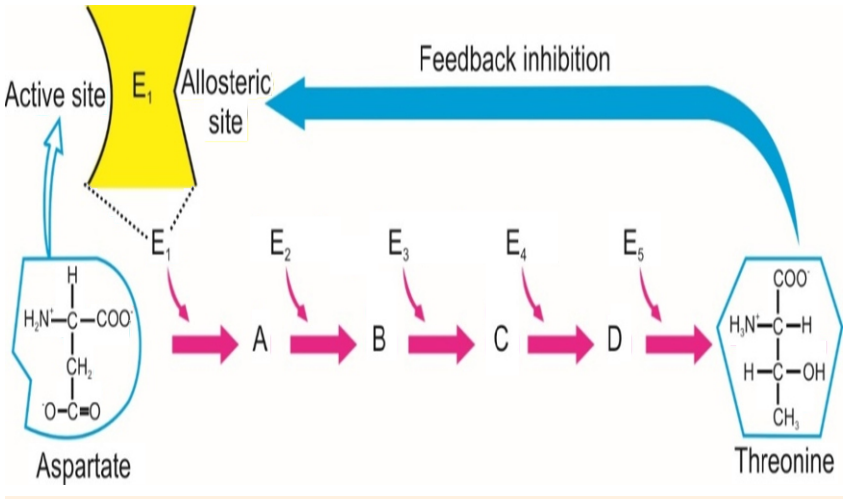


Fig: 3.12: Feedback inhibition

Skills: Analyzing

- **Identify the competitive and non-competitive inhibitors from the given list of chemical (consult any book of Biochemistry or Enzymology).** (Answer is given below)

Competitive inhibitors: Antibodies, antimetabolites, penicillin, iodoacetate, melonate, CoA (high concentration).

Non-competitive inhibitors: Acetaldehyde Di-Isopropyl fluorophosphate (DFP- nerve gas), mercury, silver, copper, cyanide.

3.5 CLASSIFICATION OF ENZYMES

Enzymes can be classified either on the basis of reaction types that they catalyze or on the basis of substrate which are acted upon by the enzyme.

3.5.1 Classification based upon reaction type

A systematic nomenclature and classification of enzymes based on reaction types and reaction mechanism was given by International Union of Biochemistry (in 1961).

On that basis all the enzymes have been classified into six groups:

1. Oxidoreductases
2. Transferases
3. Hydrolases
4. Lyases
5. Isomerases
6. Ligases

1- Oxidoreductases

These enzymes catalyze oxidation/reduction of their substrate and act by removing or adding electron or H^+ ions from or to the substrate. For example **cytochrome oxidase** oxidizes cytochrome.

2- Transferases

These enzymes catalyze the transfer of specific functional group other than hydrogen from one substrate to another. The chemical group transferred in the process is not in a free state, for example **hexokinase** transfers a phosphate group from ATP to glucose.

Science Titbits

How are enzymes named?

(a) Enzymes are named by adding "ase" to the name of substrate they act, e.g., proteases, lipases etc. (b) Enzymes are named according to the types of reaction they catalyse, e.g., oxidases, reductases etc. (c) Enzymes are named by taking into consideration both the substrate acted upon and the type of reaction catalysed, e.g., DNA- polymerase. (d) Some enzymes are named as per substance synthesized, e.g., rhodonase catalyses synthesis of rhodonate from hydrochloric acid and sodium thiosulphate.

3- Hydrolases

These enzymes bring about the breakdown of large complex organic molecules into smaller ones by adding water (hydrolysis) and breaking the specific covalent bonds. Examples are proteolytic enzymes which breakdown proteins into peptones and peptides such as **pepsin, renin** and **trypsin**. Other digestive enzymes that work in digestive tract are also the examples of hydrolases.

4- Lyases

These enzymes catalyze the breakdown of specific covalent bonds and removal of groups without hydrolysis. For example **histidine decarboxylase** breaks the covalent bonds between carbon atoms in histidine forming carbon dioxide and histamine.

5- Isomerases

These enzymes bring about intra-molecular rearrangement of atoms in the molecules and thus forming one isomer from another. For example **phosphohexose isomerase** changes glucose 6- phosphate to fructose 6- phosphate.

6- Ligases (Synthetases)

These enzymes bring about joining together of two molecules. The energy is derived by hydrolysis of ATP. For example **polymerases** are responsible for linking monomers into a polymer such as DNA or RNA.

Table 3.1:Classifiation of enzymes based upon reaction type

Sr. No	Enzyme Class	General Scheme of Reaction
1.	Oxidoreductases	$A_{red} + B_{ox} \rightleftharpoons A_{ox} + B_{red}$
2.	Transferases	$A—B + C \longrightarrow A + C—B$
3.	Hydrolases	$A—B + H_2O \longrightarrow A—H + B—OH$
4.	Lyases	$A—B \rightleftharpoons A + B$ (reverse reaction syntheses)
5.	Isomerases	$A—B—C \rightleftharpoons A—C—B$
6.	Ligases (synthetases)	$A + B + ATP \longrightarrow A—B + ADP + Pi$

3.5.2 Classification based upon substrate

Enzymes can be classified on the basis of substrates they use. Some of the examples are: proteases, lipases, carbohydrases and nucleases.

1- Proteases

These enzymes act upon proteins. Examples are: **pepsin** and **trypsin** (both digest large polypeptides into small polypeptides or peptones), **aminopeptidases** and **carboxypeptidases** (both digest peptones into dipeptides) and **erypsin** (digest dipeptides into amino acids)

2- Lipases

These enzymes hydrolyze lipids into fatty acids and glycerols. Examples are **pancreatic lipases.**

3- Carbohydrases

These enzymes cause breakdown of carbohydrates. Examples are:

(a) **amylase** (digest starch or glycogen into maltose)

(b) **cellulase** (digest cellulose into cellubiose, a disaccharide)

(c) **maltase** (digest maltose into glucoses)

(d) **sucrase** (digest sucrose into glucose and fructose)

(e) **lactase** (digest lactose into galactose and glucose)

4- Nucleases

These are involved in the breakdown of DNA and RNA. Examples are:

(a) **RNAases** (digest RNA into ribonucleotides)

(b) **DNAases** (digest DNA into deoxyribo nucleotides).

(c) **ATPases** (cause hydrolysis of ATP in muscles etc.)

Science, Technology and Society Connections

- **List the diagnostic uses of enzymes.**

(a) Aldolase: progressive muscular dystrophy, viral hepatitis and advanced cancer of the prostate
(b) Creatine Phosphokinase: damage to muscle cells.
(c) Gamma-glutamyl Transpeptidase: in assessing liver function.
(d) Lactic Dehydrogenase: in differentiating heart attack, anemia, lung injury, or liver disease.
(e) Lipase: Damage to the pancreas.

Science, Technology and Society Connections

- **Venoms as enzyme inhibitors**

Snake venom is highly modified saliva that is produced by special glands of certain species of snakes. Snake venom is a combination of many toxins (proteins) and different enzymes, use for the purposes like increasing the prey's uptake of toxins. Snake venom inhibits cholinesterase to make the prey lose control of its muscles. Venom is an inhibitor for an essential enzyme cytochrome oxidase in the cells. There are three distinct type of venom that act on the body differently.

(1) Hemotoxic venoms act on the heart and cardiovascular system.

(2) Neurotoxic venom acts on the nervous system and brain.

(3) Cytotoxic venom has a localized action at the site of the bite. Venom occupies the active site of the enzyme or combining with the iron which may present in the prosthetic group or which may be required as an enzyme activator.

Activity

1. Performing of chemical test to demonstrate that enzymes are proteins
2. Performing amylase test on starch with boiled amylase and un-boiled amylase in separate test tubes and confirmation through iodine test

Exercise

MCQs

1. Select the correct answer

(i) The catalytic activity of an enzyme is restricted to its small portion called

(A) active site (B) passive site

(C) regulation site (D) allosteric site

(ii) Which of the following has a coenzyme activity?

(A) NAD^+ (B) Ca^{++}

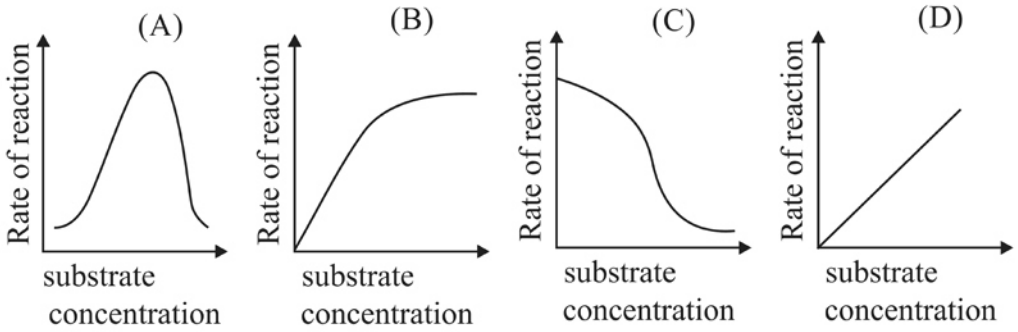
(C) both “a” and “b” (D) none of them

(iii) Non-competitive inhibitors react with enzymes at:

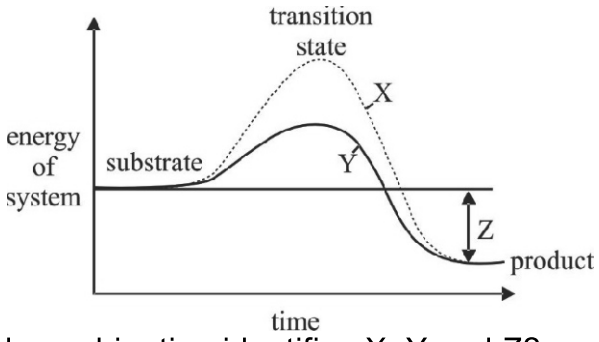
(A) active site (B) allosteric site

(C) both “a” and “b” (D) none of them

(iv) Which graph shows the expected relationship between enzyme activity and substrate concentration?



(v) The graph shows the effect of an enzyme on a reaction.



Which combination identifies X, Y and Z?

	X	Y	Z
A	catalyzed reaction	uncatalyzed reaction	activation energy
B	catalyzed reaction	uncatalyzed reaction	energy lost during reaction
C	uncatalyzed reaction	catalyzed reaction	energy gained by product
D	uncatalyzed reaction	catalyzed reaction	overall energy change

(vi) Combination of apoenzyme and coenzyme produces

(A) prosthetic group (B) holoenzyme

(C) enzyme (D) isoenzyme

(vii) The specificity of enzyme is due to their

(A) surface configuration (B) pH

(C) hydrogen bonding (D) high molecular weight

(viii) An essential feature of a competitive inhibitor is its ability to

(A) activate an operator gene (B) combine with prosthetic group

(C) modify a substrate (D) occupy an active site

(ix) The reaction rate of salivary amylase with starch decreases as the concentration of chloride ions is reduced. Which of the following describe the role of the chloride ions?

(A) allosteric inhibitors (B) cofactors

(C) coenzyme (D) competitive inhibitor

(x) How does an enzyme increase the rate of a reaction?

(A) by bringing the reacting molecules into precise orientation

(B) by increasing the rate of random collisions of molecules

(C) by shifting the point of equilibrium of the reaction

(D) by supplying the energy required to start the reaction

(xi) Many enzymes are secreted in inactive form to protect

(A) cell proteins (B) mitochondria

(C) cell membrane (D) cell DNA

(xii) Erypsin is an example of?

(A) carbohydrases (B) proteases

(C) lipases (D) nucleases

(xiii) Ribozymes consist of:

(A) only protein (B) protein + none protein part

(C) only RNA (D) none of them

Short Questions

2. What are ribozymes?
3. What is the structure of enzyme?
4. Explain the enzyme pepsin which does not require cofactor.
5. What is prosthetic group? Give an example.
6. What is the mechanism of enzyme action?
7. What is the role of free energy of activation in a chemical reaction?
8. List the external conditions which affect rate of enzyme reaction.
9. Compare the optimum temperatures of enzymes of human and thermophilic bacteria.
10. Describe the range of pH at which human enzymes function.

11. What are enzyme inhibitors? Name the molecules which act as enzyme inhibitors.
12. What is the importance of competitive enzyme inhibitors?
13. Describe cyanides as irreversible non-competitive inhibitor.
14. Describe ions of heavy metals as irreversible non-competitive inhibitor.
15. Write the difference between:
    (a) binding site and catalytic site of an enzyme
    (b) apoenzyme and holoenzyme
    (c) prosthetic group and coenzyme
    (d) inorganic cofactor and organic cofactor
    (e) lock and key model and Induced fit model of enzyme action
    (f) competitive and noncompetitive enzyme inhibitors
    (g) reversible non-competitive enzyme inhibitors and irreversible non-competivie enzyme inhibitors

Extensive Questions

16. Write the properties of enzymes.
17. Explain the role and component parts of the active site of an enzyme.
18. What are cofactors? Describe the two types of cofactors by giving examples.
19. Explain the mechanism of enzyme action through induced fit model.
20. Explain the mechanism of enzyme action through lock and key model.
21. Explain how an enzyme catalyzes specific reactions.
22. Explain through graph how an enzyme speeds up reaction by lowering the energy of activation.
23. Describe the effect of temperature on the rate of enzyme action.
24. Describe how the concentration of enzyme affects the rate of enzyme action.
25. Explain the effect of substrate concentration on the rate of enzyme action.
26. Describe enzymatic inhibition, its types and its significance.
27. Explain feedback mechanism with reference to enzymes.
28. Classify enzymes on the basis of reactions catalyzed.
29. Classify enzymes on the basis of the substrate they use.

4

BIOENERGETICS

After completing this lesson, you will be able to

- Explain the role of light in photosynthesis.
- Identify the two general kinds of photosynthetic pigments (carotenoids and chlorophylls).
- Describe the roles of photosynthetic pigments in the absorption and conversion of light energy.
- Differentiate between the absorption spectra of chlorophyll 'a' and 'b'.
- Describe the arrangement of photosynthetic pigments in the form of photosystem-I and II.
- State the role of CO_2 as one of the raw materials of photosynthesis.
- Explain, narrating the experimental work done, the role of water in photosynthesis.
- Describe the events of non-cyclic photophosphorylation and outline the cyclic photophosphorylation.
- Explain the Calvin cycle (the regeneration of RuBP should be understood in outline only).
- Draw the molecular structure of chlorophyll, showing the porphyrin head and the phytol tail.
- Draw the Z-scheme for explaining the events of the light-dependent reactions.
- Extract the leaf pigments and separate them by paper chromatography.
- Explain the process of anaerobic respiration in terms of glycolysis and conversion of pyruvate into lactic acid or ethanol.
- Outline (naming the reactants and products of each step of) the events of glycolysis.
- Illustrate the conversion of pyruvate to acetyl-CoA.
- Outline (naming the reactants and products of each step of) the steps of Krebs cycle.
- Explain the passage of electron through electron transport chain.
- Describe chemiosmosis and relate it with electron transport chain.
- Explain the substrate-level phosphorylation during which exergonic reactions are coupled with the synthesis of ATP.
- Justify the importance of G3P in photosynthesis and respiration.
- Outline the cellular respiration of proteins and fats and correlate these with that of glucose.
- Draw the flow charts showing the events of glycolysis and Krebs cycle.
- Illustrate the net energy output during glycolysis, oxidation of pyruvate and Krebs cycle.
- Define photorespiration and outline the events occurring through it.
- Rationalize how the disadvantageous process of photorespiration evolved.
- Explain the effect of temperature on the oxidative activity of RuBP carboxylase.
- Outline the process of C_4 photosynthesis as an adaptation evolved in some plants to deal with the problem of photorespiration.

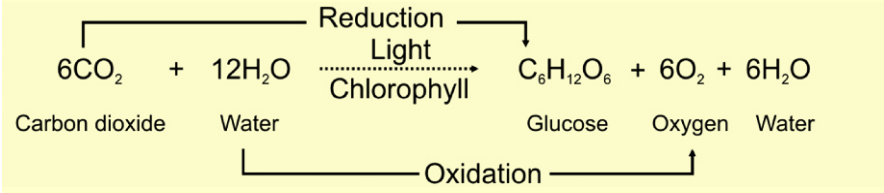
Living things cannot grow, reproduce, or exhibit any of the characteristics of life without a ready supply of energy. All metabolic reactions involve energy transformations. So the quantitative study of energy relationships in biological system is called **bioenergetics.** Biological energy transformations obey the laws of thermodynamics. You have got an introduction about bioenergetics in IX-X biology course.

This chapter deals with the most fundamental bioenergetics processes i.e., photosynthesis and respiration. You already have the general concept of these processes. The detailed learning would foster the skills of analysis and evaluation. This chapter also develops the basic concepts of photorespiration, the process that reduces plants productivity.

4.1 PHOTOSYNTHESIS

Chemically photosynthesis is a "redox" process in which CO_2 (an oxidized form of carbon) is reduced into glucose (a reduced form of carbon). Water acts as reducing agent which is oxidized into oxygen during this process. Bio-energetically photosynthesis can be defined as an energy conversion process in which energy poor molecules i.e., CO_2 and H_2O are transformed into energy rich molecule such as glucose. The extra energy is absorbed in the form of sunlight by the photosynthetic pigments.

The overall reaction of photosynthesis can be summarized as follows:



This process involves the interaction of sunlight, pigments, water and carbon dioxide.

4.1.1 Role of Light

Sunlight is an electromagnetic form of energy. The full range of electromagnetic radiation in the universe is called **electromagnetic spectrum.** Visible light is only a small part of the spectrum between 380ηm to 750ηm which is not only seen by naked eye but is also effective for the process of photosynthesis.

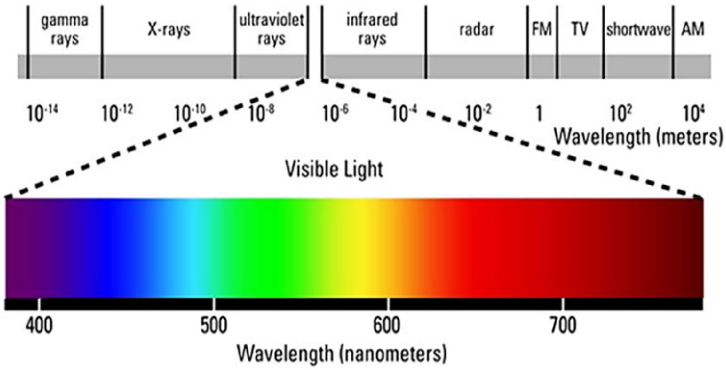


Fig. 4.1 Electromagnetic spectrum

The effectiveness of a particular wavelength of light for the process of photosynthesis primarily depends upon its absorption in plant body. As different wavelengths (colours) of visible light are differently absorbed by various photosynthetic pigments, therefore, each wavelength has its own effectiveness for the process of photosynthesis. If a plant is illuminated in different colours of light one by one, the rate of photosynthesis is measured and the data obtained in this

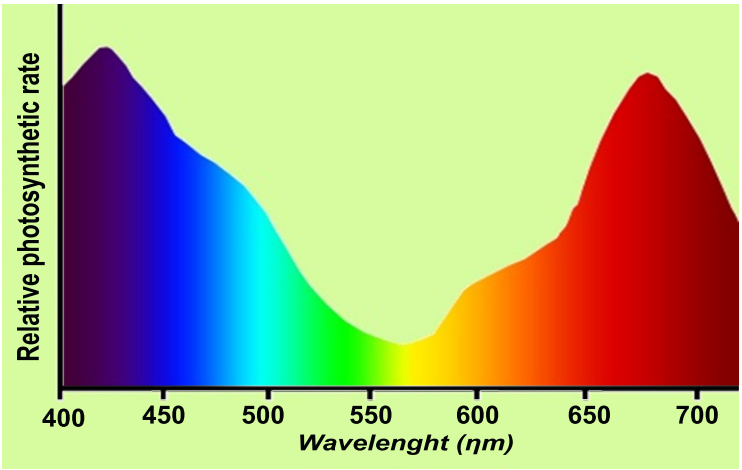


Fig. 4.2 Action spectrum of photosynthesis

way is plotted in a graph, you will see that the rate of photosynthesis will be variable in different colours of light. Such a graph which shows the effectiveness of different wavelength of light for the process of photosynthesis is called **action spectrum.** Analysis of action spectrum indicates that blue (430ηm) and red (670ηm) wavelengths of light are the most effective for the process of photosynthesis.

4.1.2 Role of Photosynthetic Pigments

Pigment is any substance that absorbs light energy. All the wavelengths which are absorbed by a pigment are disappeared. A particular pigment shows only those wavelengths which are reflected back. All the pigments that take part in photosynthesis are embedded in thylakoid membranes (grana lamellae) within chloroplasts. Higher plants have two major group of pigments i.e., chlorophyll and carotenoids.

Science Titbits

The rate of photosynthesis is directly proportional to the CO_2 consumed or O_2 released therefore; it can be measured by measuring the amount of CO_2 consumed or by measuring the amount of O_2 released during the process in a specific time.

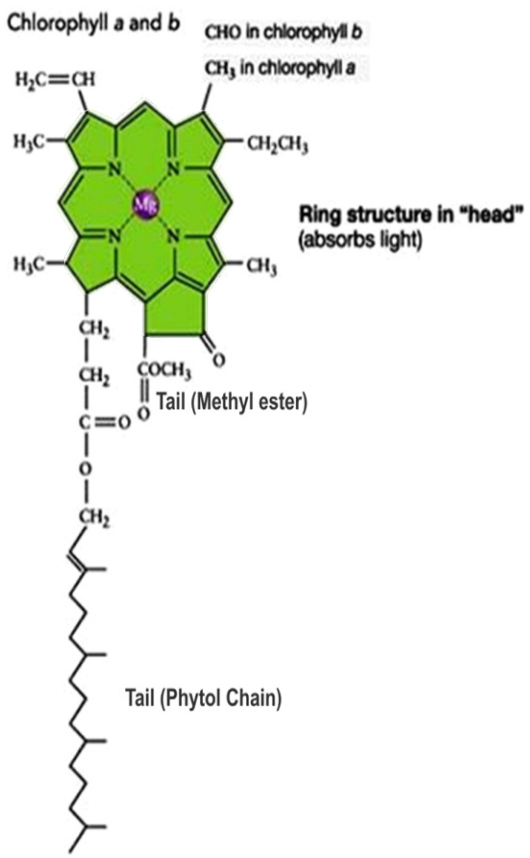


Fig 4.3: Structure of chlorophyll

Chlorophyll

Chlorophylls absorb mainly violet, blue, orange and red wavelengths. Green and yellow are least absorbed and reflected. Two major types of chlorophyll are Chlorophyll-a and Chlorophyll-b. Chlorophyll-a is a bluish green pigment which is found in all photosynthetic organisms except photosynthetic bacteria. Chlorophyll-b is yellowish green pigment which is also found in all photosynthetic organisms except brown, red algae and photosynthetic bacteria. Algae also have some other form of chlorophylls i.e., Chl-c, Chl-d and Chl-e while photosynthetic bacteria have yet another type of chlorophyll i.e., bacteriochlorophyll.

Molecular formula of chlorophyll a and b:

Chlorophyll a = $C_{55}\ H_{72}\ O_5\ N_4\ Mg$

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

A molecule of chlorophyll consists of a head and two tails. The head is composed of a **porphyrin ring** with Mg in the centre. The porphyrin ring further consists of four pyrrole rings (each pyrrole ring contains four carbons and one nitrogen atom). The nitrogen atoms of **pyrrole rings** interact with central Mg atom. The pyrrole rings also contain different groups around them. The only difference between chlorophyll-a and chlorophyll-b is that chlorophyll-a has methyl group ($-CH_3$) on 2nd pyrrole ring whereas, chlorophyll-b has

aldehyde group (-CHO) at this point. The head of chlorophyll is hydrophilic in nature. It is exposed on the surface of thylakoid membrane. It is light absorbing part of chlorophyll.

The two side chains in the chlorophyll molecule are called tails. Side chains are phytol and methyl ester **The chlorophyll tails** are hydrophobic in nature. They are embedded into the thylakoid membranes and serve to anchor the chlorophyll molecule in the membrane.

Carotenoids

Carotenoids are terpenoid lipids, which are yellow, orange, red or brown pigments. They absorb light strongly in the blue-violet range. They are seen in leaves before leaf fall, present in some flowers and fruits. The carotenoids act as accessory pigment along with chlorophyll-b as they absorb light energy and then transfer it to the chlorophyll-a. Therefore, they protect the chlorophyll-'a' from excess of light. They also attract insects, birds and other animals for pollination and dispersal.

There are two types of carotenoids: carotenes and xanthophylls. The **carotenes** are orange red pigments, composed of isoprenoid units and are found in all photosynthetic eukaryotes. The most widespread and important carotene is β (beta) carotene. **Xanthophylls** are yellow in colour and are also composed of isoprenoid units. Lutein is widely distributed xanthophylls which is responsible for yellow colour of foliage in autumn.

4.1.3 Absorption Spectrum

The absorption of different colours of light by a particular pigment can be determined by the help of spectrophotometer. The data of spectrophotometer is represented by a graph. Such a graph which shows the absorption of different colours of light by a particular pigment is called **absorption spectrum** of the pigment.

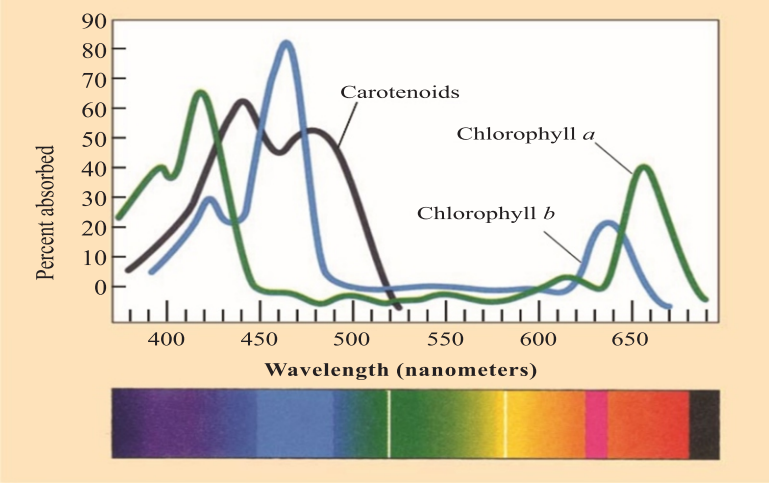


Fig: 4.4: Absorption spectra of different pigments

The absorption spectra of different pigments indicate that they absorb different wavelengths of visible light and these wavelengths are not absorbed at the same rate. The main photoreceptors are chlorophyll a and b and both show more absorption in violet blue (400ηm to 470ηm) and orange-red (630ηm to 660ηm) regions of the visible spectrum. On the other hand carotenoids show more absorption at 430ηm to 500ηm.

4.1.4 Arrangements of Pigments (Photosystems)

For efficient absorption and utilization of light energy, the photosynthetic pigments are arranged in the form of clusters in thylakoid membranes. These clusters are called **photosystems.** The peripheral part of photosystem is called **antenna complex** which

consists of accessary pigments such as chlorophyll-b and carotenoids. The central part of photosystem is called **reaction centre** which contains only chlorophyll-a and associated proteins. Since chlorophyll-a generally has an optimal absorption wavelength of 660ηm, it associates with different proteins in each type of photosystem to slightly shift its optimal wavelength, producing two distinct photosystem types i.e., photosystem-I (PS-I) and photosystem-II (PS-II). The chlorophyll-a in the reaction centre of PS-I can absorb maximum 700ηm wavelength of light, hence called P700. Similarly, the chlorophyll-a in the reaction centre of PS-II can absorb maximum 680ηm wavelength of light, hence called P680. The photosystems are named for the order in which they were discovered and not for the order in which they occur in the thylakoid membrane.

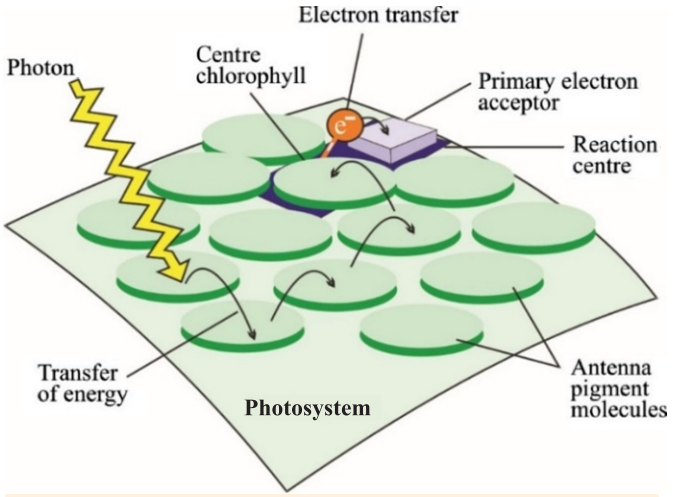


Fig: 4.5: Structure of photosystem

As chlorophyll-a can only absorb light of a narrow wavelength, it works with the pigments of antenna complex to gain energy from a larger part of the spectrum. The pigments absorb light of various wavelengths and pass along their gained energy to chlorophyll-a of the reaction centre. When the energy reaches the chlorophyll-a its electrons become so excited that they escape and move to a nearby electron transport chain. In this way chlorophyll molecule becomes oxidized.

$$\underset{\text{(reduced form)}}{\text{chlorophyll}} \xrightarrow{\text{light energy}} \underset{\text{(oxidized form)}}{\text{chlorophyll}} + \underset{\text{electron}}{e^-}$$

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

4.1.5 Role of Carbon Dioxide in Photosynthesis

Carbon dioxide acts as carbon source for the synthesis of organic compounds in photosynthesis. Plants are therefore known as autotrophs because they use inorganic compounds for the synthesis of their organic compounds. Carbon dioxide is utilized in the dark or light independent reaction (Calvin cycle) of photosynthesis. Air contains about 0.03 to 0.04 percent of carbon dioxide. Land plants use this atmospheric carbon dioxide for photosynthesis. Dissolved carbon dioxide, bicarbonates and carbonates are present in water, which are used by aquatic photosynthetic organisms as carbon source.

4.1.6 Role of Water in Photosynthesis

Water is one of the raw materials for photosynthesis. Water acts as hydrogen and electron donor in photosynthesis. It replaces the electron lost by the P680 during

photosynthesis. $2H^+$ ions are taken up the $NADP^+$ to form NADPH. The oxygen which is produced is released in atmosphere.

This role of water in photosynthesis was first reported by **Van Niel** in 1930. He hypothesized that plants split water as a source of hydrogen, releasing oxygen as a byproduct. This observation was based on investigations of photosynthesis in bacteria that make carbohydrates from carbon dioxide, but do not release oxygen.

Neil's hypothesis was confirmed in 1940, when for the first time ^{18}O in biological research was used. In first experiment water was made of ^{18}O. The water tagged ^{18}O was added to an alga suspension. The oxygen, evolved during photosynthesis, was found to be radioactive. It was separated and identified. In another experiment carbon dioxide with tagged ^{18}O was added. The oxygen evolved contained none of the isotopes. Thus the source of evolved oxygen was proved to be water. In the following summary, red denotes labelled atoms of Oxygen ^{18}O.

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{12H_2O} \xrightarrow[\text{Chlorophyll}]{\text{Light}} \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Water}}{6H_2O} + \underset{\text{Oxygen}}{6O_2}$$

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{12H_2O} \xrightarrow[\text{Chlorophyll}]{\text{Light}} \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Water}}{6H_2O} + \underset{\text{Oxygen}}{6O_2}$$

4.1.7 Mechanism of photosynthesis

The process of photosynthesis has been divided into two phases. The first phase is called light dependent phase (light reaction) because it can take place only in the presence of light. The light-dependent phase occurs in the thylakoid membranes. In this phase light energy is used to make ATP (assimilating power) and NADPH (reducing power); whereas, water and oxygen are supposed to be input and output respectively. The second phase of photosynthesis is called the light independent phase (dark reaction) because it can take place whether light is present or not. This phase actually requires the products of light reaction i.e., ATP and NADPH. Since these products are available in day therefore, dark reaction also occurs in day time. In this phase CO_2 acts as input which is converted into glyceraldehyde-3-phosphate (G3P), the output of this phase. The ATP is hydrolyzed to

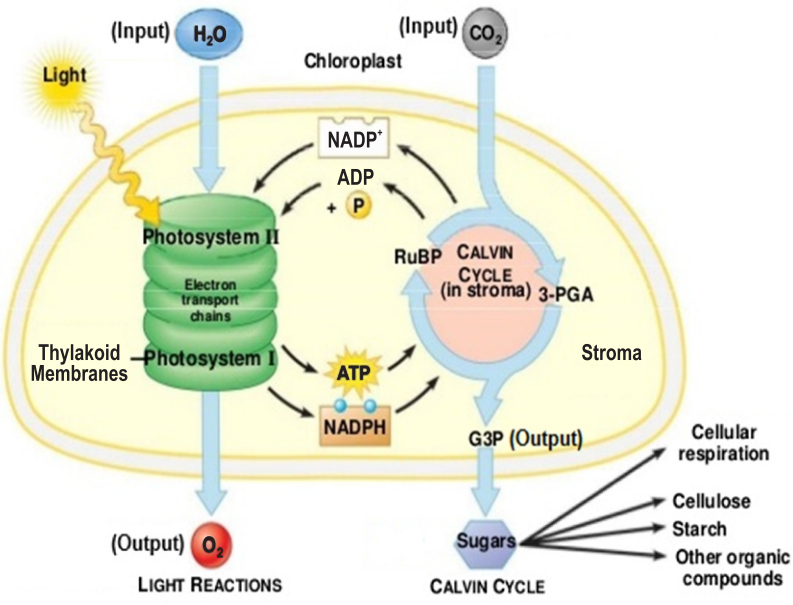


Fig: 4.6: An overview of photosynthesis

ADP and Pi (H_3PO_4) and its energy is incorporated in this phase; whereas, NADPH provides energized electron and hydrogen for the formation of G3P, which is an energy rich molecule.

4.1.8 Light Dependent Phase (Light Reaction)

Light dependent phase of photosynthesis involves the absorption of light by the photosystems, excitation and flow of electrons through an electron transport chain, chemiosmotic synthesis of ATP, and reduction of $NADP^+$ to NADPH. The flow of excited electrons through an electron transport chain during light reaction is of two different types i.e., non-cyclic and cyclic. In non-cyclic electron flow, the excited electrons after leaving a

$$\text{ADP + Pi} \longrightarrow \text{ATP}$$

particular photosystem do not comeback; these electrons after losing their energy are incorporated into another molecule. On the other hand, in cyclic electron flow, the excited electrons after leaving a particular photosystem finally comeback to their photosystem again. The most important event in light reaction is the production of ATP.

This production of ATP during light reaction is called **photophosphorylation** and the mechanism is called **chemiosmosis.** There are two types of photophosphorylation.

(a) Non-cyclic photophosphorylation

It is predominant pathway of light reaction in higher plants that occurs in routine. In this process both photosystems i.e., PS-I and PS-II are utilized and two electron transport chains are involved. When PS-II absorbs light, its excited electrons after flowing through an electron transport chain are transferred to PS-I. Similarly, the excited electrons which are liberated from PS-I are finally accepted by $NADP^+$. Therefore it is called non-cyclic electron flow. The events of non-cyclic photophosphorylation are continuous but here they are discussed in steps for convenience.

Absorption of light by PS-II and excitation of its electrons

When just two photons strike the antenna complex of PS-II, the two electrons become excited and begin to move along the atoms of different pigments within photosystem. Ultimately, the absorbed energy reaches the reaction centre of PS-II (P680) and causes its two electrons to be excited. These excited electrons are captured by the **primary electron acceptor** of PS-II and leave two “electron holes” in the photosystem behind making chlorophyll a strong oxidizing agent.

Photolysis of water

The electron holes of photosystem must be filled so that in the presence of water splitting enzyme reactions can proceed. When water reacts with oxidized state of chlorophyll in photosystem, it breaks up into $2H^+$ ions, $2e^-$ and $\frac{1}{2}O_2$. Since this breakdown occurs in the presence of sunlight therefore, it is termed as photolysis of water. The electrons released from water are used to fill the “electron holes” of PS-II.

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

Electron flow from PS-II to PS-I

The excited/energized electrons which have been released from PS-II and captured by primary electron acceptor now begin to flow to PS-I through an electron transport chain. The electrons move from primary electron acceptor to the **plastoquinone (PQ).** From PQ the electrons flow through a complex of the **cytochromes (Cyt)** which consist of **Cyt-b_6** and **Cyt-f.**

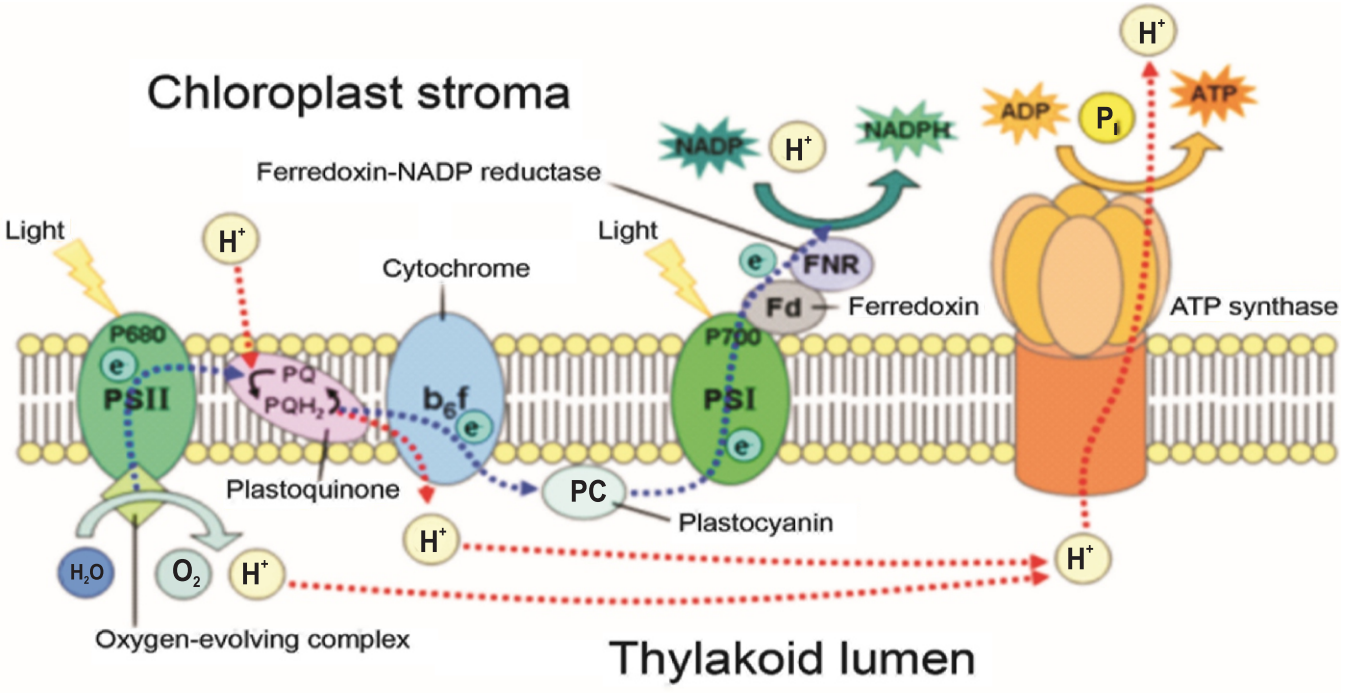


Fig: 4.7: Chemiosmotic synthesis of ATP during light reaction

The cytochrome complex is not only an electron carrier but it also works as proton pump. The electron flow through the cytochrome complex stimulates it to pump the protons from stroma to the thylakoid inner space. In this way the energy of flowing electrons is transformed into a gradient of protons (H^+) in the thylakoid inner space. The proton gradient activates an enzyme in thylakoid membrane called **ATP synthase** which not only moves the protons back into the stroma but also catalyzes a reaction in which ADP and Pi are combined to form ATP (photophosphorylation). This whole mechanism which involves flow of electron, pumping of protons and generation of ATP by thylakoid membranes is called **chemiosmosis.** This ATP, generated by light reactions will provide chemical energy for the synthesis of sugar during Calvin cycle. The energized electrons after losing their energy, move from cytochrome complex to the **plastocyanin (PC)** and finally incorporated into the PS-I

Absorption of light by PS-I and excitation of its electrons

On the other hand, when P700 in the reaction centre of PS-I molecule absorbs two photon of light, electrons are boosted to a higher energy level. P700 molecule passes these excited electrons to a primary electron acceptor of PS-I, creating “electron holes”. The electron holes of P700 are filled by the pair of electrons received from the P680 (photosystem II) via electron transport chain.

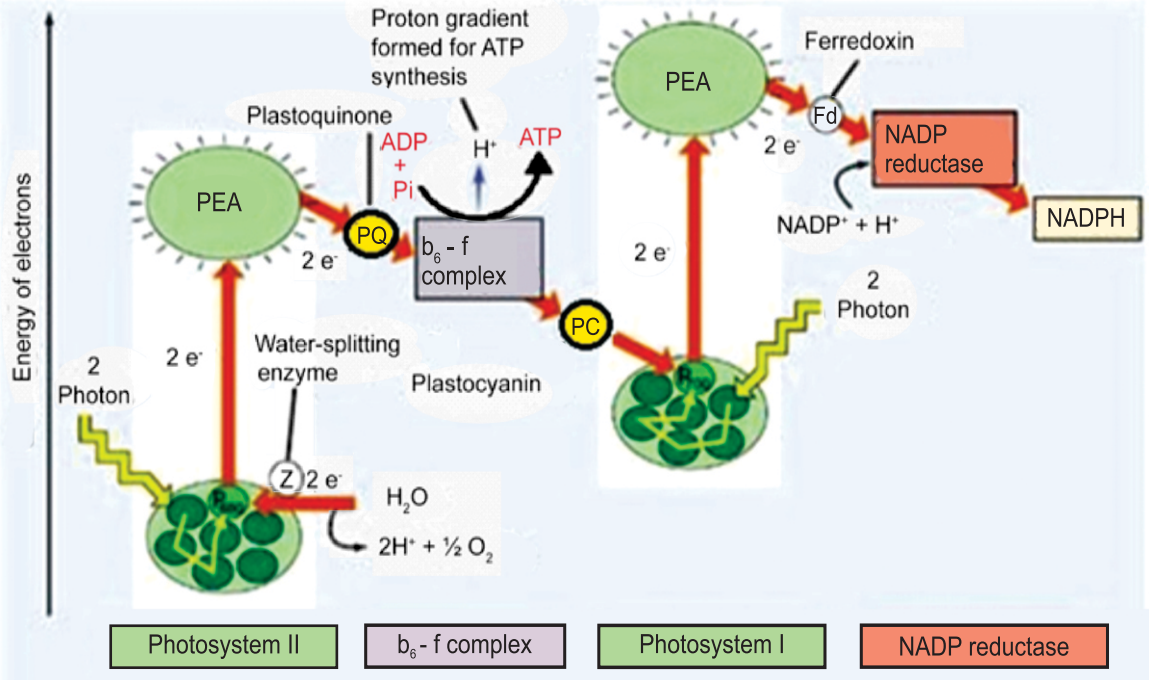


Fig: 4.8: Non-cyclic photophosphorylation (Z Scheme)

Electron flow from PS-I to $NADP^+$

The primary electron acceptor of photosystem I passes the photoexcited electrons to a second electron transport chain. The electrons are accepted by **ferredoxin (Fd).** It is an iron containing protein. An enzyme called **NADP reductase** (flavoprotein enzyme) transfers the electrons from Fd to $NADP^+$. $NADP^+$ combines with electrons and hydrogen ions to form NADPH (reduced). The NADPH will provide reducing power for the synthesis of sugar in the Calvin cycle.

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

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

(b) Cyclic photophosphorylation

The rise in NADPH and deficit of ATP may stimulate a temporary shift from a non-cyclic to cyclic electron flow until ATP supply catches up the demand. In this mechanism only PS-I is utilized. It absorbs energy in the form of photons. When energy reaches the **reaction centre** of PS-I the electrons are boosted up to higher energy level. Such excited electrons are first captured by primary electron acceptor of PS-I, then they move through an electron transport chain containing ferridoxin, cytochrome b_6-f complex and plastocyanin. When electrons are passed from cytochrome b_6-f complex an ATP is generated by chemiosmosis. Finally, the electrons after losing the energy return back to P700 chlorophyll in PS-I reaction centre. There is no production of NADPH, no occurrence of photolysis of water and therefore, no release of oxygen.

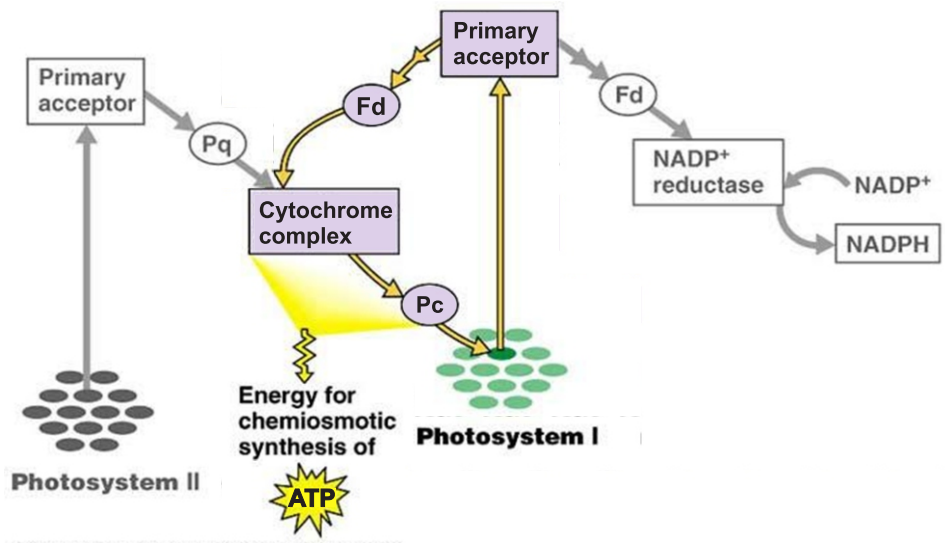


Fig: 4.9: Cyclic photophosphorylation

4.1.9 Light Independent Phase (Dark Reaction)

The light independent phase (dark reaction) takes its name from the fact that light is not directly required for these reactions to occur. This phase requires the availability of NADPH, ATP (the products of light reaction) and CO_2. In this phase of photosynthesis, NADPH is used to reduce carbon dioxide while ATP is used to incorporate energy. Finally, CO_2 is converted into a phosphorylated triose carbohydrate i.e., glyceraldehyde-3-phosphate (G3P) which are later on used to make glucose. Dark reaction generally involves a complicated metabolic pathway, the Calvin cycle or C3 pathway. However, in some plants, in addition to Calvin cycle another metabolic pathway is also involved, called **C4 pathway.** The plants in which only Calvin cycle occurs during dark reaction are called **C3 plants**.

Calvin cycle

Calvin cycle term is applied to the series of metabolic reactions in which CO_2 is reduced to produce G3P. (These reactions have been explored by **Melvin Calvin** and co-workers at the University of California. Melvin Calvin won the Nobel Prize in 1961 for this work). The Calvin cycle can be divided into three phases, carbon fixation, reduction and regeneration of carbon dioxide acceptor i.e., RuBP.

Carbon fixation

One of the key substance in this process is a five carbon phosphorylating sugar called **ribulose bisphosphate (RuBP)**. It is generally referred as **CO_2 acceptor** because it is capable of combining with carbon dioxide with the help of Ribulose bisphosphate (RuBP) carboxylase/oxygenase also known as **RuBisCO**. Three intermediate molecules of six carbons are formed during this reaction. These molecules are unstable and exist for such a short time that, they cannot be isolated. Each six carbon breaks down to form two molecules of 3-phosphoglycerate (3-PGA), a phosphorous containing compound with three

carbon atoms. Since, the carbon of inorganic compound (CO_2) becomes the part of organic compound (RuBP) during this phase, hence, it is called **carbon fixation.** As the first stable compound in the Calvin cycle is a three carbon compound (3-PGA) that is why Calvin cycle is also known as **C3 pathway.**

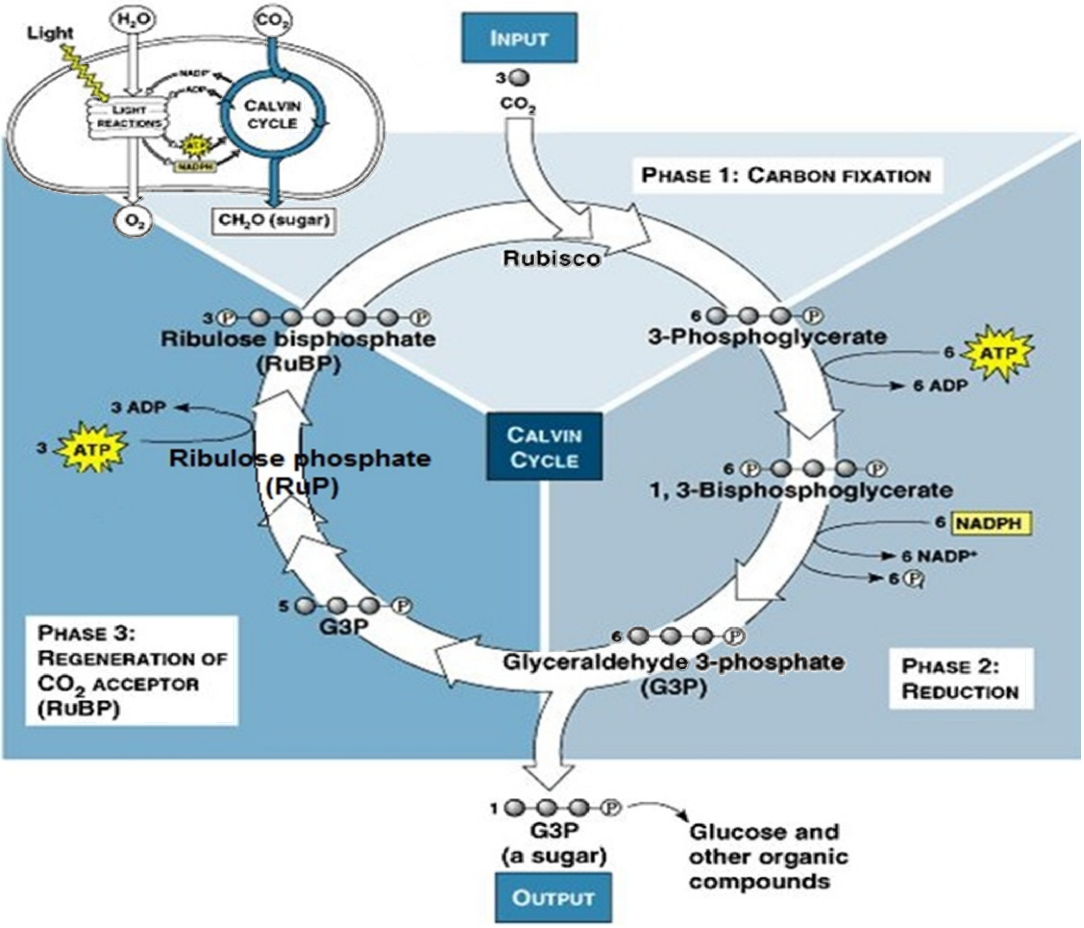
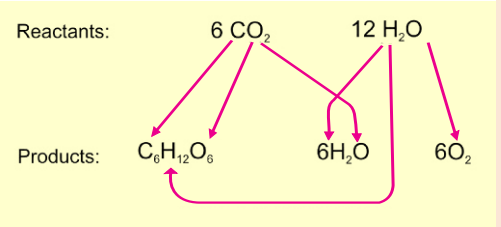


Fig 4.10: Calvin cycle

Reduction

In this phase six molecules of 3-phosphoglycerate (3-PGA) react with six ATP molecules, a phosphate from each ATP is transferred to each 3-PGA. In this way, 3-PGA molecules are changed into 1,3-Bisphosphoglycerate. These molecules are then reduced by the hydrogen of NADPH and finally glyceraldehyde 3 phosphate (G3P) molecules are produced. During this reduction process a phosphate group from each 1,3-Bisphosphoglycerate molecule is also given off. There are total six molecules of G3P are produced in this phase but only one molecule is released from the cycle while rest of the five molecules are used to regenerate the CO_2 acceptor molecules in the next phase.

Fate of the Atoms in Photosynthesis



Regeneration of CO_2 acceptor

Five molecules of G3P from the previous phase are used to regenerate the RuBP (CO_2 acceptor) in this phase. These five molecules each containing three carbon atoms undergo a series of reactions in which three molecules of ribulose phosphate (RuP) each containing five carbon atoms are produced. When three molecules of RuP react with three molecules of ATP, a phosphate group from each ATP is transferred to each RuP. Ultimately RuP are converted into RuBP which again participate in the next cycle.

The whole process of Calvin cycle indicates that there are three molecules of CO_2, six molecules of NADPH (reducing power) and nine molecules of ATP (assimilating power) are used to release just one molecule of G3P form the cycle. However, in order to produce a glucose molecule, two molecules of G3P are required. The overall process of Calvin cycle can be represented as:

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

4.2 CELLULAR RESPIRATION

In biological systems oxidation-reduction is a chemical reaction usually involves the removal of hydrogen atom from one molecule and the gain of hydrogen atom by another molecule. Cellular respiration is a series of complex oxidation-reduction reactions by which living cells obtain energy through the breakdown of organic matter.

4.2.1 Kinds of Cellular Respiration

There are two kinds of respirations: aerobic respiration and anaerobic respiration. Aerobic respiration takes place in the presence of abundant atmospheric oxygen, whereas, anaerobic respiration occurs in the absence of oxygen. The organic molecule that generally undergoes breakdown in cellular respiration in order to release energy is glucose, therefore, glucose is supposed to be **respiratory fuel.** The initial breakdown of glucose in both aerobic and anaerobic respirations is quite same, in which it is broken down into two molecules of **pyruvates**. This common step of aerobic and anaerobic respirations is called **glycolysis**. The pyruvates undergo in different respiratory pathways depending upon the availability of oxygen and the kind of organism. If oxygen is available, the further breakdown of pyruvates takes place aerobically and the final products are carbon dioxide and water with the release of large amount of energy i.e., 36 ATPs (in eukaryotes) or 38 ATPs (in prokaryotes). If oxygen is absent, then the pyruvates are broken down anaerobically and the final products are either lactic acid or ethanol and carbon dioxide with release of very small amount of energy i.e., just 2 ATPs.

4.2.2 Mechanism of Anaerobic Respiration

Anaerobic respiration takes place in many microorganisms (bacteria, yeast), muscle cells of vertebrates and in the cells of higher plants. Anaerobic respiration is incomplete breakdown of glucose in the absence of oxygen. It is also known as **fermentation.** There are two pathways of anaerobic respiration depending upon the nature of final products i.e., lactic acid fermentation and alcoholic fermentation.

Lactic acid fermentation

It consists of **glycolysis** followed by the **reduction** of pyruvate by NADH to lactic acid. The pathway operates anaerobically because after NADH transfers its electron to the pyruvate, it is "free" to return and pick up more electrons during the earlier reaction of glycolysis. The overall equation can be represented as:

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

$$2C_3H_4O_3 + 2NADH + 2H^+ \longrightarrow 2C_3H_6O_3 + 2NAD^+$$

Lactic acid fermentation occurs in anaerobic bacteria and in the muscles of mammals as well as human during strenuous exercise when oxygen supply is exhausted. The accumulation of lactic acid causes muscles fatigue i.e., muscles become unable to contract and begin to ache.

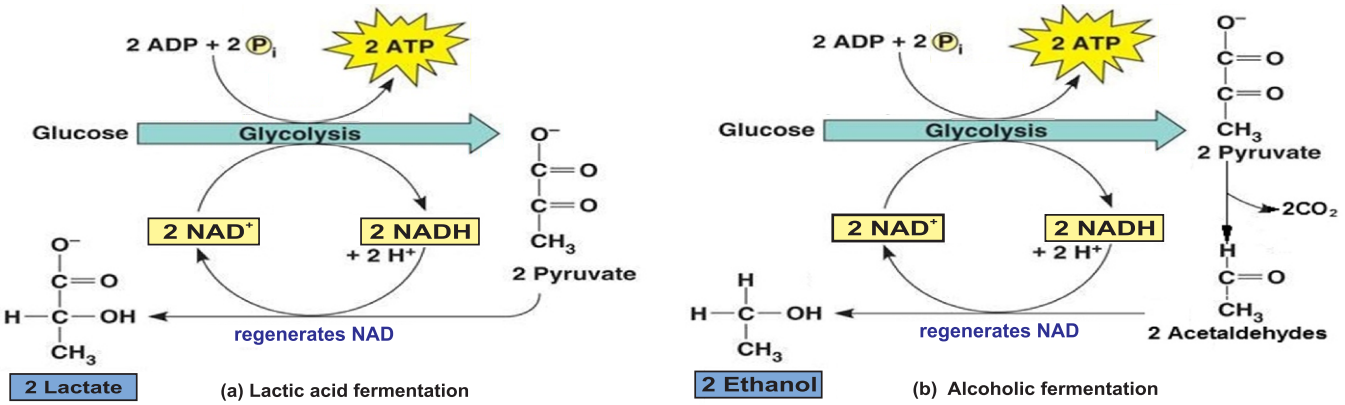


Fig: 4.11 Anaerobic respiration

Alcoholic fermentation

Alcoholic fermentation is found in yeast. It consists of **glycolysis** followed by the **decarboxylation** of pyruvate to acetaldehyde then **reduction** of acetaldehyde by NADH to ethyl alcohol or ethanol. This pathway also operates anaerobically because after NADH transfers its electron to the acetaldehyde, it is "free" to return and pick up more electrons during the earlier reaction of glycolysis. The overall equation can be represented as:

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

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

4.2.3 Mechanism of Aerobic Respiration

Aerobic respiration is a catabolic process which involves complete oxidative breakdown of organic food (especially glucose) into carbon dioxide and water with release of great deal of energy in the form of ATPs. It is predominant respiratory pathway in most of the organisms. Aerobic respiration is completed in four phases: glycolysis, oxidation of pyruvates, Krebs cycle and respiratory electron transport chain.

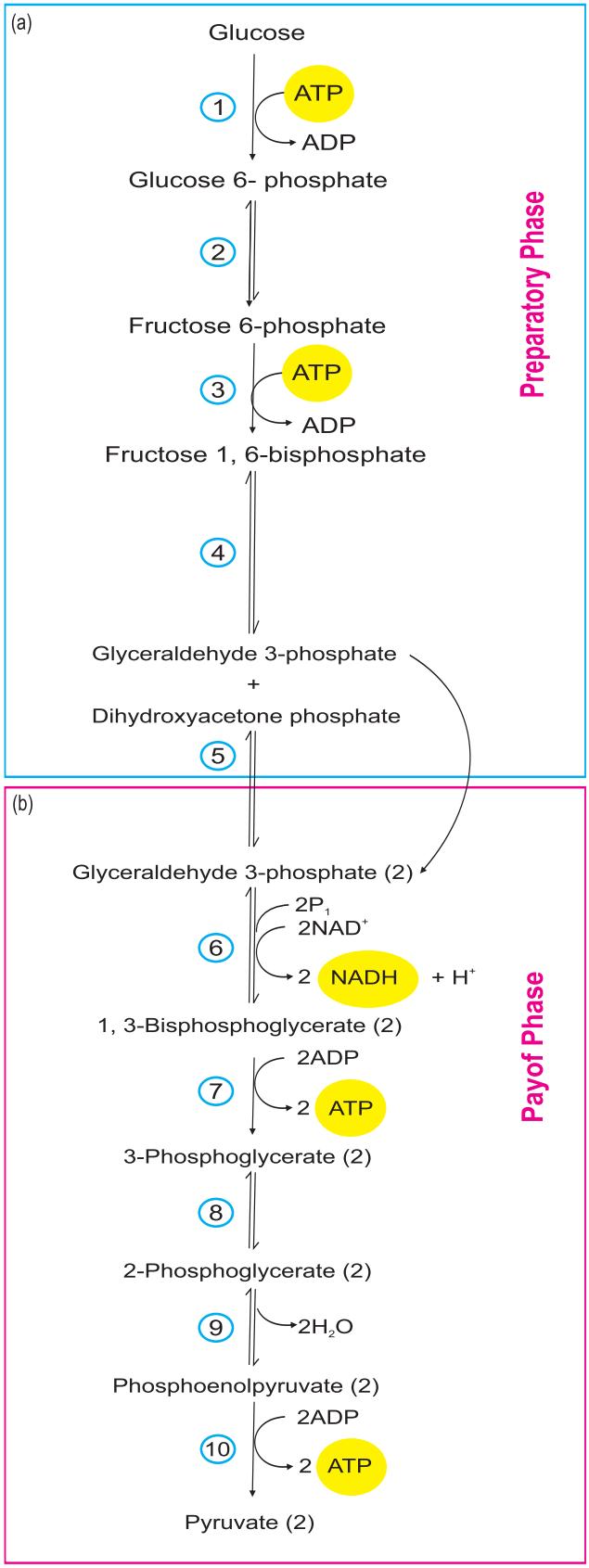


Fig: 4.13: Glycolysis

Glycolysis

Glycolysis is the process of breakdown of glucose or similar hexose sugar into two molecules of pyruvates through a series of enzymatic reactions releasing some energy (as ATP) and reduced coenzymes (as NADH). It occurs in the cytoplasm. It is completed in two phases i.e., preparatory phase and oxidative phase. **Preparatory phase** is an investment phase in which two ATPs are consumed. Its end products are two molecules of G3P. On the other hand **oxidative phase** is **pay off phase** in which not only ATPs are produced through substrate level phosphorylation but it also produces NADH which upon further oxidation in respiratory electron transport chain yields more ATPs. The whole glycolysis pathway takes place in the following sub steps.

1. Phosphorylation: When glucose reacts with ATP, a phosphate group from ATP is transferred to glucose. In this way glucose is phosphorylated to **glucose-6-phosphate**.

2. Isomerization: Glucose-6-phosphate is changed to its isomer **fructose-6-phosphate.**

3. Phosphorylation: When fructose-6-phosphate reacts with another ATP, it is phosphorylated to **Fructose-1**, **6-bisphosphate.**

4. Splitting: Now fructose-1, 6-bisphosphate splits up to form one molecule each of 3-carbon compounds, **glyceraldehyde 3-phosphate** (G3P) and **dihydroxyacetone 3-phosphate.**

5. Isomerization: The dihydroxyacetone 3-phosphate is ultimately changed into its isomer, the **glyceraldehyde 3-phosphate** (G3P). In this way preparatory phase is completed. Next phase of glycolysis is proceeded by two molecules of G3P, therefore, the remaining reactions occur twice.

6. Dehydrogenation and Phosphorylation:

NADH and accepts inorganic phosphate (Pi) to form **1, 3-bisphosphoglycerate.**

7. Formation of ATP: The direct synthesis of ATP from organic phosphorylated substrate is called **substrate level phosphorylation.** In this step a molecule of ATP is formed from 1, 3-bisphosphoglycerate which is changed into **3-phosphoglycerate.**

8. Isomerization: In this step position of phosphate group is changed from C3 to C2 of phosphoglycerate to form 2-phosphoglycerate.

9. Dehydration: In this step, 2-phosphoglycerate undergoes dehydration and is converted into **phosphoenol pyruvate** (PEP).

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

10. Formation of ATP: Again a molecule of ATP is produced by **substrate level phosphorylation** when phosphoenol pyruvate loses phosphate group which is taken up by the ADP to form ATP in the presence of an enzyme (**pyruvate kinase**). The phosphoenol pyruvate is finally converted into **pyruvate.**

4.2.4 Oxidation of Pyruvate

Pyruvates are produced in cytosol. Because pyruvate is a charged molecule, it must enter the mitochondrion via active transport with the help of the transport protein. On entering the mitochondria, pyruvates do not directly participate in Krebs cycle but they

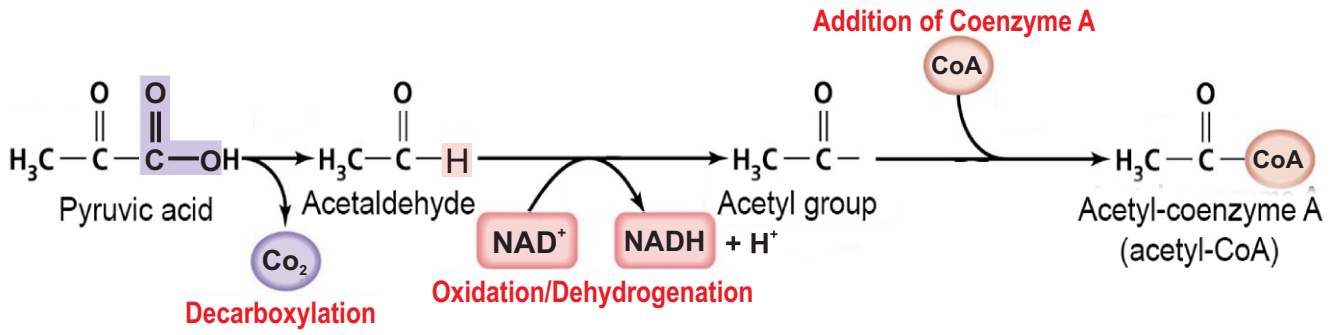


Fig: 4.14 Pathway of oxidation of pyruvate

undergo an intermediate phase, called **oxidation of pyruvate** or **link reaction** as it links the pathway of aerobic respiration that occurs outside the mitochondria with that occurs inside the mitochondria.

The oxidation of pyruvate takes place in three steps. First, it undergoes **decarboxylation** in which a molecule of CO_2 is removed from pyruvate to form **acetaldehyde.** Then NAD^+ removes hydrogen from acetaldehyde. As a result of this oxidation/ dehydrogenation a 2C fragment acetyl and NADH are produced. Finally, acetyl group is combined with coenzyme-A to form **acetyl CoA.**

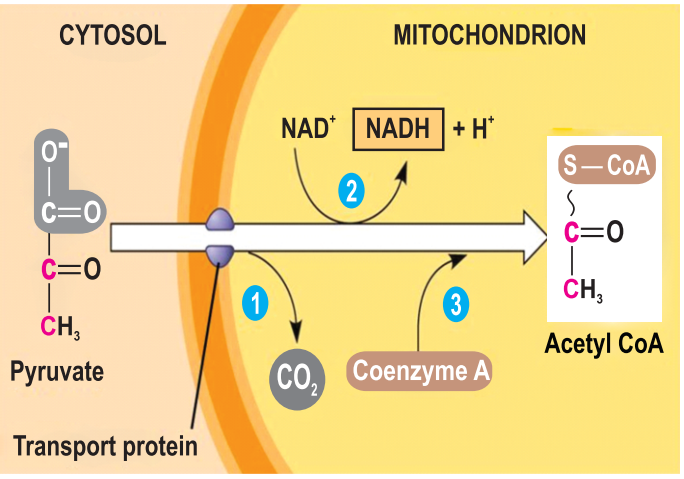


Fig: 4.15 Site of oxidation of pyruvate: Conversion of pyruvate to acetyl CoA, the junction between glycolysis and the citric acid cycle.

Science Titbits

A complex oxidation-reduction involves NAD or NADP. NAD and NADP act as intermediate in cellular reactions involving electron transfer. Many of the electrons removed from reduced carbon compounds in various enzyme-catalyzed reactions are transferred to NAD to produce NADH. When a molecule of NAD or NADP gains electrons and becomes reduced, a hydrogen ion combines with it as well. Thus the reduced form is symbolized as NADH or NADPH. In fact, another hydrogen ion becomes closely associated with each reduced molecule. Technically it is more accurate to represent the reduced form as NADH + H^+ or NADPH + H^+. For convenience, these reduced forms i.e., NADH + H^+ and NADPH + H^+ can be represented as $NADH_2$ and $NADPH_2$ respectively.

4.2.5 Krebs Cycle

This cycle was discovered by British scientist **Sir Hans Krebs**, therefore, called **Krebs cycle.** It is also called **Citric acid cycle** or **Tri carboxylic acid** (TCA) cycle because the first compound which is formed in the cycle is **citrate** (citric acid) that contains three carboxylic acid groups.

The Krebs cycle comprises following nine steps.

1. Synthesis

Acetyl CoA (2-carbon compound) and a water molecule combine with oxaloacetate (4-carbon compound) to form a 6-carbon compound called **citrate** (citric acid). It is the first product of Krebs cycle. CoA is liberated.

2. Dehydration

Citrate undergoes reorganization by the removal of a water molecule. The resulting compound is **cis-aconitate.**

3. Hydration

Cis-aconitate is converted into **isocitrate** with the addition of water. Actually, citrate and isocitrate are isomers of each other.

4. Oxidative decarboxylation

This is a two-step process, which involves oxidation/ dehydrogenation of isocitrate, followed by the **decarboxylation** to form **alpha-ketoglutarate**. The hydrogen and electrons which are released from isocitrate are taken up by NAD^+ to form NADH while the carboxyl group is released in the form of CO_2.

5. Oxidative decarboxylation and addition of CoA

α-Ketoglutarate again undergoes oxidative decarboxylation. The hydrogen and electrons which are released from **α-ketoglutarate** are taken up by NAD^+ to form NADH while the carboxyl group is released in the form of CO_2. Then, it combines with coenzyme A to form **succinyl CoA.**

6. Formation of ATP

Coenzyme A is removed from Succinyl CoA to form **succinate.** The reaction releases sufficient energy which is used to combine GDP and Pi forming GTP. GTP reacts with ADP to form ATP while GTP is again converted into GDP. In this way a molecule of ATP is generated in this reaction.

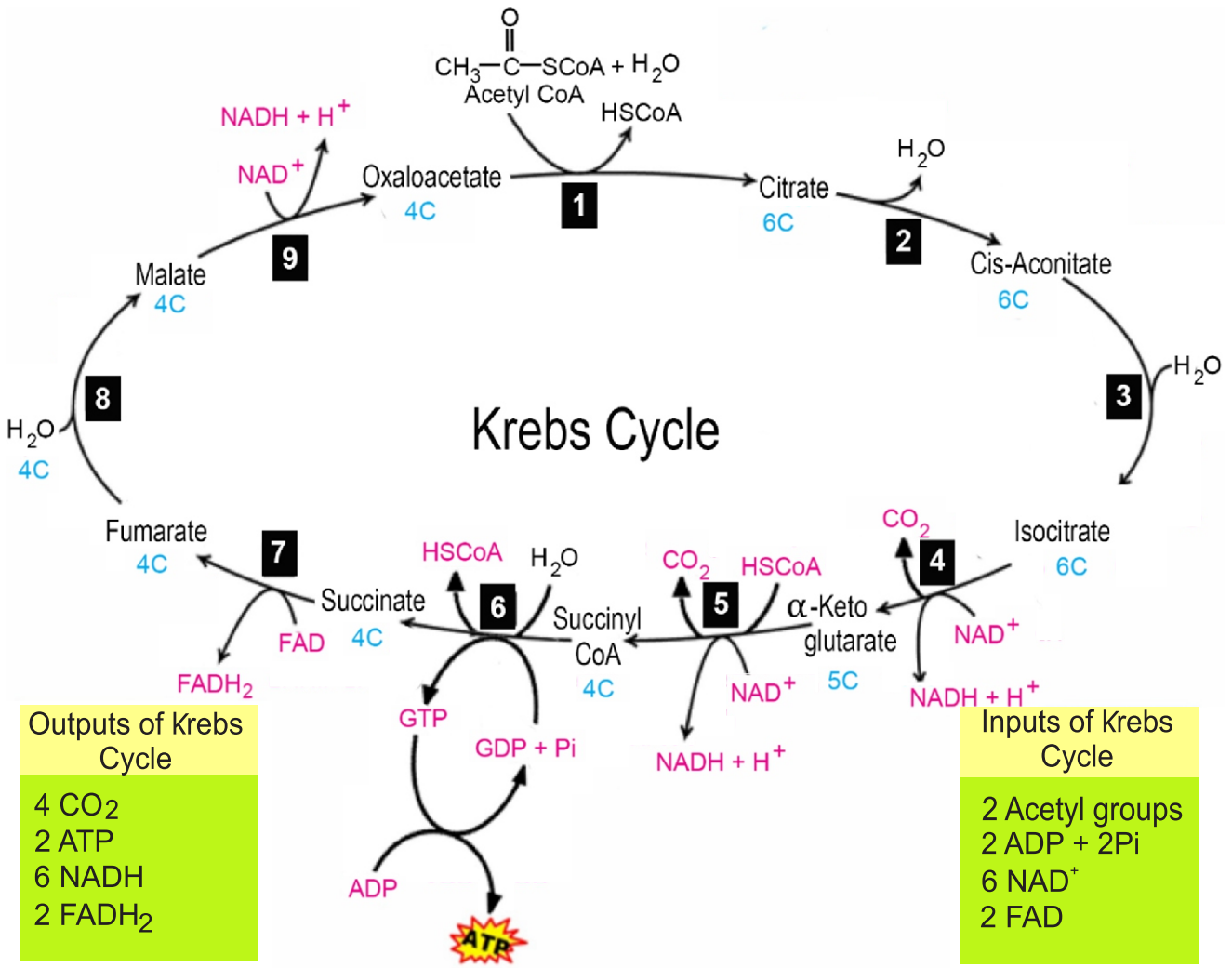


Fig: 4.16 Krebs cycle (Citric acid cycle or TCA cycle)

7. Dehydrogenation/oxidation

Succinate undergoes dehydrogenation/oxidation to form **fumarate.** The hydrogen and electrons which are released from succinate are taken up by FAD to form $FADH_2$.

8. Hydration

A molecule of water gets added to fumarate to form **malate.**

9. Dehydrogenation/oxidation

Malate undergoes dehydrogenation/oxidation to produce **oxaloacetate**. The hydrogen and electrons which are released from malate are taken up by NAD^+ to form NADH. Oxaloacetate picks up another molecule of acetyl CoA to repeat the cycle.

4.2.6 Electron Transport Chain (ETC)

After Kreb's cycle most of the energy of glucose is in the form of NADH and $FADH_2$, These two molecules enter into the electron transport chain. In this chain, the reduced NADH and $FADH_2$ are oxidized and their electrons are passed along a series of oxidation reduction reaction to the final acceptor i.e., molecular oxygen.

Components of electron transport chain

The components of electron transport chain include: (1) **NADH- dehydrogenase complex (I)**, (2) **FADH-dehydrogenase complex (II)** (3) **coenzyme Q** (4) **Cytochrome reductase complex (III)** (5) **Cytochrome-c** (6) **Cytochrome oxidase complex (IV).**

Passage of electron flow

NADH is oxidized when it reacts with **NADH- dehydrogenase complex (I)**. Electrons now move to the **co-enzyme Q**. If $FADH_2$ is to be oxidized through ETC, it also hands over its electrons to coenzyme Q, via **FADH dehydrogenase complex (II).**

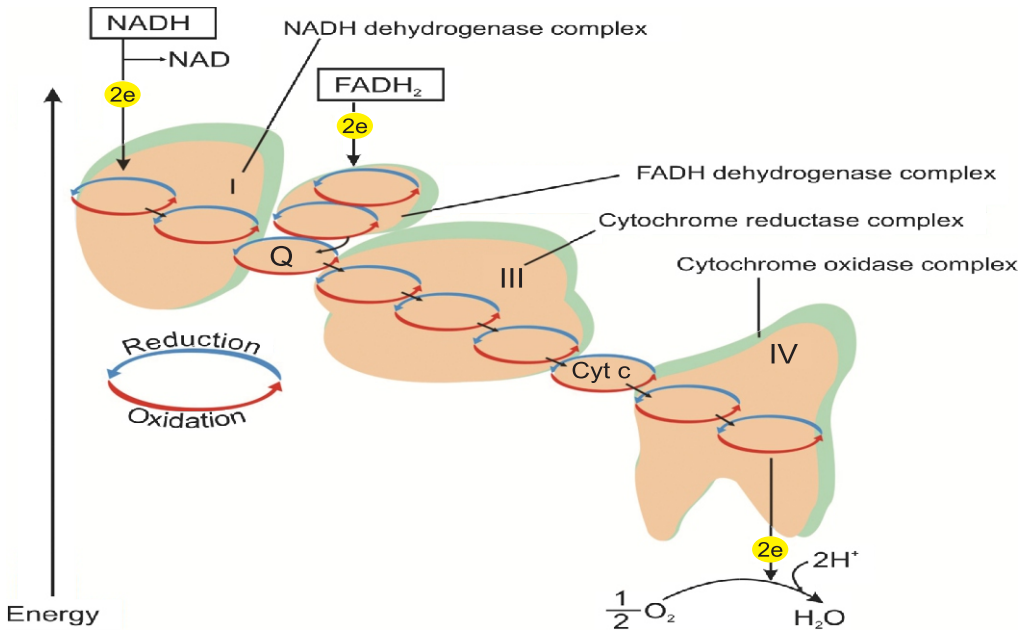


Fig: 4.17 Sequence of electron carriers in respiratory ETC

The flowing electrons from coenzyme **Q** are now transferred to **cytochrome reductase complex (III)** which hands over its electron to **cytochrome c**. Like co-enzyme Q, cytochrome c is also mobile carrier of electrons. Cytochrome c delivers the electrons to **cytochrome oxidase complex (IV).**

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

> **Science Titbits**
>
> Ubiquinone is not a protein, but a small molecule soluble in lipids and insoluble in water Cytochromes literally means "cell colour". The reduced cytochromes are pink in colour. They are protein plus pigment molecules containing iron. They can gain or lose an electron.

Energy released during passage of electrons from one carrier to the next is used to pump protons (H^+) from the mitochondrial matrix to the inter membrane space. There are three such sites, corresponding to three enzymes present in the electron transport chain i.e. NADH-dehydrogenase complex (I), cytochrome reductase complex (III) and cytochrome oxidase complex (IV).

The electron transport chain makes no ATP directly. Its function is to ease the fall of electrons from food to oxygen releasing energy in manageable amounts. How does the mitochondrion couple this electron transport chain and energy to ATP synthesis? The answer is a mechanism called chemiosmosis.

4.2.7 Chemiosmosis and Oxidative Phosphorylation

Oxidative phosphorylation is the synthesis of ATP molecules with the help of energy liberated during oxidation of reduced co-enzymes (NADH, $FADH_2$) produced in respiration. The enzyme required for this synthesis is called ATP synthetase.

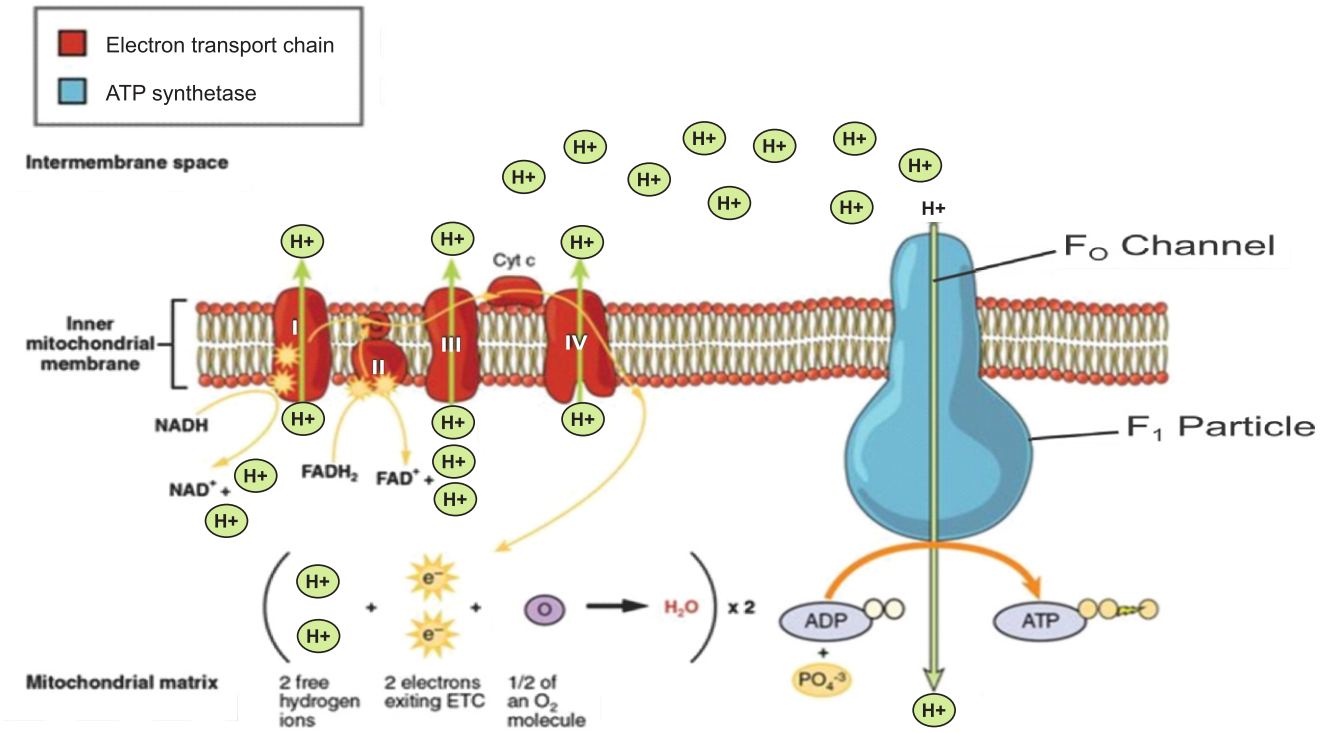


Fig: 4.18: Mechanism of chemiosmosis in respiratory electron transport chain

It is located in the inner mitochondrial membrane. It consists of two parts i.e., F_0 and F_1. F_0 is embedded in the membrane and involves in the movement of protons from inter-membrane space to mitochondrial matrix. F_1 or elementary particle is a head like part which is projected from the surface of membrane towards matrix. It catalyzes ATP synthesis by the combination of ADP and Pi. ATP-synthetase becomes active in ATP formation only when a proton gradient having higher concentration of H^+ or protons on the F_0 side as compared to F_1 side is established. The flow of protons through the F_0 channel induces F_1 particles to function as ATP-synthetase i.e., the energy of the proton gradient is used in attaching a phosphate to ADP by high energy bond. This produces ATP. Oxidation of one molecule of $NADH_2$ produces 3 ATP molecules while a similar oxidation of $FADH_2$ forms 2 ATP molecules. The theory of ATP production by this mechanism is called **chemiosmosis.**

4.2.8 Substrate Level Phosphorylation

The prime objective of cellular respiration is to generate ATPs. There are two ways to do this during aerobic respiration: chemiosmosis and substrate level phosphorylation, the former we have already discussed.

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

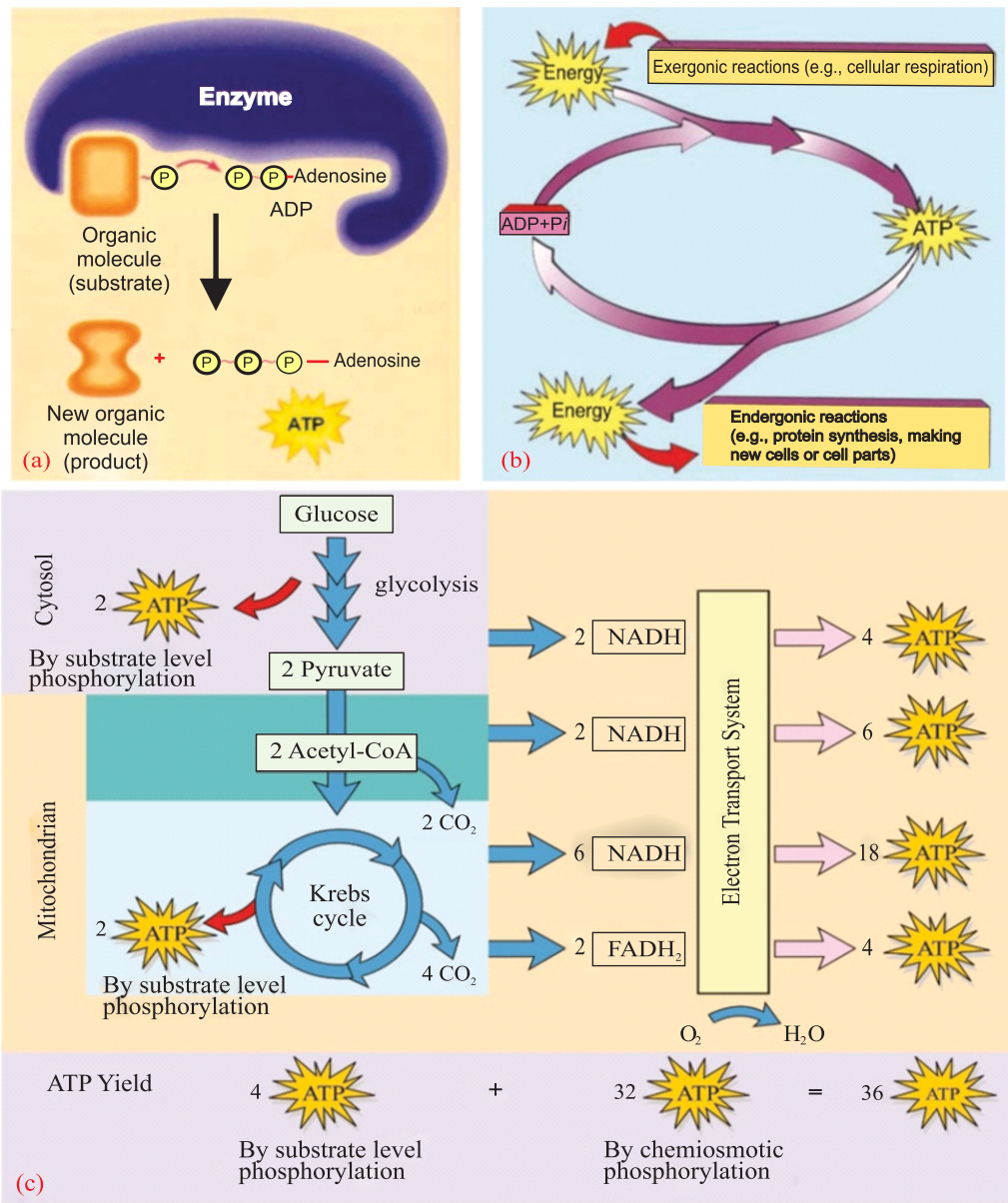


Fig:4.19: (a)Substrate level phosphorylation. (b) Because ATP is responsible for coupling many endergonic and exergonic reactions it is an important link between anabolism and catabolism in living cells. (c) ATP Budget in aerobic respiration

Note:
Actually, the two molecule of the NADH of glycolysis are produced in cytoplasm. These cannot be taken up by mitochondria because the mitochondrial membrane is impermeable for NADH. Therefore, at the time of their uptake only the energized electrons of NADH are transferred inside the mitochondrion by a complex mechanism. These electrons are received by two molecules of FAD^+ in the mitochondrial matrix to produce two molecule of $FADH_2$. Hence, four ATP molecules are produced instead of six. So, eukaryotes yield two less number of ATP than prokaryotes.

In glycolysis, substrate level phosphorylation occurs, when 1,3-bisphosphoglycerate is converted into 3-phosphoglycerate (7th reaction) and when phosphoenol pyruvate is converted into pyruvate (10th reaction). There are four ATPs produced by this mechanism during glycolysis but two of them are supposed to be consumed in preparatory phase so net product by substrate level phosphorylation is 2 ATP.

In Krebs cycle, substrate level phosphorylation occurs when succinyl CoA is converted into succinate. There are two molecules of ATP produced at this occasion. Since, ATP can be synthesized directly from the organic substrates of exergonic reactions (energy releasing reactions e.g., cellular respiration), therefore, it is said that substrate level phosphorylation couples the exergonic reactions with the synthesis of ATP. These ATP are then used to drive endergonic reactions (energy storing reaction e.g., protein synthesis). In this way, out of total 36 ATP which are produced during aerobic respiration in most of human cells, 4 ATP are the result of substrate level phosphorylation and remaining 32 ATP are produced by chemiosmosis through electron transport chain.

4.2.9 Importance of G3P

Glyceraldehydes 3-phosphate (G3P) is an important intermediate of respiration and photosynthesis. In respiration, G3P appears during glycolysis pathway which leads to the formation of pyruvate. In the Calvin cycle of photosynthesis, G3P molecules are converted into glucose phosphate within the chloroplast. Glucose phosphate is then converted to glucose, fructose, sucrose and starch.

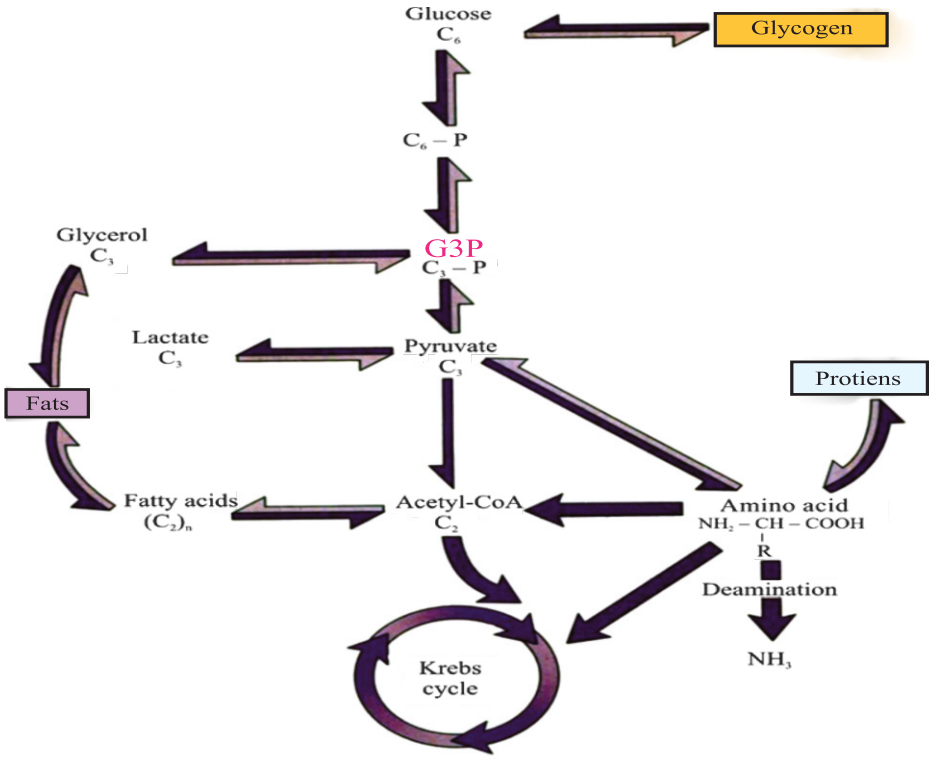


Fig: 4.20: The matabolic pool concept: When they are used as energy sources carbohydrates, fats and proteins enter degradative pathways at specific points. Degradation produces metabolites that can be used for synthesis of other compounds.

4.2.10 Cellular Respiration of Fats and Proteins

When a fat is used as an energy source, it breaks down to glycerol and three fatty acids. As figure 4.20 indicates, glycerol is converted to G3P, a metabolite in glycolysis. The fatty acids are converted to acetyl-CoA, which enters the Krebs cycle. An 18-carbon fatty acid results in nine acetyl-CoA molecules.

The hydrolysis of **proteins** results in amino acids whose R-group size determines whether the carbon chain is oxidized in glycolysis or the Krebs cycle. The carbon chain is produced in the liver when an amino acid undergoes deamination, i.e., the removal of the amino group. The amino group becomes ammonia (NH_3), which enters the urea cycle and becomes part of urea.

4.3 PHOTORESPIRATION

The respiratory activity that occurs in green cells in the presence of light resulting in release of carbon dioxide is termed as **photorespiration**. It needs oxygen and produce CO_2 and H_2O like aerobic respiration. However ATP is not produced during photorespiration.

4.3.1 Mechanism of Photorespiration

When the CO_2 levels inside the leaf drop to around 50 ppm (part per million), ribulose bisphosphate carboxylase/oxygenase (RuBisCO) starts to combine O_2 with RuBP instead of CO_2. The net result of this is that instead of producing two 3C molecules of phosphoglycerate (PGA), only one molecule of PGA and a toxic 2C molecule called **phosphoglycolate** are produced. The plant must get rid of the phosphoglycolate. First it immediately gets rid of the phosphate group, converting the molecule to **glycolate**.

$$\text{RuBP} + O_2 \longrightarrow \text{Phosphoglycolate} + \text{Phosphoglycerate} \longrightarrow \text{Glycolate}$$

The glycolate is then transported to the peroxisome and there converted to **glycine**. The glycine is then transported into the mitochondria where it is converted into **serine**. The serine is then used to make other organic molecules.

$$\text{Glycolate} \longrightarrow \text{Glycine}$$

$$2\ \text{Glycine} \longrightarrow \text{Serine} + CO_2$$

Effect of temperature on the activities of RuBisCO

Photorespiration is related to the functioning of the enzyme ribulose bisphosphate (RuBP) **carboxylase/oxygenase**. It is often called **RuBisCO** because it can have an oxygenase activity in addition to carboxylase activity. Its activity depends upon the relative concentration of O_2 and CO_2 in leaves. Photorespiration starts when the CO_2 levels inside a leaf become low. This happens on hot dry days when plant begins to secrete abscisic acid which causes closing of stomata to prevent excess water loss. If the plant continues CO_2 fixation in photosynthesis when its stomata are closed, the CO_2 will be used up and the O_2 released from photosynthesis will be prevented to release out of plant body. In this way, ratio of O_2 in the leaf will increase relative to CO_2 concentrations.

Disadvantages and Evolution of Photorespiration

Photorespiration costs the plant energy and results in the net loss of CO_2 fixation from the plant. Thus, it reduces the rate of photosynthetic process. In most plants,

photorespiration reduces the amount of carbon fixed into carbohydrate during photosynthesis by 25 percent. Photorespiration is not essential for plant. It is also observed that if photorespiration is inhibited chemically, the plant can, still grow. Furthermore, some plants are naturally resistant to photorespiration. Then why photorespiration exists? The common simple answer to this question is that the active site of RuBisCO is evolved to bind both carbon dioxide and oxygen. Originally it was not a problem as there was no oxygen in the atmosphere at the time of establishment of earth so the carbon dioxide binding activity was the only one used. The photorespiration started when the oxygen began to accumulate in the atmosphere.

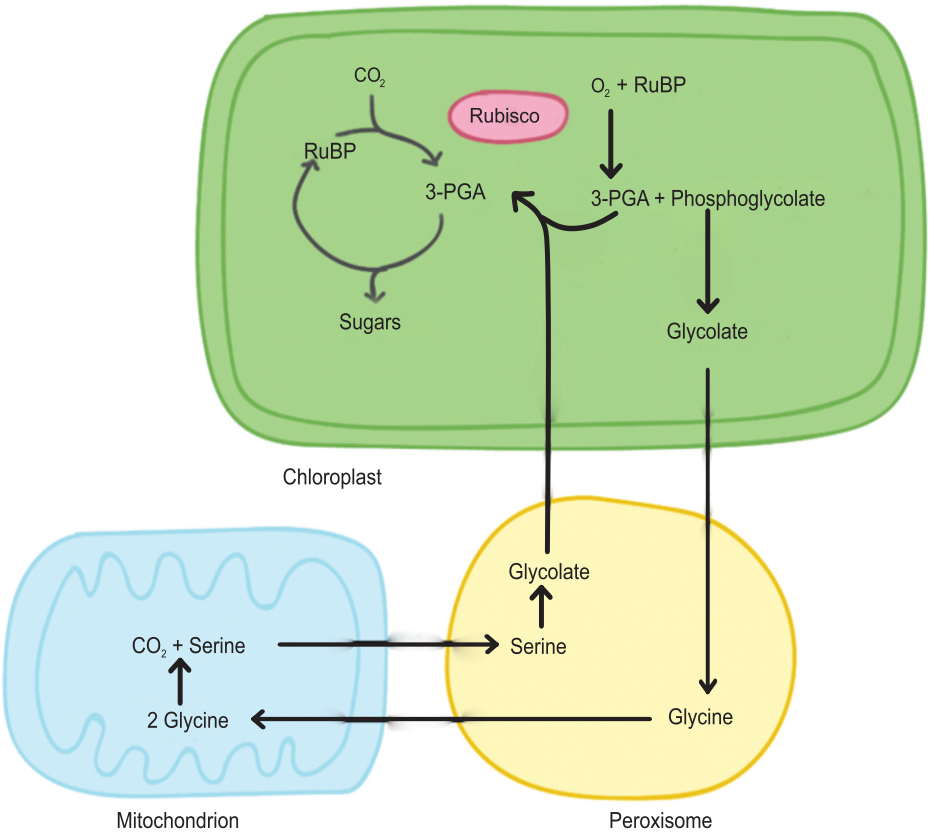


Fig: 4.21: Schematic representation of pathway involved in photorespiration in chloroplast, peroxisomes and mitochondria

Science, Technology and Society Connections

- **Analyze the impact of photorespiration on the agriculture yield in the tropic climates.**

Photorespiration decreases net photosynthesis because a portion of CO_2 fixed in photosynthesis escapes from the leave after it is fixed. Under certain conditions, up to 5% of the photosynthetic potential is lost in photorespiratory metabolism. Thus photorespiration reduces dry matter production and agricultural yield in tropical climate.

4.3.2 C_4 photosynthesis: An adaptation to the problem of photorespiration

Some plants which grow in tropical climate have an adaptation to the problem of photorespiration. They have an additional metabolic pathway in light independent phase of

photosynthesis beside Calvin cycle. This metabolic pathway is called Hatch-Slack cycle of C_4 pathway in which **phosphoenol pyruvate** (PEP) carboxylase is used instead of RuBisCO to fix CO_2 to phosphoenol pyruvate (a C_3 molecule), and the result is **oxaloacetate**, a C_4 molecule. It takes place in cytoplasm of mesophyll cells.

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

As the first product of CO_2 fixation is a 4-carbon compound oxaloacetate, so the plants are called C_4 plants e.g., maize, sugarcane, sorghum, etc. Oxaloacetate is then transported to the chloroplasts of mesophyll cells. It is then converted to another 4-C compound, the **malate**, with the help of NADH, produced in the photochemical phase. The malate is then transported to the chloroplasts of bundle sheath cells. Here malate is converted to **pyruvate** (C_3) with the release of CO_2. Thus concentration of CO_2 increases in the bundle sheath cells. These cells contain enzymes of Calvin cycle. Because of high concentration of CO_2, RubisCO participates in Calvin cycle and not in photorespiration. Sugar formed in Calvin cycle is transported into the phloem. Pyruvate generated in the bundle sheath cells re-enters mesophyll cells and regenerates phosphoenol pyruvate (PEP) by consuming one ATP.

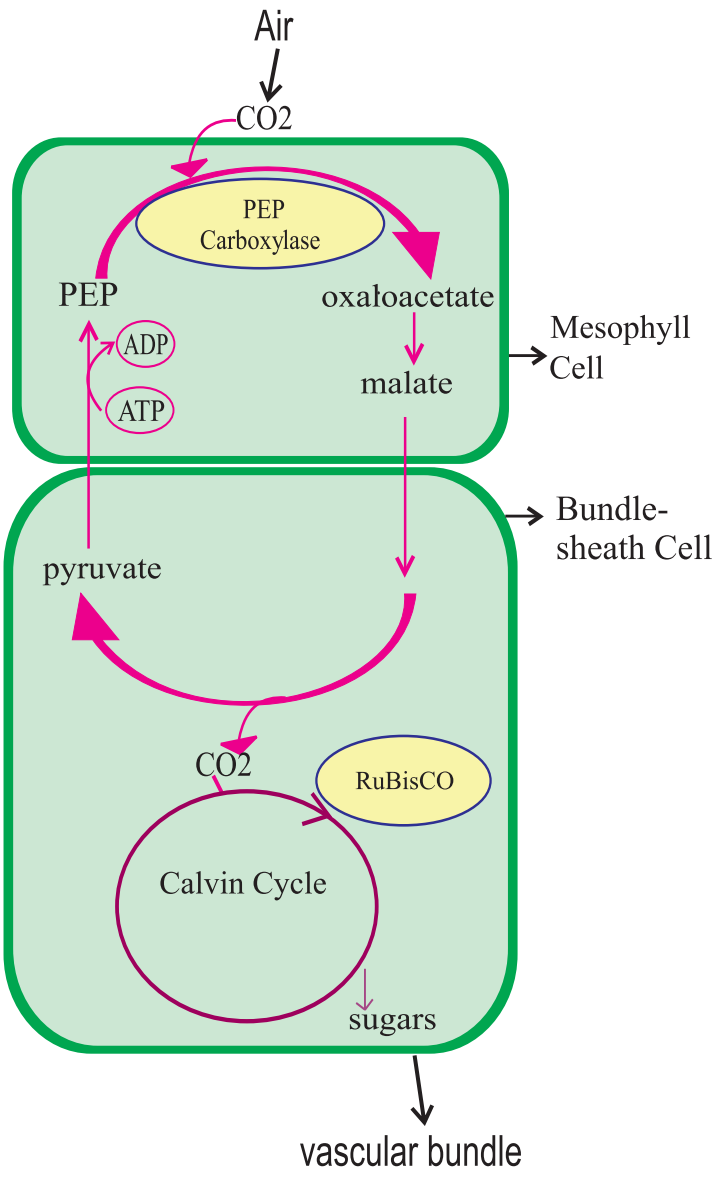


Fig. 4.22: C_4 photosynthesis

Exercise

MCQs

1. Select the correct answer

(i) Removal of the source of carbon dioxide from photosynthesizing chloroplasts results in rapid changes in the concentration of certain chemicals. Which one of the following represents the correct combination of concentration changes?

	ATP	Ribulose bishposphate	Phosphoglyceric acid (PGA)
A	decreases	decreases	increases
B	decreases	increases	no change
C	increases	increases	decreases
D	increases	no change	decreases

(ii) What are the products of the light reactions in photosynthesis?

(A) ATP and NADP (B) ATP, $NADPH_2$ and oxygen

(C) ATP, PGA and $NADH_2$ (D) ATP, PGA and oxygen

(iii) During the light dependent stage of photosynthesis, the photoactivated pigment removes an electron from the hydroxylation derived from the water molecule. The fate of the free hydroxyl radical is that it

(A) is broken down into oxygen and a free radical of hydrogen

(B) is used to raise the activation level of chlorophyll by donating a positive charge

(C) is used to produce adenosine triphosphate from adenosine diphosphate

(D) reduces carbon dioxide to sugar

(iv) Carbon dioxide labeled with ^{14}C has been used to identify the intermediate compounds in the Calvin cycle, the light-independent stage in photosynthesis. Which compound would be the first to contain the ^{14}C?

(A) glucose (B) PGA (C) RuBP (D) starch

(v) The rate of photosynthesis of a freshwater plant is measured using five spectral colours. Which sequence of colours would give an increasing photosynthetic response?

Smallest →					Largest response
A	blue	green	yellow	orange	red
B	green	yellow	orange	red	blue
C	red	orange	yellow	green	blue
D	yellow	green	orange	blue	red

(vi) During dark reactions the three carbon atoms of 3-PGA are derived from

(A) RuBP only (B) CO_2 only

(C) RuBP + CO_2 (D) RuBP + CO_2 + PEP

(vii) Chlorophyll is soluble in

(A) water (B) organic solvent

(C) water and organic solvent (D) not in any solvent

(viii) Photorespiration takes place only in

(A) root (B) mitochondria

(C) green parts of the plant (D) all cells of the plant

(ix) In C_4 plants, fixation of CO_2 occurs in

(A) palisade tissue (B) cortex of stem

(C) spongy mesophyll and bundle of sheath (D) phloem tissue

(x) ATP synthesis during light reactions is

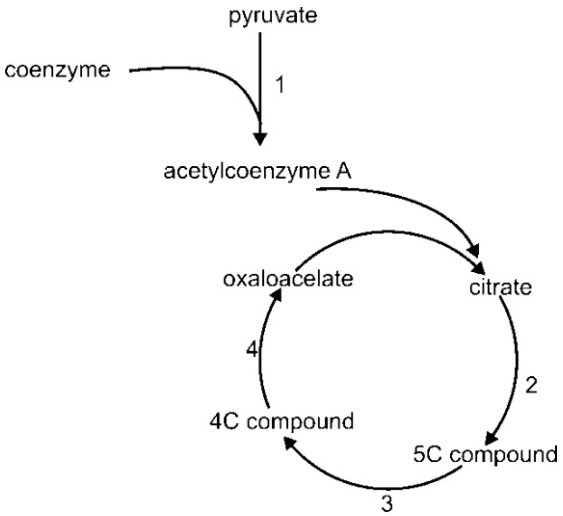
(A) oxidative (B) photolysis

(C) substrate phosphorylation (D) photophosphoryation

(xi) In C_3 plants first stable product of photosynthesis during dark reaction is

(A) PGA (B) G3P (C) RuBP (D) oxaloacetate

(xii) The diagram shows the Krebs cycle. At which numbered stages does decarboxylation take place?



(A) 1 and 2 (B) 1, 2 and 3

(C) 1, 3 and 4 (D) 1, 2, 3 and 4

Short Questions

2. What is electromagnetic spectrum?
3. Explain ‘action spectrum’ of photosynthesis.
4. What are the types of chlorophyll?
5. What is the importance of carotene?
6. Describe ‘absorption spectrum’ in photosynthesis.
7. What is photosystem? Explain.
8. What is the role of carbon dioxide in photosynthesis?
9. How it was confirmed that ‘plants split water as a source of hydrogen releasing hydrogen as a byproduct?
10. What is the importance of G3P?
11. What is the effect of temperature on the activities of RuBisCO?
12. What are the disadvantages of photorespiration?
13. How photorespiration evolved?
14. Write the differences between:

(a) chlorophyll a and chlorophyll b
(b) carotene and xanthophyll
(c) action spectrum and absorption spectrum
(d) absorption spectrum of chlorophyll a and b
(e) antenna complex and reaction centre
(f) photosystem I and photosystem II
(g) light dependent reaction and light independent reaction of photosynthesis
(h) oxidative phosphorylation and photophosphorylation
(i) cyclic photophosphorylation and non-cyclic photophosphorylation
(j) C_4 carbon fixation and C_3 carbon fixation
(k) lactic acid fermentation and alcoholic fermentation
(l) Calvin cycle and Krebs cycle
(m) oxidative phosphorylation and substrate level phosphorylation

Extensive Questions

15. What is photosynthesis? Explain the role of light in photosynthesis.
16. Describe the structure of chlorophyll.
17. Write a note on the photosynthetic pigment carotene.
18. Explain the arrangement of photosystems.
19. Describe the role of water in photosynthesis.
20. Describe the mechanism of photosynthesis.
21. Explain in detail the light dependent phase of photosynthesis?
22. Explain in detail the light independent phase of photosynthesis?
23. Describe cyclic photophosphorylation.
24. Describe Calvin cycle.
25. Describe the kinds of cellular respiration.
26. Give an account of ‘Glycolysis’.
27. Explain oxidation of pyruvate.
28. Explain Krebs cycle.
29. Explain electron transport chain.
30. Explain chemiosmosis and oxidative phosphorylation.
31. Describe substrate level phosphorylation.
32. Give an account of photorespiration in plants.
33. Explain that C_4 photosynthesis is an adaptation to the problem in photorespiration.

About the Content Authors

Prof. Jawaid Mohsin Malick

Prof. Jawaid Mohsin Malick was born on 8th February 1945 in the province of Bihar. Malick is the title given to his ancestor Syed Ibrahim by the King Muhammad Tughlaq. Syed Ibrahim was a saint, the commander in chief of the army and conqueror of Bihar. Syed Ibrahim is the descendent of Hazrat Ghos-e-Azam, Syed Abdul Qadir Jilani (رحمة لله عليه) at the seventh generation. The ancestors of Syed Ibrahim migrated from Iraq to Afghanistan and settled in the village 'But Nagar' near Ghazni. Prof. Jawaid served as lecturer in Quaid-i-Azam College and Notre Dame College Dhaka. He is a former head of the department of Zoology, F.G. Postgraduate College, H-8,Islamabad where he served for more than twenty five years. He is also a former Principal, Federal Government College, H-9 , F-10/4 Islamabad, and Director Colleges and Director Administration, Federal Directorate of Education, Islamabad. He did his post-graduation in Zoology with specialization in Entomology from Dhaka University, East Pakistan (former). He taught various classes for more than forty five years in various capacities. He has also worked as Education Officer, in Nigeria for four years. He has successfully completed the 61st advance course in administration and development held in 1996 at National Institute of Public Administration (NIPA), Karachi. In 1995, he was awarded a shield by the honourable Mr. Rafiq Tarrar, the then President of Pakistan, for his services to humanity.

He published four research papers in Science Journals of Pakistan on Butterflies of Pakistan. He has contributed articles on science and sports in Urdu and English dailies of Islamabad. He is co-author and managing author of more than forty five textbooks on General Science and Biology as well as Biology Practical Notebooks. He has travelled to Singapore, Thailand, Indonesia, India, Bangladesh, UAE, Saudi Arabia, Egypt, Italy, Holland, UK, Qatar, USA and Nigeria. He has also served as a National Consultant, Science Education, JICA sponsored project for the promotion of Student Centred and Inquiry Based (SCIB) learning, National Institute of Science and Technical Education, Ministry of Education, Islamabad.

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Dr. (Mrs.) Sarwat Jawaid is the daughter of Prof.J.M.Malick. She has served as Medical Officer (Burn Centre) in Pakistan Institute of Medical Sciences, Islamabad. She did her graduation in Medicine from Isra University Hyderabad (2005) and Master in Public Health from Sarhad University, Peshawar (2009). She is a co-author of Biology textbooks of grade 9, 10, 11 and 12 as well as practical notebooks. She has also written a thesis on "Effect of health awareness programme in the reduction of burn injuries incidence among the community of Islamabad territory".

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Prof. Abid Ali Mughal is serving as Assistant Professor and Head of Biology Department, Islamabad Model College for Boys, H-9, Islamabad. He started his teaching career as lecturer in Botany at F. G. Degree College for Men, Wah Cantt in 2003. Before that he had also served as Research Fellow in Plant physiology and Biotechnology divisions of Nuclear Institute of Agriculture, Tandojam Dist. Hyderabad, which is an agricultural research centre of Pakistan Atomic Energy Commission. He did his M.Sc. (Hons), Botany in 2002 from University of Sindh, Jamshoro and was awarded Gold Medal. He did M.Phil. Biotechnology from Quaid-i-Azam University in 2009. His field of specialization is Plant physiology and genetic engineering. He is Principal Author of Textbook of Biology for Grade-12 according to National Curriculum 2006, published by Khyber Pakhtun Khua Textbook Board Peshawar. He has also been Resource Person in the demonstration and laboratory sessions of Teacher's Training Workshop on "Laboratory Methods in Biology", held at Department of Animal Science, Quaid-e-Azam University Islamabad. He is now Ph.D Research Scholar in the Department of Environmental sciences, University of Arid Agriculture, Rawalpindi.

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قومی ترانہ

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تو نِشانِ عزمِ عالی شان ارضِ پاکستان
مرکزِ یقین شاد باد!

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