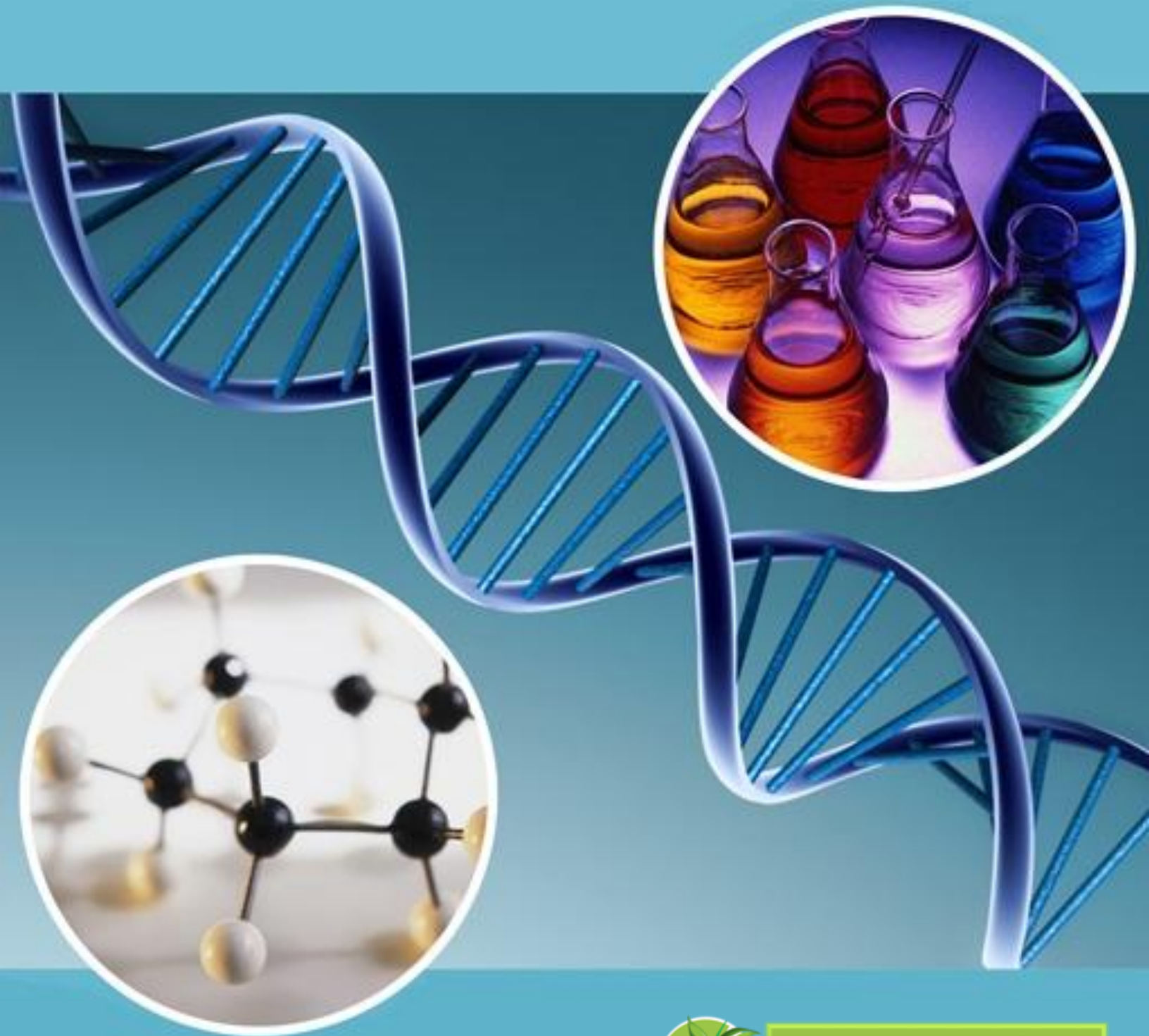


FUNDAMENTALS OF BIOCHEMISTRY



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All About Agriculture...

Fundamentals of Biochemistry

AUTHOR

TNAU



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Lecture-1

Introduction, Carbohydrates – importance & classification

Biochemistry, as the name implies, is the **chemistry of living organisms**. Living organisms, whether they are microorganisms, plants or animals are basically made up of the same chemical components. Biochemistry is the study of the way in which these components are synthesized and utilized by the organisms in their life processes. It bridges the gap between the conventional chemistry and biology.

In other words, life is nothing but thousands of ordered chemical reactions or chemistry is the logic of all biological phenomena.

History of biochemistry

During 17th and 18th centuries, important foundations were laid in many fields of biology.

- The 19th century observed the development of concepts - the cell theory by **Schleiden and Schwann**, **Mendel's study of inheritance** and **Darwin's theory of evolution**.
- The real push to biochemistry was given in 1828 when total synthesis of urea from lead cyanate and ammonia was achieved by **Wohler** who thus initiated the synthesis of organic compound from inorganic compound.
- **Louis Pasteur**, during 1857, did a great deal of work on fermentations and pointed out the central importance of enzymes in this process.
- The breakthrough in enzyme research and hence, biochemistry was made in 1897 by **Edward Buchner** when he extracted enzyme from yeast cells in crude form which could ferment a sugar molecule into alcohol.
- **Neuberg** introduced the term biochemistry in 1903.

The early part of 20th century witnessed a sudden outburst of knowledge in **chemical analysis, separation methods, electronic instrumentation for biological studies (X-ray diffraction, electron microscope, etc)** which ultimately resulted in understanding the structure and function of several key molecules involved in life processes such as proteins, enzymes, DNA and RNA.

- In 1926, **James Sumner** established the protein nature of enzyme. He was responsible for the isolation and crystallization of urease, which provided a breakthrough in studying of the properties of specific enzymes.
- The first metabolic pathway elucidated was the glycolytic pathway during the first half of the 20th century by **Embden and Meyerhof**. **Otto Warburg, Cori**

and Parnas also made very important contributions relating to glycolytic pathway.

- **Krebs** established the citric acid and urea cycles during 1930-40.
- In 1940, **Lipmann** described the central role of ATP in biological systems.
- The biochemistry of nucleic acids entered into a phase of exponential growth after the establishment of the structure of DNA in 1953 by **Watson and Crick** followed by the discovery of DNA polymerase by **Kornberg** in 1956.

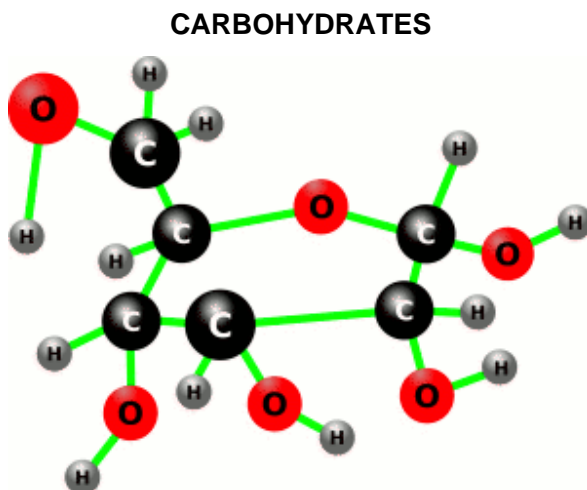
From 1960 onwards, biochemistry plunged into an interdisciplinary phase sharing much in common with biology and molecular genetics.

- **Frederick Sanger's** contributions in the sequencing of protein in 1953 and nucleic acid in 1977 were responsible for further developments in the field of protein and nucleic acid research.

The growth of biochemistry and molecular biology was phenomenal during the past two decades.

- The development of recombinant DNA research by **Snell** and coworkers during 1980 allowed for further growth and emergence of a new field, the genetic engineering.

Thus there was progressive evolution of biology to biochemistry and then to molecular biology, genetic engineering and biotechnology.



Compounds with empirical formula, $(\text{CH}_2\text{O})_n$, were called as carbohydrates (hydrates of carbons). With the discoveries of many diverse carbohydrates it was noticed that many, but not all, carbohydrates have the above empirical formula; some also contain nitrogen, phosphorus or sulfur. There are some carbohydrates (derivatives) that

do not possess $(CH_2O)_n$. On the other hand, there are a few non-carbohydrate compounds like lactic acid with empirical formula $(CH_2O)_n$. **Hence, carbohydrates are chemically defined as polyhydroxy aldehydes or ketones, their derivatives and their polymers.**

Occurrence and importance

- The carbohydrates comprise one of the major groups of naturally occurring biomolecules. This is mainly because; the light energy from the sun is converted into chemical energy by plants through primary production and is transferred to sugars and carbohydrate derivatives.
- The dry substance of plants is composed of 50-80% of carbohydrates. The structural material in plants is mainly **cellulose** and related **hemicelluloses**.
- **Starch** is the important form of storage polysaccharide in plants.
- **Pectins** and sugars such as **sucrose and glucose** are also plant constituents.
- Many non-carbohydrate organic molecules are found conjugated with sugars in the form of **glycosides**.
- The carbohydrates in animals are mostly found in combination with proteins as **glycoproteins**, as well as other compounds.
- The storage form of carbohydrates, **glycogen**, found in liver and muscles, the **blood group substances, mucins, ground substance between cells in the form of mucopolysaccharides** are few examples of carbohydrates playing important roles in animals.
- **Chitin** found in the exo-skeleton of lower animals, is a polymer of N-acetyl glucosamine.

Carbohydrates are also universally found in other polymeric substances. For example,

- Fats are fatty acid esters of a sugar alcohol, **glycerol**.
- **Ribose and deoxyribose** are constituent of nucleic acids.

Moreover, in all living forms, the energy needed for mechanical work and chemical reactions are derived from carbohydrates.

- **Adenosine triphosphate** and related substances that contain ribose as a constituent are key substances in energy storage and transfer.
- The carbon skeletons of almost **all organic molecules** are derived from carbohydrates.

Besides, the carbohydrates are the basic raw material of many important industries including **sugar and sugar products, starch products, paper and wood pulp, textiles, plastics, food processing and fermentation.**

CLASSIFICATION

Carbohydrates are classified into three major groups:

- ❖ Monosaccharides
- ❖ Oligosaccharides
- ❖ Polysaccharides

Classification of carbohydrates

Monosaccharides (Simple sugars)	Oligosaccharides	Polysaccharides (Glycans)
Low molecular weight carbohydrates and cannot be hydrolysed further	Contain 2-10 monosaccharides joined by glycosidic bonds. Low molecular weight carbohydrates which can be hydrolysed by enzymes or acids to yield monosaccharides	Contain many monosaccharides joined by glycosidic bonds. They can be hydrolysed by enzymes or acids.
Crystalline, soluble in water, and sweet in taste.	Powdery or crystalline, soluble in water and sweet in taste	Insoluble in water, tasteless, linear or branched
Classified into triose, tetrose, pentose, hexose and heptose depending upon the number of carbon atoms. They may be either aldoses or ketoses depending upon whether they contain a free aldehyde or ketone group, respectively	Classified into disaccharide, trisaccharide, tetrasaccharide and pentasaccharide depending upon the number of monosaccharides they contain.	Classified into homoglycans and heteroglycans depending upon the kind of monosaccharides present. Depending upon the function, they are classified as storage and structural polysaccharides.

All monosaccharides are reducing in nature	Some of them are reducing and some of them are non reducing in nature.	Non reducing in nature and give deep blue (amylose) or red colour (amylopectin) with iodine.
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Monosaccharides:

Monosaccharides are the simplest form that cannot be hydrolyzed further into smaller units. They are classified into a) simple monosaccharides b) derived monosaccharides

Simple monosaccharides are further classified

- based on the **type of functional group** and
- the **number of carbon atoms** they possess.

Derived monosaccharides include the derivatives of simple monosaccharides such as oxidation products, reduction products, substitution products and esters

Classification of monosaccharides

Monosaccharides	No. of carbon atoms	Aldose	Ketose	Occurrence
Simple				
Triose	3	D-Glycerose	Dihydroxy acetone	Intermediary metabolites in glucose metabolism
Tetrose	4	D-Erythrose	D-Erythrulose	
Pentose	5	D-Ribose	D-Ribulose	Ribose is a constituent of nucleic acid
		L-Arabinose	-	Occurs in oligosaccharides
		D-Xylose	D-Xylulose	Gum arabic, cherry gums, wood gums, proteoglycans
Hexose	6	D-Glucose	D-Fructose	Fruit juices and cane sugar

		D-Galactose	-	Lactose, constituent of lipids
		D-Mannose	-	Plant mannosans and glycoproteins
Heptose	7	-	D-Sedoheptulose	Intermediate in carbohydrate metabolism
Derived				
Deoxysugar	5	2-Deoxyribose	-	DNA
	6	L-Rhamnose	-	Component of cell wall
Aminosugar	6	D-Glucosamine	-	A major component of polysaccharide found in insects and crustaceans (chitin)
Polyol	6	Sorbitol	-	Berries
	6	Mannitol	-	Commercially prepared from mannose and fructose
Aldonic acid	6	Gluconic acid	-	-
Uronic acid	6	Glucuronic acid	-	Constituent of chondroitin sulfate
	6	Galacturonic acid	-	Constituent of pectin
Aldaric acid (Saccharic acid)	6	Glucaric acid	-	Oxidation product of glucose
	6	Mucic acid	-	Oxidation product of galactose

Oligosaccharides:

They contain two to ten monosaccharide units joined by glycosidic linkages that can be easily hydrolyzed.

Polysaccharides:

They are high molecular weight polymers containing more than ten monosaccharides. They are either linear or branched in structure.

Polysaccharides are further classified based on

a) the kind of monosaccharides present as:

- **Homopolysaccharides** when made from a single kind of monosaccharide.
Eg starch, cellulose, inulin, glycogen, chitin
- **Heteropolysaccharides** are made up of more than one type of monosaccharides. Eg. Hemicellulose, Mucopolysaccharides – Chondroitin sulphate, Hyaluronic acid Heparin and Keratan sulphate

b) functional aspect as:

- **Storage Polysaccharide** eg. Starch, glycogen, inulin, Galactomannan
- **Structural Polysaccharide** eg. Cellulose, Chitin, Hemicellulose

Lecture: 2

OCCURRENCE AND STRUCTURE OF MONOSACCHARIDES

The simplest monosaccharide that possesses a hydroxyl group and a carbonyl group with an asymmetric carbon atom is the **aldotriose -glyceraldehyde**. (A carbon is said to be asymmetric if four different groups or atoms are attached to it. The carbon is also called as a chiral center).

- Glyceraldehyde is considered as a reference compound and it exists in two optically active forms, D and L

The two families of monosaccharides, D-and L occur based on the configuration of D and L glyceraldehydes. In general, the D-family of sugars occur in nature.

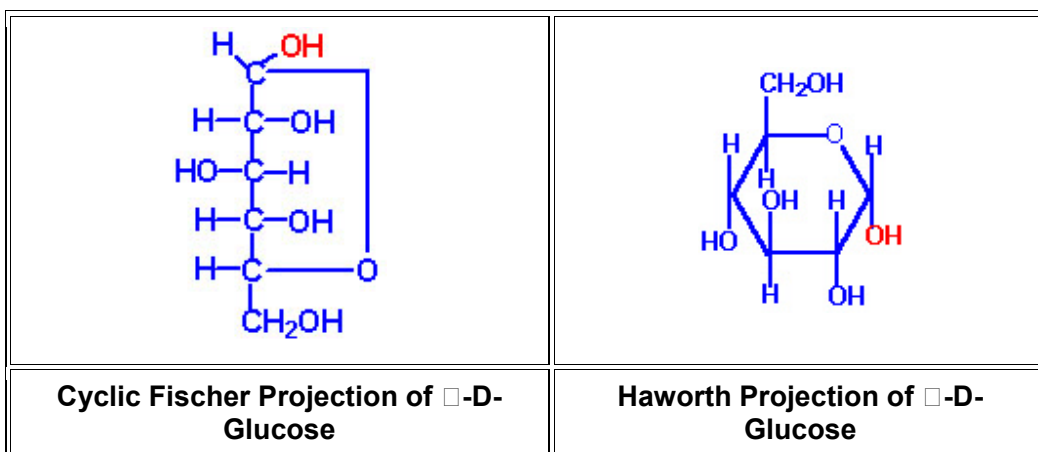
- For monosaccharides with two or more asymmetric carbons, the prefixes D or L refer to the configuration of the penultimate carbon (i.e, the asymmetric carbon farthest from the carbonyl carbon).
- If the hydroxyl group on the **penultimate** carbon is on the **right-hand side** of the carbon chain when the aldehyde or ketone group is written at the top of the formula it belongs to the **D family** and if on the **left hand side** it belongs to **L family**. The D or L has nothing to do with optical activity. D sugars may be dextro- or levorotatory.
- The important monosaccharides containing aldehyde group belonging to the D family are
 - the aldotetrose - D-erythrose
 - the aldopentoses - D-ribose, D-arabinose and D-xylose
 - the aldohexoses - D-glucose, D-mannose and D-galactose
- The important monosaccharide belonging to the L-family is L-arabinose.
- The important ketoses are
 - Ketotriose - dihydroxy acetone (It is optically inactive since there is no asymmetric carbon);
 - the ketotetrose - D-erythrulose;
 - the ketopentoses - D-ribulose and D-xylulose
 - the ketohexose - D-fructose

Cyclic structure of Monosaccharides:

The monosaccharides exist either in cyclic or acyclic form. There are many evidences to show that the pentose and hexose monosaccharides are present in cyclic form. The evidences are 1. Glucose and other aldoses fail to give the Schiff 's test for

aldehydes. 2. Solid glucose is quite inert to oxygen whereas aldehydes are easily auto-oxidizable. 3. Glucose and other aldoses do not form bisulfite or aldehyde ammonia compound. 4. Glucose pentaacetate does not react with hydroxylamine. 5. Presence of two forms of glucose with different physical and chemical properties. 6. X-ray analysis definitely proves the existence of the ring structure and also the size of the ring. 7. Mutarotation.

- When an aldehyde or a ketone group is present in a molecule that also possesses hydroxyl groups, an **intramolecular arrangement** may occur to form a **hemiacetal or a hemiketal**, respectively. This intramolecular hemiacetal or hemiketal is the basis for the cyclic structure of the sugars. Hence, **Haworth** (an English chemist) proposed a cyclic hemiacetal structure that accounts completely for its chemical properties



- Two types of ring structures are possible, **the five-membered furanose** and **the six-membered pyranose ring** if the carbonyl group interact with hydroxyl group. These names are derived from the parent compounds 'furan' and 'pyran'.
- The most common ring structure for aldohexoses is the **pyranose ring** structure that involves the first carbonyl carbon and the hydroxyl group attached to the fifth carbon.
- The **furanose ring** structure is formed by interaction of carbonyl carbon with the hydroxyl group attached to the fourth carbon. This **furanose** form is **less stable** than the pyranose structure and is not very common among aldohexoses.
- Very seldom is a seven-membered ring formed.

- Fructose exists in solution and in compounds as a furanose; however, in the crystalline state only the pyranose ring is believed to exist.
- **Ribose** occurs as the **furanose structure** in many important biological compounds.
- A **new asymmetric carbon** is introduced in the molecule due to this rearrangement. As a result of this new asymmetric centre, two isomers are formed.
- Isomeric forms of monosaccharides that differ only in their configuration about the hemiacetal or hemiketal carbon atom are called **anomers** and the carbon is referred as **anomeric carbon**.
- When the newly formed hydroxyl group in C₁ and the ring are on the same orientation, it is **α - anomer**.
- When the newly formed hydroxyl group in C₁ and the ring are on opposite orientation, it is **β - anomer**.

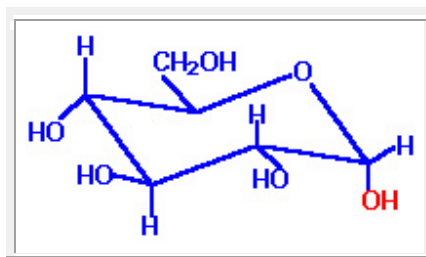
While writing the cyclic form (Haworth) of monosaccharides it is sometimes difficult to judge whether an OH group should be above or below the plane of the ring.

A few rules can be followed for writing Haworth's structure for carbohydrates.

- Write the **oxygen** at the upper right hand corner of the ring structure (pyranose) and the carbons clockwise around the ring. At the fifth carbon it is necessary to rotate the bond to 90° to make the ring closure. For the D-family of sugars, it is customary to write the terminal CH₂OH above the plane of the ring.
- If the **hydroxyl group or hydrogen atom occurs on the right-hand side** of the carbon chain in the linear structure it is **placed below the plane of the ring** in the cyclic structure.
- Conversely, if the **hydroxyl group or hydrogen atom is on the left-hand side** of the carbon chain, it is placed **above the plane of the ring** in the structure formula

Conformational structure:

The six-membered pyranose ring is not actually planar, as suggested by Haworth, but assume usually the **stable chair conformation**.



Chair form of α -D-Glucose

- The substituents are represented either axially or equatorially.
- The axial substituents project almost parallel with the vertical axis through the ring
- The equatorial substituents project roughly perpendicular to this axis.
- Substituents in the equatorial positions are less sterically hindered by neighbouring substituents. Conformations with their bulky substituents in equatorial positions are favoured.

Derived monosaccharides

The important functional groups present in monosaccharides are hydroxyl and carbonyl groups. The hydroxyl group forms esters, usually with phosphoric acid or is replaced by a hydrogen or amino group. The carbonyl group undergoes reduction or oxidation to produce number of derived monosaccharides.

a) Deoxysugars

- In sugars, the hydroxyl group is replaced by a hydrogen to produce deoxy sugars (devoid of oxygen).
- The important deoxy sugar is **2-deoxy ribose** that occurs in deoxy ribonucleic acid.
- Other important deoxy sugars are L-fucose and L. rhamnose. The substitution of the hydroxyl group at C-6 of L. galactose or L.mannose with hydrogen produces fucose or rhamnose respectively.
- L-fucose occurs in the cell wall polysaccharides namely hemicelluloses and L-rhamnose occurs in pectic polysaccharides namely rhamnogalacturonan. These deoxy sugars are also found in the complex oligosaccharide components of glycoproteins and glycolipids.

b) Amino sugars

- The hydroxyl group, usually at **C-2**, is replaced by an amino group to produce aminosugars such as glucosamine, galactosamine and mannosamine.
- The amino group may be condensed with acetic acid to produce N-acetyl amino sugars, for example, **N-acetyl glucosamine**.

- This glucosamine derivative is important constituent of many structural polymers (**chitin, bacterial cell wall polysaccharides** etc.)

c) **Polyols (alditols)**

- Both aldoses and ketoses are reduced to **polyhydric alcohols (polyols)** when treated with enzymes, sodium amalgam, and hydrogen under high pressure with catalyst or sodium borohydride.
- Each aldose yields the corresponding alcohol upon reduction
- A ketose forms two alcohols because of the appearance of a new asymmetric carbon atom in the process.

By this reduction process, the following sugars give rise to their respective alcohols under specified conditions.

Glucose	Sorbitol
Fructose	Sorbitol and mannitol
Mannose	Mannitol
Glyceraldehyde	Glycerol
Erythrose	Erythritol
Ribose	Ribitol
Galactose	Dulcitol

- Polyols occur in many plant products.
- Sorbitol was first isolated from the berries of mountain ash (*Sorbus aucuparia*).
- Commercially sorbitol is manufactured by the hydrogenation of glucose.
- Mannitol occurs in many terrestrial and marine plants.
- Potential food applications of polyols include **confectionery products, bakery products, deserts, jams and marmalade.**
- Sorbitol is an **excellent moisture conditioner** and is used in pharmaceutical preparations such as elixirs and syrups.
- Sorbitol, as a **humectant** in creams and lotions helps to stabilize the water content, providing better moisture control.
- The use of sorbitol or xylitol in toothpaste and mouthwashes is highly desirable.

d) Oxidation products

When aldoses are oxidized under proper conditions with different types of oxidizing agents, three types of acids are produced, namely **aldonic acids, uronic acids and aldaric acids or saccharic acids**.

Aldonic acid

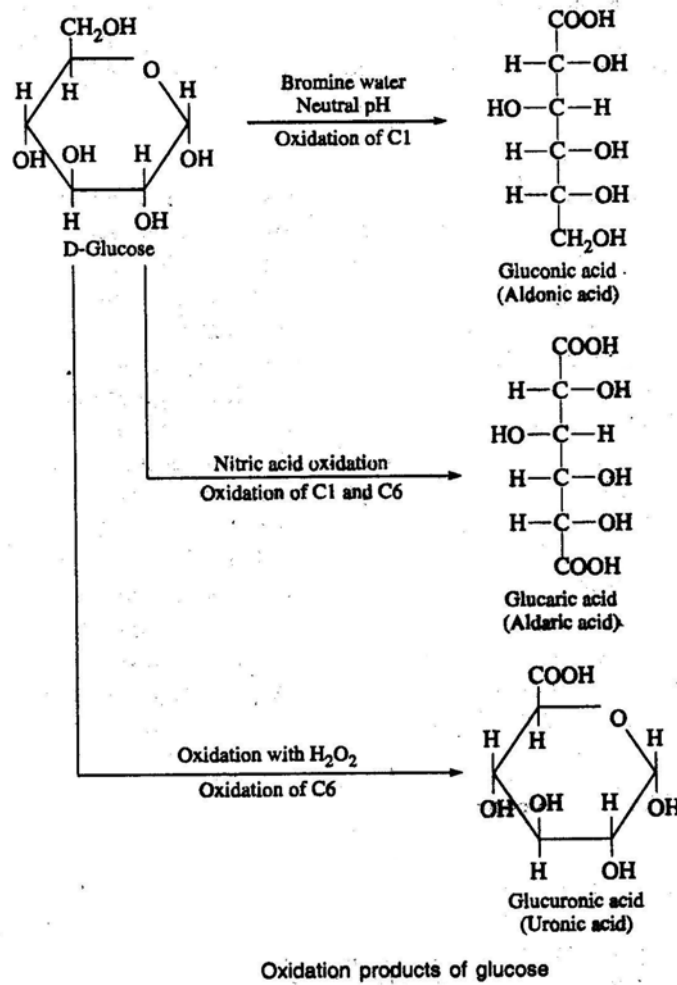
- Oxidation of an aldose with bromine water at neutral pH converts the aldehyde group (C₁) to a carboxyl group yields **Aldonic acid**.
- Hydrobromous acid formed by the reaction of water with bromine acts as an oxidizing agent.
- Ketoses are not readily oxidized by bromine water.
- Aldoses are not only oxidized by bromine water but also by the alkaline iodine solution.

Uronic acid

- When aldoses are oxidised with hydrogen peroxide (H₂O₂) uronic acids are formed.
- In this reaction only primary alcohol group(C₆) is oxidized to carboxyl group, whereas the aldehyde group remains unchanged.
- Uronic acids are constituents of pectic polysaccharides.

Aldaric or saccharic acid

- When aldoses are oxidised with nitric acid, **saccharic acids** are formed.
- Both aldehyde (C₁)and primary alcohol groups (C₆) are oxidised to carboxyl groups.
- Glucose on oxidation with nitric acid produces **glucaric or glucosaccharic acid**.
- The aldaric acid produced from galactose is called as **mucic acid**.



Lecture 3

STRUCTURE OF DISACCHARIDES & POLYSACCHARIDES

Composition, sources and properties of common disaccharides

Disaccharides	Constituent monosaccharides	Linkage	Source	Properties
Reducing disaccharides				
Maltose	α -D-glucose+ α -D-glucose	$\alpha(1\rightarrow4)$	Germinating cereal and malt	Forms osazone with phenylhydrazine. Fermentable by enzyme maltase present in yeast. Hydrolysed to two molecules of D-glucose. Undergoes mutarotation.
Lactose	β -D-glucose+ α -D-glucose	$\beta(1\rightarrow4)$	Milk. In trace amounts it can be seen in urine during pregnancy	It shows reactions of reducing sugars including mutarotation. Decomposed by alkali. Not fermentable by yeast. Hydrolysed to one molecule of galactose and one molecule of glucose by acids and the enzyme lactase.
Non-reducing disaccharides				
Sucrose	α -D-glucose+ β -D-fructose	$\alpha,\beta(1\rightarrow2)$	Sugar beet, sugarcane, sorghum and carrot roots	Fermentable. Hydrolysed by dilute acids or enzyme invertase (sucrase) to one molecule of glucose and one molecule of fructose. Relatively stable to reaction with dilute alkali.
Trehalose	α -D-glucose+ α -D-glucose	$\alpha,\alpha(1\rightarrow1)$	Fungi and yeast. It is	It is hydrolysable by acids to glucose with difficulty.

			stored as a reserve food supply in insect's hemolymph	Not hydrolysed by enzymes.
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The oligosaccharides commonly encountered in nature belong to disaccharides.

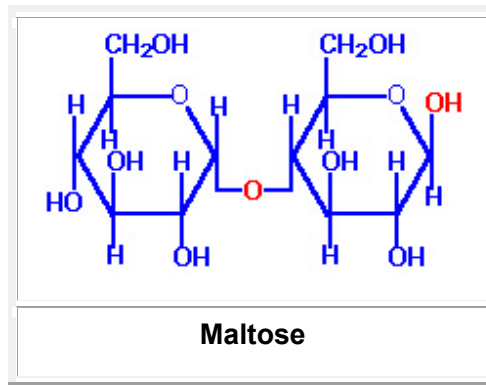
- The physiologically important disaccharides are maltose, lactose, trehalose and sucrose.
- Disaccharides consist of two monosaccharides joined covalently by an O-glycosidic bond.
- The hydroxyl group formed as a result of hemiacetal formation is highly reactive when compared to other hydroxyl groups.
- This hydroxyl group present in one monosaccharide reacts with any one of the hydroxyl groups attached to C-1, C-2, C-3, C-4, or C-6 of another monosaccharide to produce 1→1, 1→2, 1→3, 1→4, and 1→6 linked disaccharides.
- When only one anomeric carbon is involved in glycosidic bond formation, reducing disaccharides are formed.
- If both anomeric carbon atoms of monosaccharides are involved in glycosidic bond formation that results in the formation of a non-reducing disaccharides such as trehalose (aldosyl-aldosyl disaccharide) or sucrose (aldosyl-ketosyl disaccharide)'.
(aldosyl-ketosyl disaccharide)'
- In the case of reducing disaccharides, one end of the molecule having free anomeric carbon is called reducing end and the other end, where the anomeric carbon is involved in glycosidic bond, is called as non-reducing end

Reducing disaccharides

Maltose

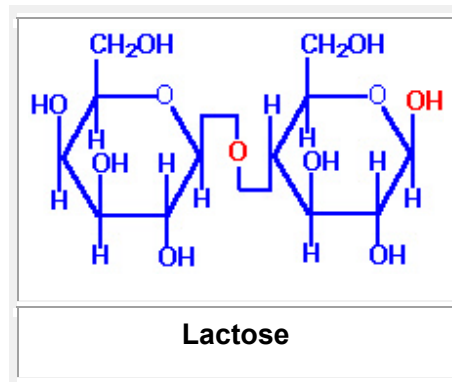
- Maltose is a disaccharide made up of **two glucose residue** joined by a **glycosidic linkage** between C-1 of one glucose residue and C-4 of the other.
- The configuration of the anomeric carbon of glucose involved in the linkage is α and hence the glycosidic linkage is α (1→4).
- The anomeric carbon atom of the second glucose is free and therefore maltose is a **reducing sugar**.

- The second glucose residue is capable of existing in α or β configuration
- Maltose has been recorded occasionally in plants. It is usually obtained as a product of the **enzyme hydrolysis of starch** during germination or malting process.



Lactose

- Lactose is a reducing disaccharide found only in **milk**.
- It is made up of galactose at the non-reducing end and glucose at the reducing end.
- They are connected by a $\beta(1 \rightarrow 4)$ linkage



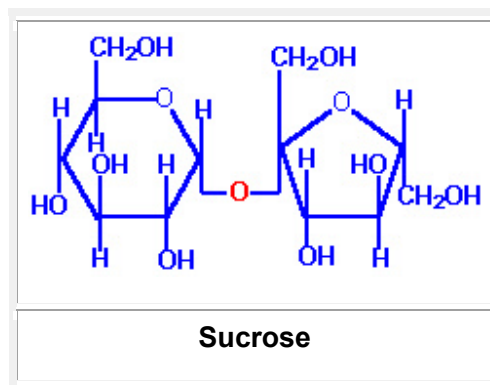
Non-reducing disaccharides

Trehalose

- Trehalose, a non-reducing disaccharide., occurs as a major constituent of the circulating fluid (hemolymph) of insects and serves as an energy storage compound.
- It is also present to a limited extent in the fat body of a variety of insects.
- It gives twice the amount of energy as that of glucose and at the same time maintains the osmotic balance.
- It has been described as an important adaptation of insects engaged in flight.
- The anomeric carbons of both glucose moieties are involved in the formation of glycosidic bond.

Sucrose

- Sucrose, a sugar of commercial importance, is widely distributed in higher plants.
- **Sugarcane and sugar beet** are the sole commercial sources.
- It is made up of **glucose and fructose**.
- The anomeric carbon atom of glucose (C-1) and fructose (C-2) are involved in linkage and is therefore a **non-reducing disaccharide**
- Sucrose is a major **intermediate product of photosynthesis** and it is the principal form in which sugar is transported from the leaves to other portions of plants via their vascular systems.



Invert sugar

- The hydrolysis of sucrose when followed polarimetrically the optical rotation changes from **positive (dextro-)** to **negative (levo-)**.
- The dextrorotatory sucrose on hydrolysis yield levorotatory mixture of glucose and fructose.

- The levorotation is due to the presence of fructose which is by itself more levorotatory (-92°) than dextrorotatory glucose (+52.2).
- This phenomenon is called inversion and the mixture of glucose and fructose is called invert sugar.
- This reaction is catalysed by the **enzyme invertase**.
- Invert sugar is more sweeter than sucrose.
- Honey contains plenty of invert sugar and therefore is very sweet.

Sucrosyl oligosaccharides

- The **degree of polymerization (DP)** of sucrosyl oligosaccharides normally ranges from 3 to 9.
- Though sucrose is found at higher concentration in all plants, members of the sucrosyl oligosaccharides occur at least in traces in each plant family.
- The main accumulation of sucrosyl oligosaccharides is found in **storage organs such as roots, rhizomes and seeds**.
- The important members of sucrosyl oligosaccharides are **raffinose (DP-3), stachyose (DP-4), verbascose (DP-5) and ajugose (DP-6)**.
- All sucrosyl oligosaccharides are **non-reducing** in nature .

Raffinose

- It occupies the second position next to sucrose in abundance in the plant kingdom.
- Raffinose occurs only at low concentration in the leaves of leguminous plants, but accumulates in the storage organs such as seeds and roots.
- Most of the leguminous seeds contain these oligosaccharides in large amounts.
- Bengal gram has higher amounts of raffinose.
- Red gram and green gram have significantly high amounts of verbascose and stachyose than Bengal gram and black gram.
- These sucrosyl oligosaccharides are responsible for **flatulence** following the consumption of these legumes.
- It serve as **reserve material**.

- It also contributes to **frost resistance**

Polysaccharides

The polysaccharides found in nature either serve a structural function (structural polysaccharides) or play a role as a stored form of energy (storage polysaccharides).

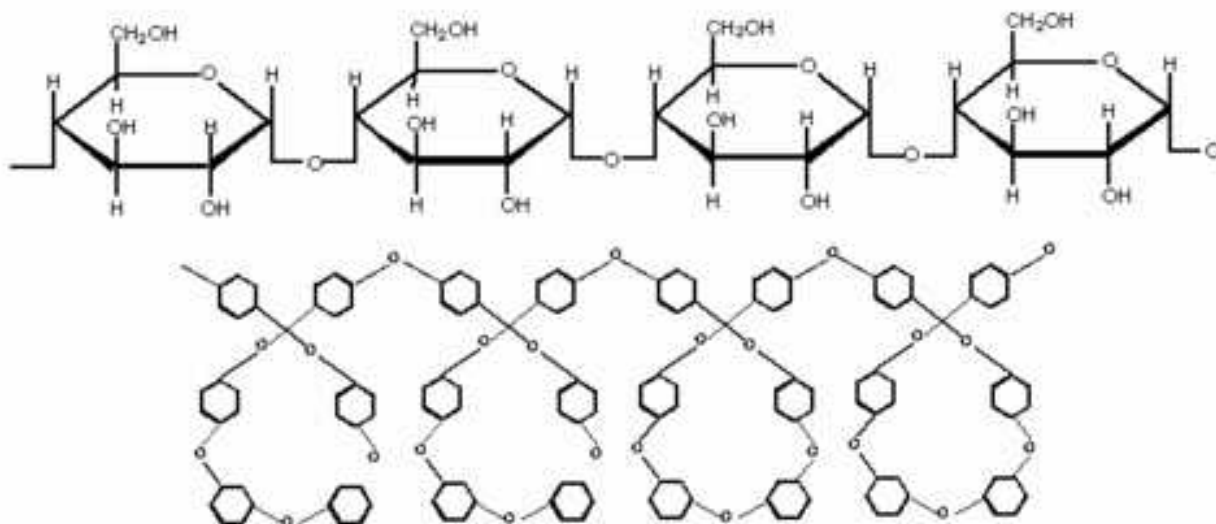
Storage polysaccharides

- Starch, galactomanans and inulin are important storage polysaccharides in plants.

Starch

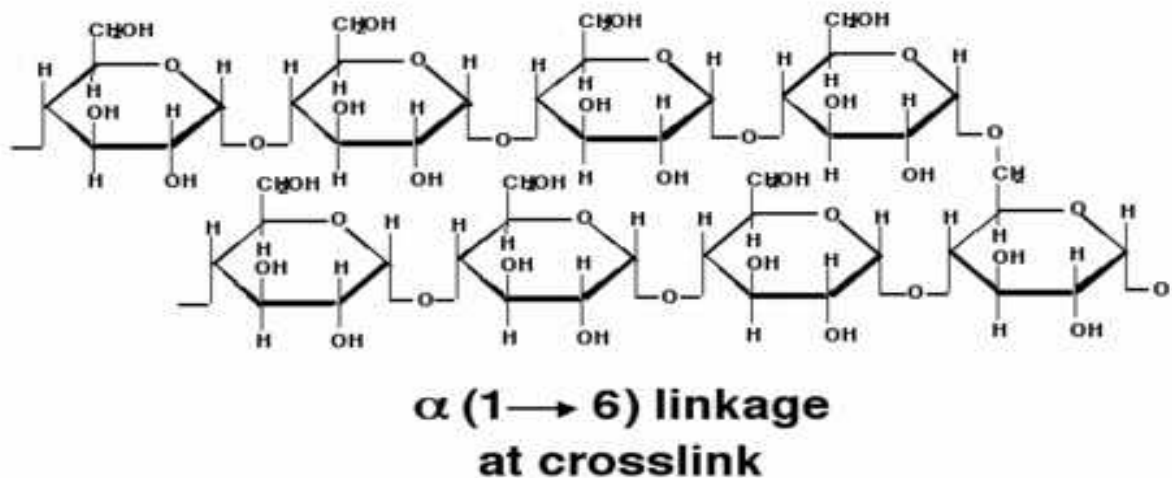
- The principal food-reserve polysaccharide in the plant kingdom is starch.
- It forms the major source of carbohydrate in the human diet.
- Starch has been found in some protozoa, bacteria and algae. But the major source is plants where it occurs in the seeds, fruits, leaves, tubers and bulbs in varying amount from a few percent to over 74%.
- Starch is an alpha-glucan that has structurally distinct components called amylose and amylopectin.
- A third component referred as the intermediate fraction has also been identified in some starches.
- Starch molecules are organized into quasicrystalline macromolecular aggregates called granules.
- The shape of the granules are characteristics of the source of the starch.
- The two components, amylose and amylopectin, vary in amount among the different sources from less than 2% of amylose in waxy rice or waxy maize to about 80% amylose in amylomaize.
- The majority of starches contain 15 to 35% of amylose.
- The ratio of amylose and amylopectin is a function of the enzymes, **granulosis bound starch synthase (GBSS) and soluble starch synthase (SSS)**.
- GBSS is able to synthesise amylose in a form that is not a substrate for branching enzyme to form amylopectin.

- Waxy mutants containing only amylopectin lack the GBSS but still contain soluble starch synthase.



- Amylose is made up of α -D-glucose units linked mostly in a linear way by α -1,4 linkages
- It has a molecular weight of 150,000 to 1,000,000 depending on its biological origin.
- It has been shown that amylose has some elements of nonlinearity.
- It consists of a mixture of linear molecules with limited, long-chain branching involving α -1,6 linkages.
- The branches contain several hundred glucose residues.
- Amylose gives a characteristic blue color with iodine due to the ability of the iodine to occupy a position in the interior of a helical coil of glucose units.
- Pure amylose binds 20% of iodine at 20°C

Amylopectin



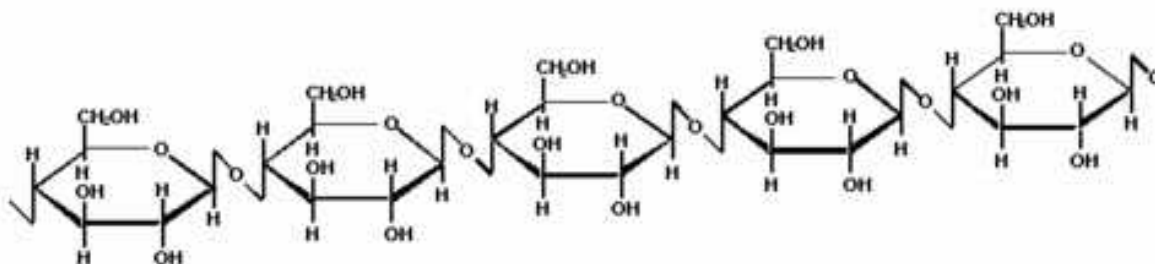
- Amylopectin is a **branched, water-insoluble polymer** comprised of thousands of D-glucose residues.
- The main chain of amylopectin consists of D-glucose residues joined by α (1 \rightarrow 4) glycosidic bonds.
- Side chains of glucose residues are attached to the main chain by α (1 \rightarrow 6) glycosidic bonds.
- Each chain contains 15-25 glucose residues joined by α (1 \rightarrow 4) bonds.
- It contains 94-96% α 1 \rightarrow 4 and 4-6% α - 1 \rightarrow 6 linkages.
- The molecular weight of amylopectin is in the order of 10^7 - 10^8 .
- Robin and co-workers have proposed a model for amylopectin
- In this model, A and B chains are linear and have degree of polymerization as 15 and 45 respectively.
- The B chain form the backbone of the amylopectin molecule and extend over two or more clusters.
- Each cluster of A chain are primarily responsible for the crystalline regions within the granule.
- The intercrystalline regions occur at regular intervals (60 - 70 \AA) containing the majority of α - 1 - 6 linkages.
- The amylopectin molecule is 100 - 150 \AA in diameter and 1200-4000 \AA long.
- Within the granule, amylose may be located between amylopectin molecules and associated with the linear regions of the amylopectin molecule.
- Amylopectin produces a purple to red color with iodine.

Inulin

- Inulin is a non-digestible fructosyl oligosaccharide found naturally in more than 36000 types of plants.
- It is a storage polysaccharide found in onion, garlic, chicory, artichoke, asparagus, banana, wheat and rye.
- It consists of mainly,if not exclusively, of β -2->1 fructosyl-fructose links
- A starting glucose moiety can be present, but is not necessary.
- Inulin is a soluble fibre that helps maintain normal bowel function, decreases constipation, **lowers cholesterol and triglycerides**.
- It is used for **fat replacement and fibre enrichment** in processed foods.

Structural polysaccharides

Cellulose



- Cellulose is the most abundant organic substance found in nature.
- It is the principal constituent of cell walls in higher plants.
- It occurs in almost pure form (98%) in cotton fibres and to a lesser extent in flax (80%), jute (60-70%), wood (40-50%) and cereal straws (30-43%).
- It is linear, unbranched homopolymer of 10,000 to 15,000 D-glucose units joined by β -1,4 linkages
- The structure of cellulose can be represented as a series of glucopyranose rings in the chair conformation.

- The most stable conformation for the polymer is the chair turned 180° relative to the adjacent glucose residues yielding a straight extended chain.
- Cellulose molecules within the plant cell walls are organized into biological units of structure known as microfibrils.
- A microfibril consists of a bundle of cellulose molecules arranged with its long axis parallel to that of the others.
- This arrangement permits the formation of intramolecular hydrogen bonding between the hydroxyl group of C-3 of one glucose residue and the pyranose ring oxygen atom of the next glucose residue.
- This hydrogen bond impart a double bond character to the glycosidic bond and impedes the rotation of adjacent glucose residues around the glycosidic bond.
- Within the microfibril, the adjacent cellulose molecules are linked by intermolecular hydrogen bond between C-6 hydroxyl group of one molecule and the glycosidic bond oxygen atom of adjacent cellulose molecule
- The cross section of the microfibril consists of a central crystalline core of about 5–30 nm short diameters.
- The central crystalline core contains around 50-100 cellulose molecules which are arranged in perfect three dimensional array and exhibits a crystalline structure.
- Surrounding this crystalline core is a region of paracrystalline matrix which contains about 100 polysaccharide molecules of cellulose and hemicellulose
- This region does not have perfect three-dimensional order and water molecules are able to penetrate the paracrystalline region but not the crystalline core.

Chemical properties of carbohydrates

Monosaccharides

Reactions of monosaccharides are due to the presence of hydroxyl (-OH) and the potentially free aldehyde (-CHO) or keto ($>C=O$) groups.

Reaction with alkali

Dilute alkali

- Sugars in weak alkaline solutions undergo isomerization to form 1,2-enediol followed by the formation of a mixture of sugars.

Strong alkali

Under strong alkaline conditions sugar undergo caramelization reactions.

Reducing property of sugars

- Sugars are classified as either reducing or non-reducing depending upon the presence of potentially free aldehyde or keto groups.
- The reducing property is mainly due to the ability of these sugars to reduce metal ions such as copper or silver to form insoluble cuprous oxide, under alkaline condition.
- The aldehyde group of aldoses is oxidized to carboxylic acid. This reducing property is the basis for qualitative (Fehling's, Benedict's, Barfoed's and Nylander's tests) and quantitative reactions.
- All monosaccharides are reducing. In the case of oligosaccharides, if the molecule possesses a free aldehyde or ketone group it belongs to reducing sugar (maltose and lactose).
- If the reducing groups are involved in the formation of glycosidic linkage., the sugar belongs to the non- reducing group (trehalose, sucrose, raffinose and stachyose).

Reaction with phenylhydrazine

- When reducing sugars are heated with phenylhydrazine at pH 4.7 a yellow precipitate is obtained.
- The precipitated compound is called as osazone. One molecule of reducing sugar reacts with three molecules of phenylhydrazine.
- D-mannose and D-fructose form same type of osazone as that of D-glucose since the configuration of C-3, C-4, C-5 and C-6 is same for all the three sugars.
- The osazone of D-galactose is different.
- Different sugars form osazone at different rates. For example, D-fructose forms osazone more readily than D-glucose.
- The osazones are crystalline solids with characteristic shapes, decomposition points and specific optical rotations.
- The time of formation and crystalline shape of osazone is utilized for identification of sugars.

- If methyl phenylhydrazine is used instead of phenylhydrazine in the preparation of osazone, only ketoses react.
- This reaction serves to distinguish between aldose and ketose sugars.

Reaction with acids

- Monosaccharides are generally stable to hot dilute mineral acids though ketoses are appreciably decomposed by prolonged action.
- Heating a solution of hexoses in a strong non-oxidising acidic conditions, hydroxyl methyl furfural is formed.
- The hydroxymethyl furfural from hexose is usually oxidized further to other products. When phenolic compounds such as resorcinol, α -naphthol or anthrone are added, mixture of coloured compounds are formed.
- The molisch test used for detecting carbohydrate in solution is based on this principle.
- When conc. H_2SO_4 is added slowly to a carbohydrate solution containing α -naphthol, a pink color is produced at the juncture.
 - The heat generated during the reaction hydrolyse and dehydrate it to produce furfural or hydroxymethyl furfural which then react with α -naphthol to produce the pink color.

Lecture 4

Muta rotation, optical activity and physical properties of sugars

A. Isomerism

In organic chemistry, isomerism is defined as the existence of more than one compound with the same molecular formula. A close observation of the structure of monosaccharides (hexoses) indicate that they possess same molecular formula ($C_6H_{12}O_6$) but with different physical and chemical properties. There are different types of isomerism

- **D-glucose and D-fructose** differ in the position of carbonyl group (aldehyde and ketone group). These two compounds are **functional isomers**.
- Another type of isomerism exhibited by compounds possessing asymmetric carbon atom like monosaccharides, is **stereoisomerism**. These stereoisomers differ in the spatial arrangement of atoms or groups. There are two types of stereoisomerisms - **geometrical and optical isomerism**.
 - **Geometrical isomers** (cis-trans) differ in the spatial arrangement of atoms across a double bond. Geometrical isomerism is not noticed among carbohydrates.
 - **Optical isomers** differ in the arrangement of atoms around an asymmetric carbon atom. The number of possible optical isomers can be calculated using the formula 2^n where n =number of asymmetric carbon atoms. For example, glucose contains four asymmetric carbon atoms and the possible optical isomers of glucose are $2^4 = 16$.

Epimers, enantiomers and diastereomers:

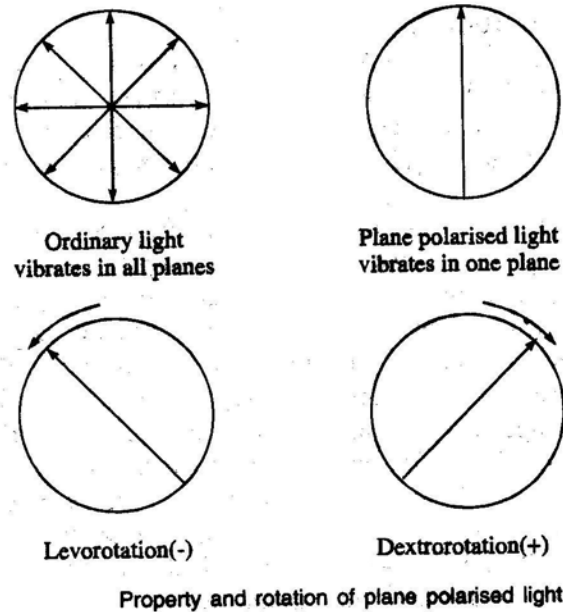
- **Epimers** are monosaccharides differing in configuration around a single carbon atom other than the carbonyl carbon. e.g. **Mannose and glucose** are epimers with respect to carbon 2. **Galactose and glucose** are epimers with respect to carbon 4.
- **Enantiomers** are non- superimposable mirror images of each other. They differ in the ability to rotate the plane polarized light. A solution of one enantiomer rotates the plane of such light to the right, and a solution of the other to the left. **D-glucose and L-glucose** are examples of enantiomers.
- **Diastereomers** are stereoisomers that are not mirror images of each other. **D-glucose, Dmannose, D-galactose** and other members of aldohexose are diastereoisomers.

B. Optical activity

A ray of ordinary light vibrates in all directions at right angles to the direction in which the ray is travelling. When this light is passed through a Nicol prism, the emerged light vibrates in only one direction and such light is called as a '**plane polarized light**'

When a beam of plane polarized light is passed through a sugar solution, that is optically active, the plane-polarized light will be rotated either to the right (clockwise) or to the left (anticlockwise).

- When the plane polarized light is rotated to the **right**, the compound is **dextrorotatory** and is written as (+).
- If the plane polarized light is rotated to the **left**, the compound is **levorotatory** (-)



Optical activity is measured using polarimeter. Optical activity varies with the concentration of the sugar solution and length of the polarimeter tube where sugar solution is placed.

Specific rotation (α) of a sugar molecule is calculated by the formula :

$$(\alpha) = \frac{\text{Observed rotation}}{\text{Length of tube (dm)} \times \text{concentration}}$$

where T = temperature and D = D line of spectrum.

The specific rotation of some important sugars are given below:

D - glucose (dextrose) + 52.2	D - fructose (levulose) -92.0	D - galactose + 80.5
D - mannose + 14.6	L - arabinose + 104.5	Sucrose + 66.5

C. Mutarotation

- Mutarotation refers to the change in optical rotation when an aqueous sugar solution is allowed to stand.
- Sugars having potential free aldehyde or keto group exhibit mutarotation.
- Many sugars exist in two crystalline forms. For example, when D-glucose is dissolved in water and allowed to crystallize out by evaporation of water, one form of D-glucose is obtained. If D-glucose is crystallized from acetic acid or pyridine, another form of D-glucose is obtained. These two forms exhibit different physical and chemical properties.
- A freshly prepared aqueous solution of α -D glucose has a specific rotation of $+113^\circ$. If the solution of α -D-glucose is allowed to stand, the specific rotation changes to $+52.2^\circ$.
- Similarly, a fresh solution of β -D-glucose has a specific rotation of $+19^\circ$ which changes to $+52.2^\circ$ on standing.
- This change in optical rotation is called **mutarotation**. On standing in solution, the hemiacetal ring opens and reforms to give a mixture of α and β -D-glucose having a specific rotation of $+52.2^\circ$.

Lecture 5

Chemical properties of carbohydrates

Monosaccharides

Reactions of monosaccharides are due to the presence of hydroxyl (-OH) and the potentially free aldehyde (-CHO) or keto ($>C=O$) groups.

Reaction with alkali

Dilute alkali

- Sugars in weak alkaline solutions undergo isomerization to form **1,2-enediol** followed by the formation of a mixture of sugars.

Strong alkali

Under strong alkaline conditions sugar undergo **caramelization reactions**.

Reducing property of sugars

- Sugars are classified as either reducing or non-reducing depending upon **the presence of potentially free aldehyde or keto groups**.
- The reducing property is mainly due to the ability of these sugars to **reduce metal ions such as copper or silver to form insoluble cuprous oxide, under alkaline condition**.
- The aldehyde group of aldoses is oxidized to carboxylic acid.
- This reducing property is the basis for qualitative (Fehling's, Benedict's, Barfoed's and Nylander's tests) and quantitative reactions.
- All monosaccharides are reducing. In the case of oligosaccharides, if the molecule possesses a free aldehyde or ketone group it belongs to reducing sugar (maltose and lactose).
- If the reducing groups are **involved in the formation of glycosidic linkage**., the sugar belongs to the non-reducing group (trehalose, sucrose, raffinose and stachyose).

Reaction with phenylhydrazine

- When reducing sugars are heated with **phenylhydrazine** at pH 4.7 a yellow precipitate is obtained.

- The precipitated compound is called as **osazone**.
- One molecule of reducing sugar reacts with three molecules of phenylhydrazine.
- D-mannose and D-fructose form same type of osazone as that of D-glucose since the configuration of C-3, C-4, C-5 and C-6 is same for all the three sugars.
- This reaction serves to distinguish between aldose and ketose sugars.

Reaction with acids

- Heating a solution of hexoses in a strong non-oxidising acidic conditions, **hydroxyl methyl furfural** is formed.
- The hydroxymethyl furfural from hexose is usually oxidized further to other products. When **phenolic compounds such as resorcinol, α -naphthol or anthrone** are added, mixture of coloured compounds are formed.
- The **molisch test** used for detecting carbohydrate in solution is based on this principle.
- When conc. H_2SO_4 is added slowly to a carbohydrate solution containing α -naphthol, a pink color is produced at the juncture.
- The heat generated during the reaction **hydrolyse and dehydrate** it to produce **furfural or hydroxymethyl furfural** which then react with α -naphthol to produce the pink color.

Lecture 6

Lipids - introduction, importance and classification

Occurrence and importance

- The word lipids is derived from the Greek word '**lipos**' meaning fat.
- Lipids are chemically heterogenous group of compounds that are **insoluble in water but soluble in non-polar solvents such as chloroform.**
- Lipids occur in plants and animals as **storage and structural components**
- Structural lipids present in animals and plants are in the form of meat and vegetables respectively.
- Storage fats occur in milk and adipose tissue of farm animals and in seed oils
- Fats supply over **twice as much energy per unit weight** as proteins or carbohydrates.
- Lipids are anhydrous due to non-polar nature and represent more energy than carbohydrates which are heavily hydrated due to polar nature.
- The presence of lipids in diet contributes considerably to palatability.
- Lipids contribute palatability in two ways. They induce olfactory responses, namely, taste in the mouth and aroma through nose.
- Secondly, they contribute to the texture of food and is responsible for the mouth-feel.
- Lipids also supply the **essential fatty acids** which are not synthesised in human beings but are essential for growth.
- Lipids are **essential for the effective absorption of fatsoluble vitamins A, D, E and K from intestine.**
- Many **enzymes require lipid molecules for maximal activity.** Examples are microsomal enzyme, glucose 6-phosphatase and mitochondrial enzyme, □ hydroxybutyrate dehydrogenase.
- **Adrenal corticosteroids, sex hormones and vitamin D3 (Cholecalciferol)** are synthesized from lipid derivative- cholesterol.
- Much of the lipid of mammals is located subcutaneously and **acts as insulation** against excessive heat loss to the environment.
- The subcutaneous lipid deposits also insulate the important organs against mechanical trauma.

Classification

Lipids are broadly classified into **simple, compound and derived lipids**

Classification of Lipids

Lipids		
Simple Lipids	Compound Lipids	Derived Lipids
Esters of fatty acids with glycerol and monohydric alcohols.	Esters Containing chemical groups in addition to alcohol and fatty acids.	Substances derived from simple and compound lipids by hydrolysis. Alcohols, fatty acids, aldehydes, ketones, sterols and hydrocarbons.
Depending upon the constituent alcohols they are further subdivided into fats or oils and waxes.	Depending upon the chemical groups they are further subdivided into phospholipids, glycolipids, sulpholipids and lipoproteins.	
Fats, also termed as triacylglycerols are esters of fatty acids with glycerol e.g. Plants-vegetable oils; Animals-ghee and butter	Phospholipids contain phosphate group. Phospholipids are further grouped as glycerophospholipids e.g., Lecithin if the constituting alcohol is glycerol or as sphingophospholipids if the alcohol is sphingosine e.g., sphingomyelin.	
Waxes are esters of fatty acids and alcohols other than glycerol e.g., Plant wax-carnauba wax;	Glycolipids contain hexose units preferably galactose alongwith fatty acids and alcohol e.g. Cerebrosides.	
Insect wax-beeswax;	Plant sulpholipids contain sulfated hexose with fatty acids and alcohol	

Animal wax – lanolin	Lipoproteins contain protein subunits along with lipids. Depending upon density and lipid compound they are further classified as VLDL, LDL and HDL.	
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Lecture - 7 -9

Plant fatty acids

- Fatty acids are **carboxylic acids** with hydrocarbon chains of 2 to 36 carbons.
- More than 200 fatty acids have been isolated from higher and lower plants.
- Of these, only a few are present in large quantities in most plant lipids. These are referred as **major fatty acids**.
- Fatty acids present in smaller proportions are called as **minor fatty acids**.
- Major and minor fatty acids are usually biosynthesised by analogous pathways.
- Fatty acids that occur only in a few plant species are called as **unusual fatty acids**.

Major fatty acids

- The major fatty acids are **saturated or unsaturated** with an unbranched carbon chain.
- The saturated fatty acids are **lauric (dodecanoic), myristic (tetradecanoic), palmitic (hexadecanoic) and stearic (octadecanoic) acid**
- The **unsaturated fatty acids** are **oleic (9-octadecenoic), linoleic (9,12-octadecadienoic) and α -linolenic (9,12,15- octadecatrienoic) acid**.
- They are usually found in the lipids from all parts of plants
- The structure of fatty acids are written as a symbol of two numbers separated by a colon: the first number denotes the carbon atoms in the chain and the second number denotes the number of unsaturation centres.
- The positions of double bonds are specified by superscript numbers following (δ).
- Thus 18:2 ($\alpha^{9, 12}$) indicates an eighteen carbon fatty acid with two double bonds between C-9 and C-10, and between C-12 and C-13.
- The double bonds of all naturally occurring unsaturated fatty acids are in **the cis configuration**.
- The non-polar hydrocarbon chain accounts for the poor solubility of fatty acids in water.

Minor fatty acids

The fatty acid composition of cow's and goat's milk are characterised by a high content of short and medium chain saturated fatty acids.

Some minor fatty acids

Common name	Carbon skeleton	Systematic name
Butyric	4:0	Butanoic
Caproic	6:0	Hexanoic
Caprylic	8:0	Octanoic
Capric	10:0	Decanoic

Unusual fatty acids

- ❖ The unusual fatty acids are found only in few individual species or genus or a whole family.
- ❖ Castor bean (*Ricinus communis*) seed oil is rich in **ricinoleic acid** (90%) which is 12-hydroxy oleic acid $\text{CH}_3(\text{CH}_2)_5\text{-CH(OH)-CH}_2\text{-CH=CH-(CH}_2)_7\text{-COOH}$.
- ❖ Rape seed (*Brassica napus*) is rich in **erucic acid** (cis-13-docosenoic acid $\text{CH}_3(\text{CH}_2)_7\text{-CH=CH-(CH}_2)_{11}\text{-COOH}$).
- ❖ **Hydnocarpic and chaulmoogric acids** are found in chaulmoogra oil which is used in the treatment of leprosy.

Essential fatty acids

- ❖ Human body is unable to synthesise all fatty acids found in the body.
- ❖ Those fatty acids that **are not synthesised in the body** but required for normal body growth and maintenance are called as **essential fatty acids**.
- ❖ These fatty acids are to be supplied through diet.
- ❖ **Linoleic and linolenic acids** are essential fatty acids
- ❖ The longer chain fatty acids can be synthesised by the body from dietary linoleic and α -linolenic acids.
- ❖ **Arachidonic acid** is essential but it can be synthesised by the body from linolenic acid. It is also present in the meat
- ❖ Linoleic acid is grouped under **n-6 family** because the 6th carbon from methyl end possesses the double bond.
- ❖ Other fatty acids that are synthesised in the body from linoleic acid such as α -linolenic and arachidonic acids also belong to n-6 family.
- ❖ α -**Linolenic acid** belongs to n-3 family and is an essential fatty acid.
- ❖ The third carbon from the methyl end possess the double bond

- ❖ The organs and tissues that perform the more routine and generalized functions such as adipose tissue, liver, muscle, kidney and the reproductive organs tend to have membranes in which n-6 family of polyunsaturated fatty acids predominate.
- ❖ Nervous tissue and retina of the eye have a larger proportion of the longer chain acids with 5 or 6 double bonds predominantly of the n-3 family.
- ❖ Fish oils and spirulina are rich in fatty acids of n-3 family.
- ❖ **Arachidonic acid** serves as precursor for the **synthesis of prostaglandins, thromboxanes and prostacyclins.**
- ❖ These fatty acid derivatives are called as 'eicosanoid' meaning 20 C compounds.
- ❖ The main source of these eicosanoids are the **membrane phospholipids** from which they are released by the action of phospholipase-A.
- ❖ **Phosphatidyl inositol** which contains a high concentration of arachidonic acid in carbon-2 of glycerol provides a major store of eicosanoid precursors.
- ❖ Phosphatidyl inositol is an important constituent of cell membrane phospholipids; upon stimulation by a suitable animal hormone it is cleaved into diacylglycerol and inositol phosphate, both of which act as **internal signals or second messengers**

Simple lipids

- ❖ Lipids containing **only fatty acids and glycerol or long chain alcohols** (monohydric) are called as **simple lipids** which include **fats, oils and waxes.**

Fats and oils

- ❖ Triacylglycerols are the simplest lipids constructed from fatty acids and glycerol.
- ❖ They are also referred as triglycerides, fats or neutral fats.
- ❖ Triacylglycerols are composed of **three fatty acids esterified to the three hydroxyl groups of glycerol**

- ❖ When all the 3 fatty acid molecules are of the same kind the triacylglycerol is said to be **simple triacylglycerol.**
- ❖ **Mixed triacylglycerol** possesses two or more different fatty acids.
- ❖ Triacylglycerol that are solid at room temperature are called as **fats**
- ❖ Liquid triacylglycerols are called as oils.
- ❖ Neutral fats or oils are mostly composed of mixed triacyl glycerol.

- ❖ Fats are usually **rich in saturated fatty acids** and the unsaturated fatty acids predominate in oils.
- ❖ Most oil-producing plants store their lipids in the form of triacylglycerols.

Storage fats or oils

- ❖ Triacylglycerols are widely distributed in the plant kingdom. They are found both in vegetative as well as reproductive tissues.
- ❖ Triacylglycerols are normally stored in the **endosperm of the seed** although some plants store appreciable quantities of fat in the **fleshy fruit mesocarp**, for example, avocado.
- ❖ Some plants like the **oil palm**, store oils in both the **mesocarp (Palm oil)** and the **endosperm (Palm kernel oil)**.
- ❖ The oil present **as droplets** in the cytoplasm of the **seed cells**.
- ❖ These droplets are called as **oil bodies** and are surrounded by a membrane composed of phospholipids and protein.
- ❖ Most of the common edible oils (groundnut, sunflower, gingelly, soybean, safflower, rice bran) contain limited number of the common fatty acids such as palmitic, stearic, oleic, linoleic and linolenic acids.
- ❖ Palm kernel and coconut oils contain higher amount of medium chain saturated fatty acids.
- ❖ Seed oils contain small amount of phospholipids, carotenoids, tocopherols, tocotrienols and plant sterols depending on the species of plant and degree of processing.

Structural or hidden fats in plants

- ❖ The leaves of higher plants contain upto 7% of their dry weight as fats;
- ❖ Some of them are present as surface lipids, the others as components of **leaf cells**, especially in the **chloroplast membrane**.
- ❖ The fatty acid composition of plant membrane lipids is very simple.
- ❖ Six fatty acids- palmitic, palmitoleic, stearic, oleic, linoleic and α -linolenic generally account for over 90% of the total fatty acids.

Waxes

- ❖ Waxes are **esters of long-chain saturated and unsaturated fatty acids with long chain alcohol**.

- ❖ The carbon number of fatty acids vary from 14 to 34 and that alcohol from 16 to 30.

For example, beeswax is an ester of palmitic acid with a 30 carbon alcohol, **triacontanol**

- Waxes are the **chief storage form of metabolic fuel** in marine phytoplanktons.
- Biological waxes find a variety of applications in the pharmaceutical, cosmetic and other industries.
- Lanolin from lamb's wool, beeswax, carnauba wax, spermaceti oil from whales are widely used in the **manufacture of lotions, ointments and polishes**.
- Waxes are not easily hydrolysed like fats or digested by lipases.

Liquid wax - Jojoba oil

- About 50% of the **seed dry weight of jojoba** consists of a liquid wax which is unique in the plant kingdom and is similar to sperm whale oil.
- The wax is made up of straight chain esters with an average total chain length of 42 carbons
- Jojoba wax has a wide range of industrial uses including cosmetics, pharmaceuticals, extenders for plastics, printers ink, gear oil additives and various lubricants.
- The oil is highly stable and can be stored for years without becoming rancid.

Cuticular wax

- The outermost surface of the cell walls of epidermal cells are covered with a **hydrophobic cuticle** which contains wax called cuticular wax.
- The main components of cuticular waxes are hydrocarbon (odd chain alkanes) and its derivatives, wax esters, free aldehydes, free acids, free alcohols and other components like mono esters of phenolic acids and aliphatic alcohols.
- The main function of the cuticular wax is to **reduce the excessive losses and gains of water** by the underlying tissue.
- It also helps in protecting the tissues from chemical, physical and biological attack.

Compound lipids

Compound lipids contain certain chemical groups in addition to alcohol and fatty acids.

- These group of lipids include **glycerophospholipids, sphingo phospholipids, glycolipids, sulpholipids and lipoproteins**.

Glycerophospholipids

- The important **structural lipid in biological membrane** is glycerophospholipid which contains **glycerol, fatty acids phosphoric acid and a nitrogenous base**.
- The general structure of a glycerophospholipid is given below

- Without alcoholic residue (X), it is called as **phosphatidic acid**
- Depending on the alcoholic residue attached to phosphatidic acid, they are named as
 - i. Phosphatidyl choline (lecithin)
 - ii. Phosphatidyl ethanolamine (cephalin)
 - iii. Phosphatidyl serine
 - iv. Phosphatidyl inositol
 - v. Phosphatidyl glycerol (which include monophosphatidyl glycerol and diphosphatidyl glycerol or cardiolipin).

Phosphatidyl choline (lecithin)

- Lecithin contains **glycerol, fatty acids, phosphoric acid and a nitrogenous base, choline**
- Lecithins are widely distributed in the membranes of cells having both metabolic and structural functions.
- **Dipalmityl lecithin** is a very effective **surface active agent** preventing adherence due to surface tension of the inner surfaces of the lungs.
- Most phospholipids have a saturated fatty acid in the C1 position but an unsaturated fatty acid in the C2 position.

Phosphatidyl ethanolamine (cephalin)

- The cephalin differs from lecithin only in the nitrogenous group where ethanolamine is present instead of choline

Phosphatidyl serine

- The hydroxyl group of the amino acid L-serine is esterified to the phosphatidic acid

Phosphatidyl inositol

- Phosphatidyl inositol is an important **constituent of cell membrane phospholipids**;

- upon stimulation by a suitable animal hormone it is cleaved into **diacylglycerol and inositol phosphate**, both of which act as **internal signals or second messengers**.

Phosphatidyl glycerol and diphosphatidyl glycerol (Cardiolipin)

- **Cardiolipin** is a phospholipid that is found in **membranes of mitochondria**.
- It is formed from phosphatidylglycerol

Sphingophospholipids

- The phosphate and fatty acids are attached to the alcohol **sphingosine** instead of glycerol in sphingophospholipids.
- The fatty acids are attached through an **amide linkage** rather than the ester linkage.
- The base present is normally **choline**.
- The structure of the parent compound sphingosine and phytosphingosine are shown below
- C-1, C-2 and C-3 of the sphingosine or phytosphingosine bear functional groups, -OH, -NH₂ and -OH respectively, which are structurally homologous with the three hydroxyl groups of glycerol.
- Carbon 4 to 18 in sphingosine and C-5 to 18 in phytosphingosine resembles that of a fatty acid.
- When a fatty acid is attached by an amide linkage to the -NH₂ group the resulting compound is a **ceramide** which is similar to diacyl glycerol
- **Ceramide** is the fundamental structural unit common to all sphingophospholipids
- **Sphingophospholipids** are found in the seeds of several plant species.
- There is a range of molecular species among the phospholipid sub groups which differ from one another in the fatty acid composition
- All the sub groups of phospholipids are found in plant photosynthetic tissue
- Animal phospholipids contain mostly fatty acids with chain length between 16 and 20. The predominant fatty acids are palmitic, stearic, oleic, linoleic and arachidonic.
- Plant leaf phospholipids have a more limited range with very few fatty acids greater than C-18.
- The approximate proportion of each phospholipid expressed as a percentage of the total phospholipid present is phosphatidyl choline, 45%; phosphatidyl ethanolamine, 10%;

- Trace amounts of phosphatidyl serine, phosphatidyl inositol, 8%; monophosphatidyl glycerol, 35%, diphosphatidylglycerol, 2%.
- The **diphosphatidyl glycerol** is present in the **inner mitochondrial membrane**.
- The phospholipids are only **minor components of seed lipids** in which triacylglycerol predominate.
- The **most abundant** mammalian phospholipid is **phosphatidyl choline**.
- The phospholipids carry an electrical charge and interact with water. They are called as **polar or hydrophilic molecules and also as amphiphilic molecules**.
- The sphingomyelins, the main sphingophospholipids of animals, are not present in plants.

Glycolipids and sulpholipids

- Glycolipids are structurally characterised by the presence of one or more monosaccharide residues and the **absence of a phosphate**.
- They are O-glycoside of either sphingosine or glycerol derivative. The monosaccharides commonly attached are **D-glucose, D-galactose or N-acetyl D-galactosamine**.
- Monogalactosyl diglycerides and digalactosyl diglycerides have been shown to be present in a wide variety of higher plant tissues
- The 3 position of 1, 2-diacylglycerol is linked to 6- sulpho-6-deoxy D-glucose by an **β-glycosidic bond in plant sulpholipid**
- The predominant fatty acid present in sulpholipid is **linolenic acid**.
- The sulpholipid is mostly present in **chloroplasts, predominantly in the membranes of thylakoid**.
- **Cerebrosides** are composed of a monosaccharide residue glycosidically linked to C-1 of an N-acylated sphingosine derivative.
- The monosaccharide is **D-glucose in plants and D-galactose in animals**.

Lipoprotein

- Protein molecules associated with triacylglycerol, cholesterol or phospholipids are called lipoproteins.
- Triacylglycerols derived from intestinal absorption or from the liver are not transported in the free form in circulating blood plasma, but move as **chylomicrons, as very low density lipoproteins (VLDL) or as free fatty acids (FFA) - albumin complexes**.

- Besides, two more physiologically important groups of lipoproteins are **low density lipoprotein (LDL) and high density lipoprotein (HDL)**.
- The major lipid components of **chylomicrons and VLDL are triacylglycerol**, whereas the predominant lipids in **LDL and HDL are cholesterol and phospholipid respectively**.
- The protein part of lipoprotein is known as **apoprotein**.
- Lipoproteins occur in milk, egg-yolk and also as **components of cell membranes**

Sterols

- The characteristic structure of sterol is their **steroid nucleus** consisting of four fused rings, three with six carbons (Phenanthrene) and one with five carbons (cyclopentane).
- This parent structure is known as **perhydro cyclopentano phenanthrene**.
- The steroid nucleus is almost **planar** and relatively rigid.
- Steroids with methyl groups attached to carbons 10 and 13 and 8-10 carbon atoms in the side chain at position 17, **an alcoholic group at position 3 and a double bond between carbons 5 and 6 are classified as sterols**.
- **Cholesterol** is the **most abundant sterol** in animals.
- Cholesterol is a **major component of animal plasma membranes** and occurs in lesser amounts in the membranes of their subcellular organelles.
- Its polar OH group gives it a **weak amphiphilic character**, whereas its fused ring system provides it with greater stability than other membrane lipids.
- Cholesterol is therefore an **important determinant of membrane properties**.
- It is also abundant in blood plasma lipoproteins where 70% of it is esterified to long chain fatty acids to form cholesteryl esters.
- Plants contain little cholesterol. Rather, the most common sterol components of their membranes are **stigmasterol and β -sitosterol** which differ from cholesterol only in their aliphatic side chains.
- Yeast and fungi have another sterol named **ergosterol** which has a double bond between C7 and C8.
- In animal system, cholesterol functions as a **precursor of various physiologically important compounds such as vitamin D, bile acids, female sex hormones and corticosteroids**.

- In plants, cholesterol functions as an intermediate compound in the **synthesis of various phytosteroids** such as **saponins, cardiac glycosides, phytoecdysteroids and brassinosteroids.**

Brassinosteroids

- In 1979, a **novel plant growth regulating steroidal substance** called **brassinolide** was isolated from rape (*Brassica napus*) pollen
- More than 24 compounds are known (designated as BR1, BR2).
- Pollen is the richest source.
- Brassinosterols are active at concentration much lower (nM to pM range) than those of other types of hormones.
- Brassinosterols elicit a pronounced **stem elongation response** in dwarf pea epicotyls, mung bean epicotyls that are sensitive also to gibberellic acids but not auxins.
- Brassinosteroids are thought by some to be a new class of plant hormones.
- The evidences are
 - i. They are widely distributed in the plant kingdom.
 - ii. They have an **effect at extremely low concentration.**
 - iii. They have a range of effects which are different from the other classes of plant hormones.
 - iv. They can be **applied to one part of the plant and transported to another where in very low amounts elicit a biological response.**
- They are widely distributed including dicots, monocots, gymnosperms and algae, and in various plant parts such as pollen, leaves, flowers, seeds, shoots and stems.
- Among the naturally occurring **brassinosteroids, brassinolide and castasterone** are considered to be the most important because of their wide distribution as well as their potent physiological activity.

Physiological effects of brassinosteroids

- i. Promotion of ethylene biosynthesis by **stimulating ACC synthase activity.**
- ii. Promote **elongation of vegetative tissue** in a wide variety of plants at very low concentration.
- iii. They are powerful inhibitors of root growth and development (via ethylene).

- iv. They have been shown to interfere with ecdysteroids at their site of action, and are thus the first true **antiecysteroids**.
- v. They enhance **resistance to chilling, disease, herbicides** and salt stress, promote germination and decrease fruit abortion and drop.

Practical application of BR

- Large scale field trials in China and Japan over a six year period have shown that **24-epibrassinolide**, an alternative to brassinolide, increased the production of agronomic and horticultural crops (**wheat, corn, tobacco, watermelon and cucumber**).
- **Environmental stresses** were also seem to be alleviated by treatment with brassinolide.

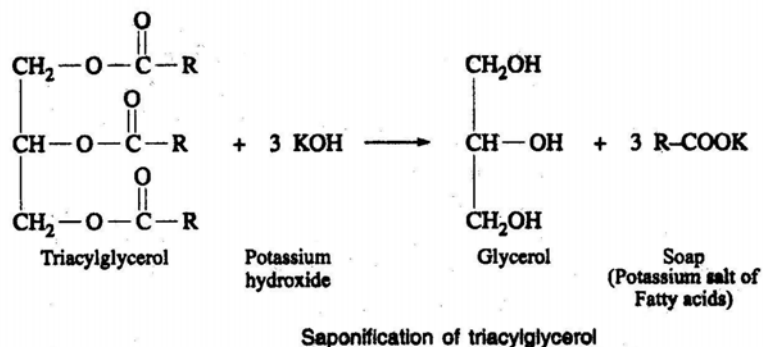
Properties of fat

Physical

- Fats are greasy to touch and leave an oily impression on paper.
- They are **insoluble in water** and soluble in organic solvents.
- Pure triacylglycerols are tasteless, odourless, colourless and neutral in reaction.
- They have **lesser specific gravity** (density) than water and therefore float in water.
- Though fats are insoluble in water, they can be broken down into minute droplets and dispersed in water. This is called **emulsification**.
- A satisfactory emulsion is one highly stable and contains very minute droplets with diameter less than 0.5 μ m.
- Examples of **naturally occurring emulsions are milk and yolk of egg**. But they are not mere fat droplets in water.
- They contain hydrophilic colloidal particles such as proteins, carbohydrates and phospholipids which act as stabilizing agents.
- **Emulsification greatly increases the surface area of the fat** and this is an essential requisite for digestion of fat in the intestine.

Chemical

- The most important chemical reaction of neutral fat is their hydrolysis to yield three molecules Alkali hydrolysis (saponification)The process of alkali hydrolysis is called '**saponification**'



- The **alkali salt of fatty acid** resulting from saponification is **soap**.
- The soaps we use for washing consists of Na or K salts of fatty acids like **palmitic, stearic and oleic acid**.
- The potassium soaps are soft and soluble whereas the sodium soaps are hard and less soluble in water.

Enzyme hydrolysis

- Hydrolysis of triacylglycerol may be accomplished enzymatically through the action of **lipases**.
- Lipases are widespread in both plants and animals.

Rancidity

- Development of disagreeable odour and taste in fat or oil upon storage is called **rancidity**.
- Rancidity reactions may be due to **hydrolysis of ester bonds** (hydrolytic rancidity) or due to **oxidation of unsaturated fatty acids** (oxidative rancidity).

Hydrolytic rancidity

- This involves **partial hydrolysis of the triacylglycerol** to mono and diacylglycerol.
- The hydrolysis is hastened by the presence of **moisture, warmth and lipases** present in fats or air.
- In fats like butter which contains a high percentage of volatile fatty acids, hydrolytic rancidity produces disagreeable odour and taste due to the liberation of the **volatile butyric acid**.
- Butter becomes rancid more easily in summer.

Oxidative rancidity

- The unsaturated fatty acids are oxidised at the double bonds to form **peroxides**, which then decompose to form aldehydes and acids of objectionable odour and taste.

Hydrogenation

- The **degree of unsaturation** of the fatty acids present in triacylglycerol determines whether a fat is liquid or solid at room temperature.
- The presence of more unsaturated fatty acids **lower the melting point**.
- The presence of highly unsaturated fatty acids makes the oil more susceptible to **oxidative deterioration**.
- The objective of hydrogenation is to **reduce the degree of unsaturation and to increase the melting point of the oil**.
- The oil can be selectively hydrogenated by careful choice of **catalyst and temperature**.
- **Hydrogenation of unsaturated fats in the presence of a catalyst** is known as **hardening**.
- Normally the process of hydrogenation is partial so as to get desired characteristics and to avoid products with high melting points.
- Hydrogenation is carried out in a closed container in the presence of **finely powdered catalyst (0.05 - 0.2% of nickel) at temperature as high as 180°C**.
- The catalyst is usually removed by **filtration**.
- During hydrogenation process a proportion of the **cis double bonds are isomerized to trans double bonds** and there is also **migration of double bonds**.
- The hydrogenation process has made it possible to extend the food uses of a number of vegetable oils and marine oils whose melting points are too low.

Constants of fats and oils

- Since fats and oils form essential nutrient of human diet, it is necessary to **identify a pure fat or to determine the proportion of different types of fat or oil mixed as adulterant in edible oils and fats like butter and ghee**.
- With an adequate knowledge of the characteristic composition of fats or oils, it is possible to identify the fat or oil under investigation.
- **The chemical constants also give an idea about the nature of fatty acids present in fats or oils**.

- Even though **gas chromatographic method** is available to identify and quantify the fatty acids present in fat or oil, the physical and chemical constants are still used in routine public health laboratories where such sophisticated facilities are lacking.

Lecture 10

Physical constants

i. Specific gravity

- Since different oils have different specific gravity, any variation from normal value shows mixture of oils.

ii. Refractive index

- Fats have **definite angles of refraction**.
- Variation from the normal value indicates adulteration of fats or oils.

iii. Solidification point or setting point

- Solidification point is **the temperature at which the fat after being melted, sets back to solid or just solidifies**.
- Each fat has a specific solidification point.

Chemical constants

i. Saponification number

- It is defined as **milligrams of KOH required to saponify 1 gm of fat or oil**.
- Saponification number is **high for fat or oil containing low molecular weight** or short chain fatty acids and vice versa.
- It gives a clue about the molecular weight and size of the fatty acid in the fat or oil.

ii. Iodine Number

- It is defined as the **number of grams of iodine taken up by 100 grams of fat or oil**.
- Iodine number is a **measure of the degree of unsaturation of the fatty acid**.
- Since the quantity of the iodine absorbed by the fat or oil can be measured accurately, it is possible to calculate the relative unsaturation of fats or oil.

iii. Reichert-Meisel number (R.M.number)

- This is a **measure of the volatile soluble fatty acids**.
- It is confined to butter and coconut oil.
- It is defined as **the number of millilitres of 0.1 N alkali required to neutralise the soluble volatile fatty acids contained in 5 gm of fat**.
- The determination of Reichert-Meisel number is important to the food chemist because it helps to **detect the adulteration in butter and ghee**.

- Reichert-Meisel value is reduced when animal fat is used as adulterant in butter or ghee.

iv. Polanski number

- Ghee may be adulterated by the addition of **insoluble, non-volatile fatty acids (by addition of animal fat)**.
- This can be tested by finding out the Polanski number.
- It is defined as **the number of millilitres of 0.1 N potassium hydroxide solution required to neutralise the insoluble fatty acids (not volatile with steam distillation) obtained from 5 gm of fat.**

v. Acetyl number

- It is defined as **the amount in millilitres of potassium hydroxide solution required to neutralise the acetic acid obtained by saponification of 1 gm of fat or oil after acetylation.**
- Some fatty acids contain **hydroxyl groups. In order to determine the proportion of these, they are acetylated by means of acetic anhydride.**
- This results in the introduction of acetyl groups in the place of free hydroxyl groups.
- The acetic acid in combination with fat can be determined by titration of the liberated acetic acid from acetylated fat or oil with standard alkali.
- Acetyl number is thus a **measure of the number of hydroxyl groups present in fat or oil.**

vi. Acid number

- It is defined as **the milligram of potassium hydroxide required to neutralise the free fatty acids present in one gram of fat or oil.**
- Acid number **indicates the amount of free fatty acids present in fat or oil.**
- The **free fatty acid content increases with age of the fat or oil.**

Molecular aggregation of phospholipids

- Glycerophospholipids are virtually insoluble in water.
- Depending on the precise conditions and the nature of lipids used, **three types of lipid aggregates can form when amphipathic lipids are mixed with water.**

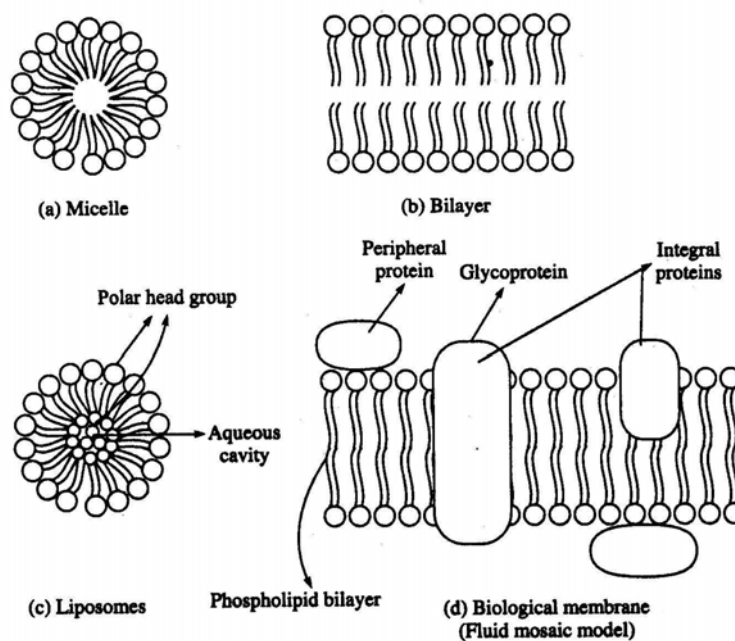
Micelles

- Free fatty acids, lysophospholipids and sodium dodecyl sulphate (SDS) form micelle.

- **Micelles** are relatively small spherical structures involving a few dozen to few thousand molecules arranged so that their **hydrophobic regions** aggregate in the interior excluding water and their **hydrophilic head groups are at the surface in contact with water**.
- This molecular arrangement eliminates unfavourable contacts between water and the hydrophobic tails

Bilayer

- A second type of lipid aggregate in water is the bilayer in which two lipid monolayers combine to form a **two dimensional sheet**.
 - The hydrophobic portions in each monolayer interact excluding water.
 - The hydrophilic head groups interact with water at the two surfaces of the bilayer
- lipid bilayers form the structural basis of biological membranes



Structures of micelle, bilayer, liposome and biological membrane

Liposomes

- The third type of lipid aggregate is formed **when a lipid bilayer folds back on itself to form a hollow sphere** called a liposome or vesicle.
- These bilayer vesicles enclose water creating a separate aqueous compartment

Biological membranes

- Proteins and polar lipids account for mass of biological membranes.

- The relative proportions of protein and lipid differ in different membranes, reflecting the diversity of biological roles.
- **Amphipathic molecules** form a lipid bilayer with the **non polar region of lipids facing outward**.
- In this lipid bilayer, globular proteins are embedded at regular intervals held by hydrophobic interactions.
- Some proteins protrude from one or other face of the membrane (**peripheral proteins**); **some span its entire width (integral proteins)**.
- The individual lipid and protein subunits in a membrane form a **fluid mosaic**
- The membrane is fluid because the interactions among lipids, between lipids and proteins are non covalent, leaving individual lipid and protein molecules free to move laterally.
- One of the key functions of a membrane is to **control the passage of substances across it**.
- They are said to be **selectively permeable**. The different membranes of the cell have different selective permeabilities.

Lecture 11

AMINO ACIDS AND PROTEINS

The word "Protein" was coined by **J.J. Berzelius** in 1838 and was derived from the Greek word "**Proteios**" meaning the 'first rank'.

- Proteins are macromolecular polymers composed of **amino acids** as the basic unit linked by peptide bonds.
- Amino acids are the **fundamental structural units of all proteins**.
- These biopolymers contain carbon, hydrogen, oxygen, nitrogen and sulphur.
- The elementary composition of most proteins is very similar; approximate percentages are C=50-55, H=6-8, O=20-23, N=15-18 and S=Traces

Occurrence

- Proteins are found in all **living cells**.
- They form essential **constituent of protoplasm, cell membrane and nuclear material**.
- They may be present as simple proteins or complexes with lipids or nucleic acids.
- Proteins from different tissues such as **muscle, bone, brain, blood and other biological fluids** differ in composition and properties.
- In cereal and leguminous plants, **seeds** contain comparatively higher amounts of protein than stem, leaves and flowers.
- Tuber crops usually contain less amounts of protein in all parts.
- **Enzymes** are specialized proteins with **catalytic activities** and are present in all living organisms.
- Proteins serve as **regulators of metabolic reactions**, directly as components of enzymes and indirectly in the form of chemical messengers known as **hormones** as well as receptors for hormones.
- They **regulate and integrate** the numerous physiological and metabolic processes in the body.
- Proteins are the **center of action** in many biological processes.

Amino acids

All proteins are formed from **20** different **amino acids**. All the amino acids have trivial or common names based on the source from which they were first isolated or based on their properties. For eg.

Asparagine was named so, as it was isolated from asparagus and **glycine** was so named because of its sweet taste (Greek: 'glykos' meaning sweet).

All the 20 amino acids, except **proline**, found in proteins have an amino group and a carboxyl group attached to the same carbon atom, namely the α -**carbon**. They differ only in the side chains (R groups). The 20 amino acids found in proteins are referred as the **standard or normal or protein amino acids**.

There are many other amino acids found in nature but do not occur in proteins. They are referred as **non-protein amino acids**.

Classification of protein amino acids

The protein amino acids are classified according to the **chemical nature** of their R groups as **aliphatic, aromatic, heterocyclic and sulphur containing amino acids**. More meaningful classification of amino acids is based on the **polarity of the R groups**. The polarity of the R groups varies widely from totally non-polar to highly polar. The 20 amino acids are classified into four main classes whose structures, three-letter and one-letter symbols are given below

a) Amino acids with non-polar or hydrophobic, aliphatic R groups

- This group of amino acids includes **glycine, alanine, valine, leucine, isoleucine and proline**. The hydrocarbon R groups are non-polar and hydrophobic.
- The side chains of alanine, valine, leucine and isoleucine are important in promoting hydrophobic interactions within protein structures.
- The minimal steric hindrance of the glycine side chain (hydrogen) allows more flexibility than other amino acids.
- On the other hand, the imino group of proline is held in a rigid conformation and reduces the structural flexibility of the protein.

b) Amino acids with non-polar aromatic R groups

- This group includes **phenylalanine, tyrosine and tryptophan** .
- All these amino acids participate in **hydrophobic interactions**, which is stronger than aliphatic R groups because of stacking one another.
- Tyrosine and tryptophan are more polar than phenylalanine due to the presence of hydroxyl group in tyrosine and nitrogen in the indole ring of tryptophan.
- The absorption of ultraviolet (UV) light at 280 nm by tyrosine, tryptophan and to a lesser extent by phenylalanine is responsible for the characteristic strong absorbance of light by proteins. This property is exploited in the characterization and quantification of proteins.

c) Amino acids with polar, uncharged R groups

- This group of amino acids includes **serine, threonine, cysteine, methionine, asparagine and glutamine** .
- The hydroxyl group of **serine and threonine**, the sulphur atom of **cysteine and methionine** and the amide group of **asparagine and glutamine**, contribute to the polarity.
- The R groups of these amino acids are more hydrophilic than the non-polar amino acids.

d) Amino acids with charged R groups

- **Acidic:** The two amino acids with acidic R groups are **aspartic and glutamic acids**. These amino acids have a net negative charge at pH 7.0.
- **Basic:** This group includes **lysine, arginine and histidine** . The R groups have a net positive charge at pH 7.0. The **lysine** has a second α -amino group; **arginine** has a positively charged guanidino group; and **histidine** has an imidazole group.

Properties of amino acids

Physical

- Amino acids are white crystalline substances.
- Most of them are **soluble in water** and insoluble in non-polar organic solvents (e.g., chloroform and ether).
- Aliphatic and aromatic amino acids particularly those having several carbon atoms have limited solubility in water but readily soluble in polar organic solvents.

- They have **high melting points** varying from 200-300°C or even more.
- They are tasteless, sweet or bitter.
- Some are having good flavour. **Sodium glutamate** is a valuable flavouring agent and is used in the preparation of certain dishes and sauces.

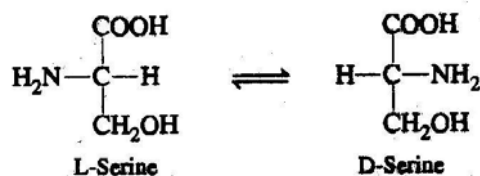
Amphoteric nature of amino acids

- Amino acids are **amphoteric** compounds, as they contain **both acidic (COOH) and basic (NH₂) groups**.
- They can react with both alkalies and acids to form salts.
- In **acid solution** amino acids carry **positive charges** and hence they move towards cathode in an electric field.
- In **alkaline solution**, the amino acids carry negative charges and therefore move towards anode.
- When an amino acid is dissolved in water, it exists as **inner salt** carrying both positive and negative charges. This occurs as a result of dissociation of carboxyl group to release the H⁺ ion, which passes from the carboxyl to the amino group. The amino acids possessing **both positive and negative charges** are called **zwitterions**.
- The zwitterion reacts as an **acid** with a base by **liberating a proton (H⁺)** from the NH₃⁺ group and as a result possesses a **net negative charge**.
- On the other hand, zwitterions reacts with an acid **as base, combining with the proton (H⁺)** of the acid resulting in the formation of a compound having a **net positive charge**. These reactions are reversible.
- The **pH** at which the amino acid has no tendency to move either towards positive or negative electrode is called **isoelectric pH or isoelectric point**.
- At isoelectric pH, the amino acid molecule bears a **net charge of zero**.

Isomerism

- All amino acids except proline, found in protein are **α-amino acids** because NH₂ group is attached to the **α-carbon** atom, which is next to the COOH group.
- Examination of the structure of amino acids reveals that **except glycine**, all other amino acids possess **asymmetric carbon** atom at the alpha position.
- Because of the presence of asymmetric carbon atom, amino acids exist in **optically active forms**.

- For example, in the steric configuration for serine, the carboxyl group is written on the **top**, while the amino group is written to the **left** in the case of L-serine and to the right in the case of D-serine. This distinction will hold good for all the amino acids having asymmetric carbon atoms.



Structure of D- and L-Serine

- 'D' and 'L' do not refer to the optical rotation, but to the steric configuration of amino group to the right and left side of the carboxyl group.
- The **direction of optical rotation** of amino acid is indicated by the symbol **+ or -**, which follows the designation 'D' or 'L'.
- The steric configuration and optical rotation of an amino acid may be simultaneously expressed as D (+) or D (-) and L (+) or L (-).
- L-forms are more common than D-forms and most of the **naturally occurring amino acids** are **L-amino acids**.

Chemical properties

a) Reactions due to amino group

Reaction with formaldehyde (Formal titration)

- Amino acid exists as zwitterion in aqueous medium. If an amino acid solution is treated with excess of **neutralized formaldehyde solution**, the amino group combines with formaldehyde forming **dimethylol amino acid** which is an amino acid formaldehyde complex.
- Hence the **amino group is protected** and the proton released is titrated against alkali.
- This method is used to find out the **amount of total free amino acids** in plant samples.

Reaction with nitrous acid

Nitrous acid reacts with the amino group of amino acids to form the corresponding hydroxyacids and liberate nitrogen gas.

Reaction with ninhydrin

- Ninhydrin is a **strong oxidizing agent**.
- When a solution of amino acid is boiled with ninhydrin, the amino acid is **oxidatively deaminated** to produce ammonia and a ketoacid.
- The **keto acid** is decarboxylated to produce an **aldehyde** with one carbon atom less than the parent amino acid.
- The net reaction is that ninhydrin oxidatively deaminates and decarboxylates amino acids to CO_2 , NH_3 and an aldehyde.
- The reduced ninhydrin then reacts with the liberated ammonia and another molecule of intact ninhydrin to produce a purple coloured compound known as **Ruhemann's purple**.
- This ninhydrin reaction is employed in the **quantitative determination of amino acids**.
- Proteins and peptides that have free amino group(s) (in the side chain) will also react and give colour with ninhydrin.

b) Reactions due to carboxyl group

Decarboxylation

- The carboxyl group of amino acids is **decarboxylated** to yield the corresponding **amines**. Thus, the vasoconstrictor agent, **histamine** is produced from histidine.
- Histamine stimulates the **flow of gastric juice into the stomach** and the **dilation and constriction of specific blood vessels**.
- Excess reaction to histamine causes the **symptoms of asthma** and various **allergic reactions**.

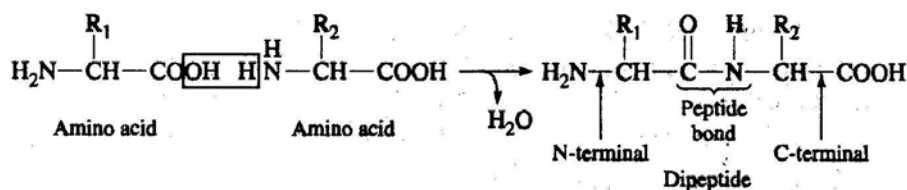
Essential amino acids

- Most of the prokaryotic and many eukaryotic organisms (plants) are capable of synthesizing all the amino acids present in the protein. But higher animals including man possess this ability only for certain amino acids.
- The amino acids, which are needed for normal functioning of the body but **cannot be synthesized from metabolic intermediates**, are called **essential amino acids**.
- These must be obtained from the **diet** and a deficiency in any one of the amino acids prevents growth and may even cause death.

- **Methionine, Arginine, Threonine, Tryptophan, Valine, Isoleucine, Leucine, Phenylalanine, Histidine, and Lysine** are the essential amino acids (Remember **MATTVILPHLy**).

Peptide

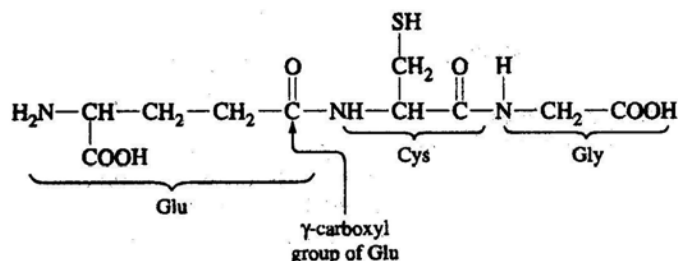
- Amino acids are linked together by formation of **covalent bonds**.
- The covalent bond is formed between the **□-carboxyl group of one amino acid and the □-amino group of the next amino acid**.
- The bond so formed between the carboxyl and the amino groups, after elimination of a water molecule is called as a **peptide bond** and the compound formed is a **peptide**.
- The peptide formed between two amino acids is a dipeptide; three amino acids is a tripeptide; few amino acids are an oligopeptide and many amino acids is a polypeptide.
- In writing the peptide structure, the amino terminal (N-terminal) amino acid is written first and carboxyl terminal (C-terminal) amino acid written last.



Formation of peptide from amino acids

Peptides of physiological interest

- **Glutathione** is a commonly occurring tripeptide (**□-glutamyl cysteinyl glycine**) in many living organisms.



Structure of glutathione, a tripeptide

- It has a role in **detoxification of toxic compounds** in physiological system.

- The nanapeptides (nine amino acids), oxytocin and vasopressin are important animal peptide hormones.
- **Oxytocin** induces labor in pregnant women and controls contraction of uterine muscle.
- **Vasopressin** plays a role in control of blood pressure by regulating the contraction of smooth muscles.
- A dipeptide **L-aspartyl-L-phenylalanine**, is of commercial importance. This dipeptide is about 200 times sweeter than cane sugar. The methyl ester of this dipeptide is called as **aspartame** and marketed as an artificial sweetener for **diabetics**.

Lecture 12

Proteins

Classification of protein

Proteins are classified based on their

- Solubility and composition
- Function
- Shape & size

A. Classification based on solubility and composition

According to this classification, proteins are divided into three main groups as **simple, conjugated and derived proteins.**

(i) Simple proteins

- Simple proteins yield on hydrolysis, **only amino acids.**
- These proteins are further classified based on their solubility in different solvents as well as their heat coagulability.

Albumins

- Albumins are readily soluble in water, dilute acids and alkalies
- coagulated by heat.
- Seed proteins contain albumin in lesser quantities.
- Albumins may be precipitated out from solution using high salt concentration, a process called '**salting out**'.
- They are deficient in **glycine.**
- Serum albumin and ovalbumin (egg white) are examples.

Globulins

- Globulins are **insoluble or sparingly soluble in water**, but their solubility is greatly increased by the addition of neutral salts such as sodium chloride. These proteins are coagulated by heat.
- They are deficient in **methionine.**
- Serum globulin, fibrinogen, myosin of muscle and globulins of pulses are examples.

Prolamins

- Prolamins are insoluble in water but soluble in 70-80% aqueous alcohol.
- Upon hydrolysis they yield much proline and amide nitrogen, hence the name prolamins.

- They are deficient in **lysine**.
- Gliadin of wheat and zein of corn are examples of prolamins.

Glutelins

- Glutelins are **insoluble in water** and **absolute alcohol but soluble in dilute alkalis and acids**.
- They are **plant proteins** e.g., glutenin of wheat.

Histones

- Histones are small and stable basic proteins
- They contain fairly large amounts of basic amino acid, **histidine**.
- They are soluble in water, but insoluble in ammonium hydroxide.
- They are not readily coagulated by heat.
- They occur in **globin of hemoglobin and nucleoproteins**.

Protamines

- Protamines are the simplest of the proteins.
- They are **soluble in water and are not coagulated by heat**.
- They are basic in nature due to the presence of large quantities of **arginine**.
- Protamines are found in association with nucleic acid in the sperm cells of certain fish.
- **Tyrosine and tryptophan** are usually absent in protamines.

Albuminoids

- These are **characterized by great stability and insolubility in water and salt solutions**.
- These are called albuminoids because they are essentially similar to albumin and globulins.
- They are highly resistant to proteolytic enzymes.
- They are fibrous in nature and form most of the supporting structures of animals.
- They occur as chief constituent of exoskeleton structure such as hair, horn and nails.

ii. Conjugated or compound proteins

- These are **simple proteins combined with some non-protein substances known as prosthetic groups**.
- The nature of the non-protein or prosthetic groups is the basis for the sub classification of conjugated proteins.

Nucleoproteins

- Nucleoproteins are simple basic proteins (protamines or histones) in salt combination with nucleic acids as the prosthetic group.
- They are the important constituents of nuclei and chromatin.

Mucoproteins

- These proteins are composed of **simple proteins in combination with carbohydrates** like **mucopolysaccharides**, which include **hyaluronic acid and chondroitin sulphates**.
- On hydrolysis, mucopolysaccharides yield more than 4% of amino-sugars, hexosamine and uronic acid e.g., **ovomuroid** from egg white.
- Soluble mucoproteins are neither readily denatured by heat nor easily precipitated by common protein precipitants like trichloroacetic acid or picric acid.
- The term **glycoproteins** is restricted to those proteins that contain small amounts of carbohydrate usually less than 4% hexosamine.

Chromoproteins

- These are proteins containing **coloured prosthetic groups** e.g., haemoglobin, flavoprotein and cytochrome.

Lipoproteins

- These are proteins conjugated with **lipids such as neutral fat, phospholipids and cholesterol**

Metalloproteins

- These are **metal-binding proteins**.
- A β -globulin, termed **transferrin** is capable of combining with **iron, copper and zinc**.
- This protein constitutes 3% of the total plasma protein.
- Another example is **ceruloplasmin**, which contains **copper**.

Phosphoproteins

- These are proteins containing **phosphoric acid**.
- Phosphoric acid is linked to the hydroxyl group of certain amino acids like serine in the protein e.g., casein of milk.

iii. Derived proteins

- These are proteins derived by partial to complete hydrolysis from the simple or conjugated proteins by the action of acids, alkalies or enzymes.

- They include two types of derivatives, **primary-derived proteins and secondary-derived proteins.**

Primary-derived proteins

- These protein derivatives are formed by processes causing only slight changes in the protein molecule and its properties.
- There is little or no hydrolytic cleavage of peptide bonds.

Proteans

- Proteans are insoluble products formed by the action of water, dilute acids and enzymes.
- These are particularly formed from globulins but are insoluble in dilute salt solutions
- e.g., **myosan from myosin, fibrin from fibrinogen.**

Metaproteins

- These are formed by the action of acids and alkalies upon protein.
- They are insoluble in neutral solvents.

Coagulated proteins

- Coagulated proteins are insoluble products formed by the action of heat or alcohol on natural proteins
- e.g., cooked meat and cooked albumin.

Secondary-derived proteins

- These proteins are formed in the progressive hydrolytic cleavage of the peptide bonds of protein molecule.
- They are roughly grouped into **proteoses, peptones and peptides according to average molecular weight.**
- Proteoses are hydrolytic products of proteins, which are soluble in water and are not coagulated by heat.
- Peptones are hydrolytic products, which have simpler structure than proteoses.
- They are soluble in water and are not coagulated by heat.
- Peptides are composed of relatively few amino acids.
- They are water-soluble and not coagulated by heat.
- The complete hydrolytic decomposition of the natural protein molecule into amino acids generally progresses through successive stages as follows:

Protein ----> Protean -----> Metaprotein
Proteoses -----> Peptones -----> Peptides -----> amino acids

b. Classification of proteins based on function

Proteins are classified based on their functions as:

Catalytic proteins – Enzymes

- The most striking characteristic feature of these proteins is their ability to **function within the living cells as biocatalysts.**
- These **biocatalysts** are called as enzymes.
- Enzymes represent the largest class.
- Nearly 2000 different kinds of enzymes are known, each catalyzing a different kind of reaction.
- They **enhance the reaction rates** a million fold.

Regulatory proteins - Hormones

- These are polypeptides and small proteins found in relatively lower concentrations in animal kingdom but **play highly important regulatory role in maintaining order in complex metabolic reactions**
- e.g., growth hormone, insulin etc.

Protective proteins - Antibodies

- These proteins have **protective defense function.**
- These proteins combine with foreign protein and other substances and fight against certain diseases.
- e.g., immunoglobulin.
- These proteins are produced in the spleen and lymphatic cells in response to foreign substances called antigen.
- The newly formed protein is called **antibody** which specifically combines with the antigen which triggered its synthesis thereby prevents the development of diseases.
- **Fibrin** present in the **blood** is also a protective protein.

Storage proteins

- It is a major class of proteins which has the function of **storing amino acids as nutrients and as building blocks for the growing embryo.**
- Storage proteins are **source of essential amino acids**, which cannot be synthesized by human beings.
- The major storage protein in pulses is **globulins and prolamins in cereals.**
- In rice the major storage protein is glutelins.
- Albumin of egg and casein of milk are also storage proteins.

Transport proteins

- Some proteins are capable of binding and transporting specific types of molecules through blood.
- **Haemoglobin** is a conjugated protein composed of colourless basic protein, the **globin** and **ferroprotoporphyrin or haem**.
- It has the capacity to bind with oxygen and transport through blood to various tissues.
- **Myoglobin**, a related protein, transports oxygen in muscle.
- **Lipids** bind to serum proteins like albumin and transported as lipoproteins in the blood.

Toxic proteins

- Some of the proteins are toxic in nature.
- **Ricin** present in **castor bean** is extremely toxic to higher animals in very small amounts.
- **Enzyme inhibitors such as trypsin inhibitor** bind to digestive enzyme and prevent the availability of the protein.
- **Lectin**, a toxic protein present in legumes, **agglutinates red blood cells**.
- A bacterial toxin causes cholera, which is a protein.
- **Snake venom** is protein in nature.

Structural proteins

- These proteins serve as **structural materials or as important components of extra cellular fluid**.
- Examples of structural proteins are **myosin of muscles, keratin of skin and hair and collagen of connective tissue**.
- Carbohydrates, fats, minerals and other cellular components are organized around such structural proteins that form the molecular framework of living material.

Contractile proteins

- Proteins like **actin and myosin** function as essential elements in contractile system of skeletal muscle.

Secretary proteins

- **Fibroin** is a protein secreted by spiders and silkworms to form webs and cocoons.

Exotic proteins

- Antarctic fishes live in -1.9°C waters, well below the temperature at which their blood is expected to freeze.
- These fishes are prevented from freezing by **antifreeze glycoproteins** present in their body.

C. Classification based on size and shape

Based on size and shape, the proteins are also subdivided into **globular and fibrous proteins**.

- **Globular proteins** are mostly water-soluble and fragile in nature e.g., **enzymes, hormones and antibodies**.
- **Fibrous proteins** are tough and water-insoluble.
- They are used to build a variety of materials that support and protect specific tissues, e.g., skin, hair, fingernails and keratin

Lecture 13 - 14

Conformation of proteins

Conformation of a protein refers to the **three-dimensional structure** in its **native state**. There are many different possible conformations for a molecule as large as a protein. A protein can perform its function only when it is in its **native condition**. Due to the complexity of three-dimensional structures, the structure of protein is discussed at **different levels of its organization**.

Four levels of structural organization can be distinguished in proteins:

1. **Primary**
2. **Secondary**
3. **Tertiary**
4. **Quaternary**

Primary structure

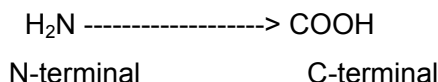
- Primary structure of protein refers to the **number of amino acids and the order in which they are covalently linked together**.
- It also refers to the location of disulfide bridges, if there are any, in a polypeptide chain.
- The peptide bond is **covalent** in nature, **quite stable** and referred as **backbone of the protein**.
- They can be disrupted by chemical or enzymatic hydrolysis but are not directly influenced by salt concentration, change in pH or solvent.
- **Frederick Sanger** in 1953 determined the complete amino acid sequence of insulin for the first time.

The important steps involved in determining the primary structure of protein are

- Determination of number of (chemically different) polypeptide chains or subunits in the protein.
- Separation of polypeptide chains if more than one are present in a protein.
- Determination of the amino acid sequence of the subunits.
- Elucidation of the position of the disulfide bonds, if any, between and within the subunits.

1. Determination of number of polypeptides or subunits

Determination of the number of C-terminal or N-terminal amino acids will indicate the number of polypeptides in a protein.



N-terminal identification

- **Fluoro dinitro benzene (FDNB)**, known as Sanger's reagent, was used to identify the N-terminal amino acid.
- This reagent was replaced by **dansyl chloride and Edman's reagent (phenyl isothiocyanate, PITC)**.
- Edman's reagent is also used to determine the amino acid sequence of a polypeptide chain from the N-terminal by subjecting the polypeptide to repeated cycles of Edman degradation.
- After every cycle, the newly liberated **phenylthiohydantoin (PTH) amino acid** was identified
- The sequence of peptides containing 30-40 amino acids can be determined using a sequencer by adopting the Edman's degradation method.

C-terminal identification

C-terminal amino acid can be determined by methods similar to those used for the N-terminal acid.

- **Hydrazine** is used to find out the C-terminal amino acid.
- It reacts with the **carbonyl group of each peptide bond** except C-terminal amino acid.
- The bond is cleaved and each amino acid derivative is released as the hydrazide derivative (hydrazinolysis).
- Since the carboxyl group of C-terminal amino acid is not involved in a peptide bond, it remains in the mixture as the only unmodified amino acid
- After chromatographic separation and comparison with the standards, the C-terminal amino acid can be identified.
- Carboxypeptidases are used for enzymic determination of the C-terminal amino acid.

Separation and purification of polypeptide chains

- Determination of C-terminal and/or N-terminal amino acids reveals the presence of one or more polypeptide chains in a protein.
- If the protein contains more than one polypeptide chain, separation of polypeptide chain is essential.

- If the polypeptide chains are connected by disulfide bond, they are cleaved to separate the individual peptide chains.
- The polypeptide is treated with **2-mercaptoethanol** (HS-CH₂-CH₂OH) so that reductive cleavage occurs and the polypeptide chains are separated.
- The resulting free-SH groups are usually alkylated by treatment with **iodoacetic acid**
- After cleaving the disulfide links using mercaptoethanol, subunits are dissociated using denaturing agents such as **urea or guanidinium ion or detergents such as sodium dodecyl sulphate (SDS)**.
- The dissociated subunits are then separated using ion exchange or gel filtration chromatographic method.

Amino acid sequencing of polypeptides

- The amino acid sequence in polypeptides with 30-40 amino acids can be determined by Edman reaction.
- For polypeptides containing **more than 40 amino acids**, both enzymatic and chemical methods are employed to break polypeptide chains into smaller peptides.
- The enzyme, **trypsin** hydrolyses the peptide bond on the **carboxyl side of the basic amino acid residues of lysine or arginine**.
- The chemical reagent, **cyanogens bromide** cleaves peptide bond on the **carboxyl side of methionine residues**.
- The hydrolyzed peptides are separated and the amino acid sequence is determined by Edman reaction.
- The hydrolysis of the original polypeptide by two different methods separately gives overlapping regions, from which the sequence is derived

Secondary structure

- Secondary structure refers to the **steric relationship of amino acids that are close to one another in the linear sequence**.
- The folding of a linear polypeptide chain occurs to form a specific coiled structure.
- Such coiling or folding is maintained by **hydrogen bonds** and hydrogen bond is the only bond responsible for secondary structure.
- X-ray studies of several polypeptides by **Linus Pauling and Robert Corey** revealed that the peptide group has a **rigid, planar structure** which is a

consequence of **resonance interactions** that give the peptide bond a 40% double bond character.

- Peptide groups mostly assume the **transconformation** in which successive C₂ atoms are on opposite sides of peptide bond joining them.
- The cis configuration creates steric interference.
- If a polypeptide chain is twisted by the same amount each of its C atoms, it assumes a helical conformation

Helix structure

- The α -helix is the **most stable** arrangement of polypeptides
- The helix structure of proteins is stabilized by **intramolecular hydrogen bonding**.
- In this structure, **hydrogen bonds are formed between the C=O group of one peptide bond and the N-H group of another after 3 amino acid units**.
- The polypeptide chain constituted by **L-amino acids form a right-handed helix**, whereas the polypeptide chains made up of D-amino acids form a left-handed helix.
- In the α -helical conformation, **all the side chains lie outside the helix** whereas C, N, O and H of the peptide bond lie in the same plane.
- Certain amino acids tend to **disrupt the α -helix**. Among these are **proline** (the N atoms is part of the rigid ring and no rotation of the N-C bond can occur) and **amino acid with charged or bulk R groups** that either electrostatically or physically interferes with helix formation.

The β -pleated sheet structure

- **Pauling and Corey** also proposed a second ordered structure, the β -pleated sheet for polypeptide.
- This structure is a **result of intermolecular hydrogen bonding** between the polypeptide chains to form a **sheet like arrangement**.
- There are two ways in which proteins chains can form the pleated sheet structure.
- One is with the **chains running in the same direction** i.e. the -COOH or NH₂ ends of the polypeptide chains lying all at the top or all at the bottom of the sheet. This is called **parallel pleated-sheet structure**.
- In another type, known as **antiparallel β -pleated sheet structure**, the polypeptide chains alternate in such a way that the -COOH end of the one

polypeptide is next to the $-NH_2$ end of the other i.e. polypeptide chains run in opposite directions.

The random coil

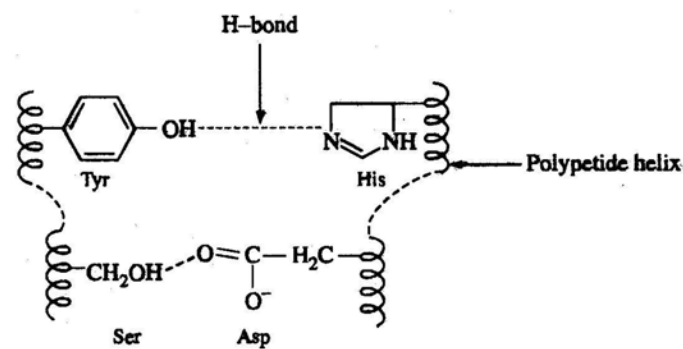
- Regions of proteins that are **not identifiably organized as helices or pleated sheets** are said to be present in **random coil conformation**.
- Considerable portion of the protein may be present in this conformation.
- The term 'random' is unfortunate which imply less biological significance than more highly repeating regions.
- But in terms of biological function, the regions of random coil are of equal importance to those of helix and pleated sheet.

Tertiary structure

- Tertiary structure refers to the **steric relationship of amino acid residues that are far apart in the linear sequence**.
- This leads to the twisting of polypeptide chains into **specific loops and bends** which are maintained chiefly by five kinds of bonds.

Hydrogen bonds

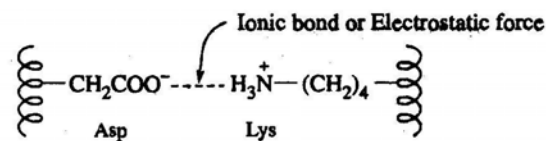
- Hydrogen bonds are formed between the side chain (R group) of amino acids having a hydrogen donor group and an acceptor group



Hydrogen bonds in polypeptide chain

Salt-linkages (electrostatic forces; ionic bonds)

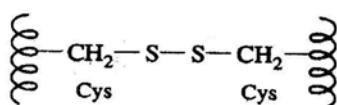
- Salt linkages are due to the interaction between amino groups of basic amino acids and the carboxyl group of acidic amino acids present in the R group



Electrostatic forces in polypeptide chain

Disulfide bonds (S-S linkages)

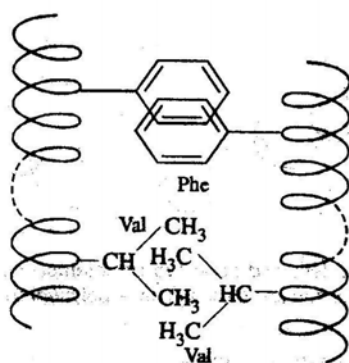
- The S-S linkages are formed by the oxidation of sulfhydryl (-SH) group of two cysteine side chains



S-S linkages in polypeptide chain

Hydrophobic bonds

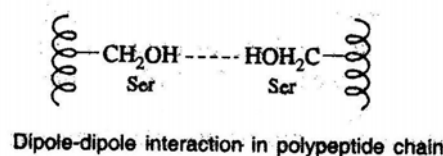
- Hydrophobic bonds are formed as a result of interaction between non-polar side chains



Hydrophobic bonds in polypeptide chain

Dipole-dipole interaction

- This interaction occurs between **polar unionized side chains**
- The folding of a polypeptide chain due to different covalent and non-covalent interactions is shown below.
- Out of the above bonds, **the disulfide bond (covalent bond) is the strongest and cannot be affected by solvent, pH, temperature and salts** whereas the above conditions.
- The disulfide bond can be split and reformed by oxidation/reduction respectively
- The tertiary structure gains special importance in the **case of enzymes**.



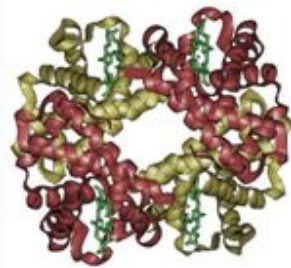
Domain

- Domains are **structurally independent units** that have the characteristics of a small globular protein.
- Domains often have a specific function such as the **binding of a small molecule**.
- A long peptide strand of a protein will often fold into **multiple, compact semiindependent folded regions or domains**.
- Each domain having a **characteristic spherical geometry** with a hydrophobic core and polar surface very much like the tertiary structure of a whole globular protein
- The domains of a multidomain protein are often interconnected by a segment of polypeptide chain lacking regular secondary structure.
- In enzymes with more than one substrate or **allosteric effector sites the different binding sites are often located in different domains**.
- In multifunctional proteins, the different domains perform different tasks.

Quaternary structure

- Proteins that have **more than one subunit or polypeptide chains** will exhibit quaternary structure.
- Quaternary structure refers to a **functional protein aggregate (organization)** formed by interpolypeptide linkage of subunits or polypeptide chains.
- These subunits are held together by **noncovalent surface interaction** between the polar side chains.
- Proteins formed like above are termed **oligomers** and the individual polypeptide chains are variously termed protomers, monomers or subunits.
- The most common oligomeric proteins contain two or four protomers and are termed dimers or tetramers, respectively.
- **Myoglobin** has no quaternary structure since, it is composed of a single polypeptide chain.

- **Hemoglobin molecule**, which consists of **four separate polypeptide chains**, exhibits quaternary structure.



A schematic of hemoglobin.

The ribbon parts represent the protein globin; the four green parts are the heme groups.

- Quaternary structure may influence the activity of enzymes.
- Some enzymes are active only in their quaternary state and become inactive when split into smaller units.
- Other enzymes are inactive in the quaternary state and are activated only when they are dissociated to form monomeric state.

Physical and chemical properties of proteins

Physical

- Pure proteins are generally tasteless, though the predominant taste of protein hydrolysates is bitter.
- Pure proteins are odourless.
- Because of the large size of the molecules, proteins exhibit many properties that are **colloidal in nature**.
- Proteins, like amino acids, are **amphoteric** and contain both acidic and basic groups.
- They possess **electrically charged groups** and hence **migrate in an electric field**.
- Many proteins are **labile** and readily modified by alterations in **pH, UV radiation, heat and by many organic solvents**.
- The **absorption spectrum of protein** is maximum at 280 nm due to the presence of **tyrosine and tryptophan**, which are the strongest **chromophores** in that region.
- Hence the absorbance of the protein at this wavelength is adapted for its determination.

Denaturation of protein

- The comparatively weak forces responsible for maintaining secondary, tertiary and quaternary structure of proteins are readily disrupted with **resulting loss of biological activity**.
- **This disruption of native structure is termed denaturation.**
- Physically, denaturation is viewed as **randomizing the conformation of a polypeptide chain without affecting its primary structure**
- Physical and chemical factors are involved in the denaturation of protein
- a) **Heat and UV radiation** supply kinetic energy to protein molecules causing the atoms to vibrate rapidly, thus disrupting the relatively weak hydrogen bonds and salt linkages. This results in denaturation of protein leading to coagulation. Enzymes easily digest denatured or coagulated proteins.
- b) **Organic solvents** such as ethyl alcohol and acetone are capable of forming intermolecular hydrogen bonds with protein disrupting the intramolecular hydrogen bonding. This causes precipitation of protein.
- b) **Acidic and basic reagents** cause changes in pH, which alter the charges present on the side chain of protein disrupting the salt linkages.
- c) **Salts of heavy metal ions (Hg²⁺, Pb²⁺)** form very strong bonds with carboxylate anions of aspartate and glutamate thus disturbing the salt linkages. This property makes some of the heavy metal salts suitable for use as antiseptics.

Renaturation

- Renaturation refers to **the attainment of an original, regular three-dimensional functional protein after its denaturation.**
- When active pancreatic ribonuclease A is treated with **8M urea or 2-mercaptoethanol**, it is converted to an inactive, denatured molecule.
- When urea or mercaptoethanol is removed, it attains its native (active) conformation.

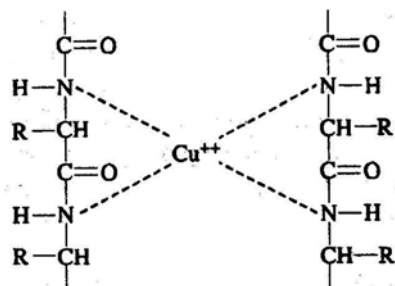
Chemical

Colour reactions of proteins

- The colour reactions of proteins are of importance in the qualitative detection and quantitative estimation of proteins and their constituent amino acids.
- **Biuret test** is extensively used as a test to detect proteins in biological materials.

Biuret reaction

- A compound, which is having more than one **peptide bond** when treated with Biuret reagent, produces a **violet colour**. This is due to the formation of **coordination complex between four nitrogen atoms of two polypeptide chains and one copper atom**



Violet coloured coordination complex

Coordination complex with peptide bonds and copper

Xanthoproteic reaction

- Addition of **concentrated nitric acid** to protein produces **yellow colour** on heating, the colour changes to **orange** when the solution is made alkaline. The yellow stains upon the skin caused by nitric acid are the result of this xanthoproteic reaction. This is due to the **nitration of the phenyl rings of aromatic amino acids**.

Hopkins-Cole reaction

- **Indole ring of tryptophan** reacts with glacial acetic acid in the presence of **concentrated sulphuric acid** and forms a **purple** coloured product. Glacial acetic acid reacts with concentrated sulphuric acid and forms glyoxalic acid, which in turn reacts with indole ring of tryptophan in the presence of sulphuric acid forming a **purple coloured** product.

Lecture 15

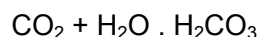
ENZYMES

One of the **unique characteristics** of a living cell is its **ability to permit complex reactions** to proceed rapidly at the temperature of the surrounding environment.

- The **principal agents** which participate in the remarkable transformations in the cell belong to a **group of proteins named enzymes**. In the absence of enzymes in the cell, these reactions would proceed too slowly.
- **Enzymes are proteins specialised to catalyse biological reactions** with the following characteristics.

Characteristics of enzymes

- Enzymes being proteins **exhibit all properties of proteins**.
- They have their **specific isoelectric points** at which they **are least soluble**.
- Like proteins, they can be **denatured by changes in pH and temperature**.
- The enzyme-catalysed reactions occur below 100°C, at atmospheric pressure and nearby **neutral pH**.
- Enzymes **undergo physical changes during the reaction** but **revert to their original form at the end of the reaction**.
- Enzymes exhibit **enormous catalytic power**. The rates of enzymatically catalysed reactions are **10⁶ - 10¹² times greater** than those of the corresponding uncatalysed reactions and several times greater than those of the corresponding chemically catalysed reactions.
- For example the **carbonic anhydrase enzyme** catalyses the conversion of **carbondioxide to carbonic acid**.



- In this reaction, each enzyme molecule can hydrate 10⁵ molecules of CO₂ per second.
- **Enzyme activity is regulated** in a variety of ways, ranging from controls over the **amount of enzyme protein synthesised by the cell** or **modulation of activity** through reversible interaction with **metabolic inhibitors and activators** or through **isoenzymes**.

Specificity of the enzymes

- One of the characteristic feature which distinguishes enzymes from catalysts is their **specificity**.

- Enzymes are specific in the **reaction catalysed** and in their **choice of substrates**.
- It usually catalyses a single chemical reaction or a set of closely related reactions

Three kinds of specificities are observed.

i. Absolute specificity

- When enzymes **catalyse only one particular reaction** they are said to exhibit **absolute specificity**.
- e.g. **Urease** acts only on urea.

ii. Group specificity

- Enzymes acting on a **group of substances** that **possess a particular type of linkage** common to that group of substances are said to exhibit group specificity.
- **Amylase** hydrolyses the group of substances like starch, dextrin and glycogen, which have the same type of glycosidic linkages (α 1,4).

iii. Optical specificity

- Almost all enzymes show a high degree of optical specificity.
- There are certain enzymes which catalyse the **hydrolysis of same group of substances possessing same optical activity**
- **Eg. D-amino acid oxidase acts on D-amino acid and L-amino acid oxidase acts on L-amino acid.**
- **Maltase** catalyses the **hydrolysis of α -but not β - glycosides**.

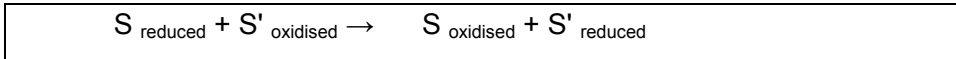
Classification of enzymes

- In **olden days** enzymes have been named by **adding the suffix -ase** to the name of the substrate (the molecule on which the enzyme acts).
- **Ex. Urease** (Substrate urea) **Arginase** (Substrate arginine)
- Recent studies on the **mechanism of enzyme catalysed reactions** have led to a more rational classification of enzymes.
- **The International Union of Biochemistry (IUB)** established a commission on enzyme nomenclature to adopt a systematic classification and nomenclature of all the existing and yet to be discovered enzymes.
- This system is **based on the substrate and reaction specificity**.
- Although, this **International Union of Biochemistry** system is complex, **it is precise, descriptive and informative**.

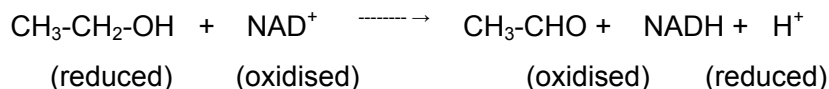
- IUB system classifies enzymes into **six major classes** (should be written in specific order only)
 - Oxidoreductases**
 - Transferases**
 - Hydrolases**
 - Lyases**
 - Isomerases**
 - Ligases**
- Again each class is divided into subclasses according to the **type of reaction catalysed**.
- Each enzyme is assigned a **recommended name** usually a short for everyday use, a **systematic name** which identify the reaction it catalyses and a **classification number** which is used where accurate and unambiguous identification of an enzyme is required.

I. Oxidoreductases

- Enzymes **catalysing oxido-reductions between two substrates, S and S'**.



Example:



Enzyme: Recommended name **Alcohol dehydrogenase**

Systematic name **Alcohol:NAD⁺ oxido-reductase**

Enzyme Commission number **E.C.1.1.1.1**

First digit 1 indicates **oxido-reductase (Major class)**

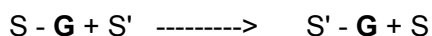
Second digit 1 indicates **enzymes acting on CH-OH group of donors (Sub-class)**

Third digit 1 indicates **NAD⁺ as the electron acceptor (Sub-sub class)**

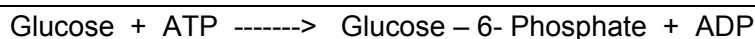
Fourth digit 1 indicates the **specific enzyme**

II Transferases

- Enzymes catalysing the **transfer of a functional group (G) other than hydrogen between substrates**.



Example: Phosphorylation of glucose by **hexokinase**



Enzyme : Recommended name: **Hexokinase**

Systematic name: **ATP:D-hexose, 6- phosphotransferase**

Enzyme commission No: **2.7.1.1**

2 → Transferase group (major class)

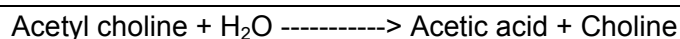
7 → Transfer of phosphate group (sub-class)

1 → Alcohol group as acceptor of phosphate group (Sub-sub-class)

1 → Hexokinase

III Hydrolases

- Enzymes **catalysing hydrolysis of ester, peptide or glycosidic bonds.**
- Example



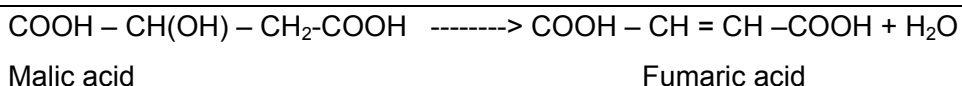
Enzyme: **Acetyl choline esterase**

Systematic name : **Choline:acetyl hydrolase**

E.C : 3.1.1.8

IV Lyases

- Enzymes catalysing the **removal of groups from substrates by mechanism other than hydrolysis leaving a double bond in one of the products.**
- Example: conversion of malic acid to fumaric acid by fumarase



Enzyme : **Fumarase (Fumarate hydratase)**

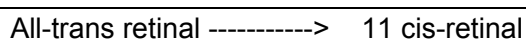
Systematic name: **L. Malate hydrolyase**

E.C.No.4.2.1.2

V. Isomerases

- Enzymes catalysing **interconversion of optical, geometrical or positional isomers**

Example



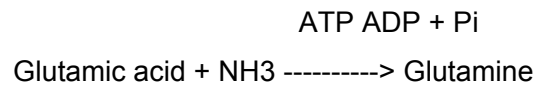
Enzyme **Retinene isomerase**

Systematic name : **All-trans retinene:11-cis isomerase**

E.C.No. 5.2.1.3

VI. Ligases

- Enzymes catalysing **the joining together of two compounds with the hydrolysis of a high energy compound.**
- Example



Enzyme: **Glutamine synthetase**

L.Glutamate: Ammonia ligase

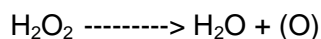
E.C.6.3.1.2

Lecture 16

MECHANISM OF ENZYME ACTION

- A chemical reaction such as $A \rightarrow P$ takes place because a certain fraction of the **substrate possesses enough energy to attain an activated condition called the transition state.**
- This transition state is at the top of the energy barrier separating the reactants and products.
- **The rate of a given chemical reaction is proportional to the concentration of this transition state species.**
- **The energy of activation** is the amount of energy required to bring all the molecules in 1 mole of a substance at a given temperature to the transition state.
- Enzymes combine transiently with the substrate to produce a transition state intermediate having a lower energy of activation than the uncatalysed reaction. Thus, they accelerate chemical reactions by **lowering the energy of activation**

Example



Catalase

Reaction condition	Activation energy (KCal mol ⁻¹)
Uncatalysed	18
Catalysed by colloidal Pt	13
Catalysed by catalase	7

It is generally believed that the catalytic reactions occur in at least two steps.

Step 1: A molecule of enzyme(E) and a molecule of substrate(S) collide and react to form an intermediate called the enzyme-substrate complex (ES).

Step 2: The decomposition of ES complex to give product(s) and the active enzyme



The formation of an ES complex affords a lower activation energy.

Active site

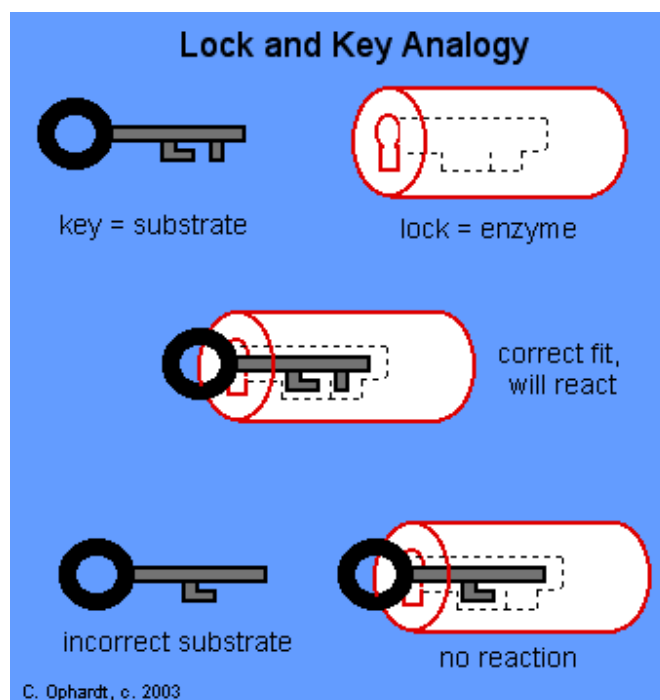
- **The substrate binding site in the enzyme** is referred as **active site.**
- The functional groups that are essential for the formation of ES complex occur at a specific location on the surface of the enzyme molecule.

- This section of enzyme **where substrate binding and transformation of substrate to product** occurs is called as **active site**.
- Many attempts have been made to implicate **specific amino acid residues (side chain or R groups) as being part of the active site of various enzymes**.
- Some of the amino acids occurring at the active site of enzymes are hydroxyl group of serine, sulfhydryl group of cysteine, imidazole group of histidine and carboxyl group of aspartic acid.

Two theories were proposed to explain the mechanism of enzyme action.

1. Fischer's lock and key theory (Rigid template model)

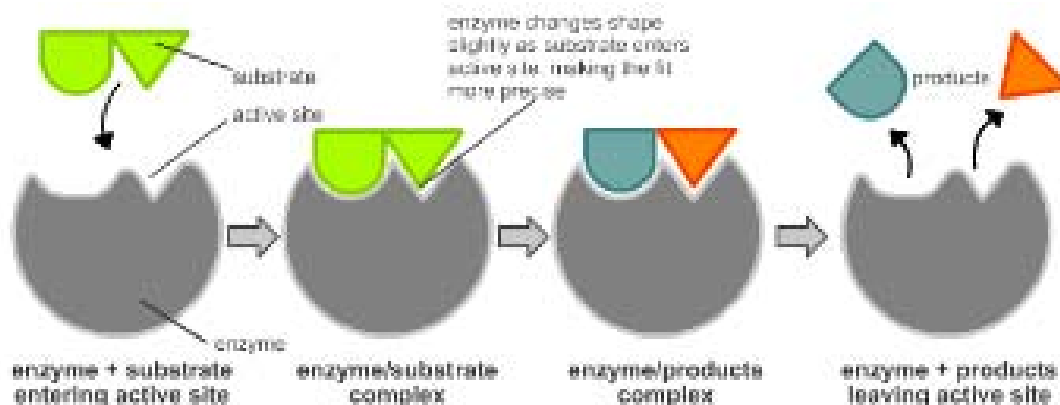
- During 1890, **Emil Fischer** proposed this theory
- According to this, the **active site possesses a unique conformation which is complementary to the structure of the substrate** thus enabling the two molecules to fit together in much the same way as a key fits into a lock



- An unfortunate feature of this model is the **implied rigidity of the catalytic site**.

2. Koshland's induced-fit theory

- Koshland had advocated a theory **to account for the specificity of enzymes**.
- He postulated that the essential functional groups on the active site of the free enzyme are not in their optimal positions for promoting catalysis.
- When the substrate molecule is bound by the enzyme, **the catalytic groups assume favourable geometrical position to form the transition state**.
- The enzyme molecule is unstable in this active conformation and tends to revert to its free form in the absence of substrate.
- In the induced fit model, the substrate induces a conformational change in the enzyme which aligns the amino acid residues or other groups for substrate binding, catalysis or both.



Factors affecting enzymatic reaction

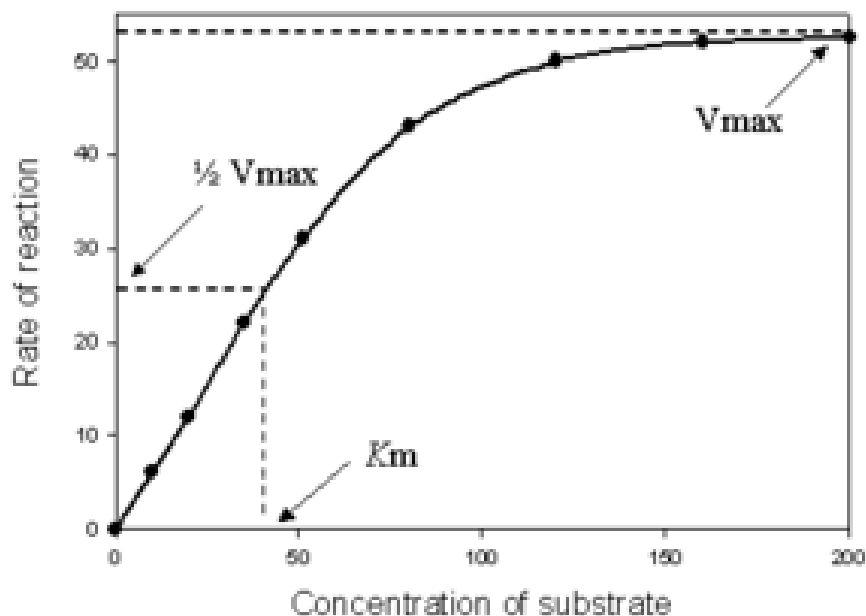
The factors that mainly influence any enzyme-catalysed reaction are:

1. **Substrate concentration**
2. **Enzyme concentration**
3. **Temperature**
4. **pH**
5. **Inhibitors**

Other factors such as **state of enzyme (oxidation), time and activators** also affect enzyme-catalysed reaction to certain extent.

Substrate concentration

- Keeping the factors such as pH, temperature and enzyme concentration at optimum levels, if the **substrate concentration is increased, the velocity of the reaction recorded a rectangular hyperbola.**
- At **very low substrate concentration** the initial reaction velocity (v) is nearly proportional to the substrate concentration (first order kinetics).
- However, if the substrate concentration is increased the rate of increase slows down (mixed order kinetics).
- With a further increase in the substrate concentration the reaction rate approaches a constant (zero order-reaction where velocity is independent of substrate concentration).
- At initial point, eventhough the substrate molecules are present in excess than enzyme on molar basis, not all the enzyme molecules present combine with the substrate.
- Hence, increasing the substrate concentration will increase the amount of enzyme associated with substrate as ES and thus v will depend on $[S]$.
- At V_{max} , all the enzyme molecules are saturated with substrate molecules so that further increase in $[S]$ cannot result in increased reaction rate.
- Michaelis-Menten derived an equation to explain this type of behaviour.



$$v = \frac{V_{max} [S]}{K_m + [S]}$$

[S] = Substrate concentration V_{max} = Maximum velocity
 v = Velocity of the reaction

At half maximal velocity [S] = K_m

$$\text{i.e. } \frac{V_{max}}{2} = \frac{V_{max} [S]}{K_m + [S]}$$

$$\frac{K_m + [S]}{2} = \frac{V_{max} [S]}{V_{max}}$$

$$K_m + [S] = 2 [S]$$

$$K_m = 2 [S] - [S] = [S]$$

Hence, Michaelis - Menten constant, **K_m** , is defined as the substrate concentration at half maximal velocity and is expressed as mole per litre.

- The Michaelis-Menten equation can be algebraically transformed into more useful way to plot the experimental data.
- Lineweaver and Burk have taken the reciprocal of both [S] and v of the Michaelis-Menten equation to give

$$\frac{1}{v} = \frac{K_m}{V_{max} [S]} + \frac{1}{V_{max}}$$

- A plot of $1/v$ versus $1/[S]$ (the double reciprocal) yields a straight line.
- This line intercept X-axis at $-1/K_m$ and Y-axis at $1/V_{max}$.
- The slope of the line is **K_m/V_{max}** .
- The Lineweaver-Burk plot has the great advantage of allowing more accurate determination of V_{max} and K_m

Significance of K_m

- K_m value may vary with substrate.

- ii. An enzyme whose K_m is very low will have a high degree of affinity for its substrate

Enzyme concentration

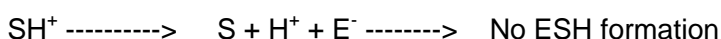
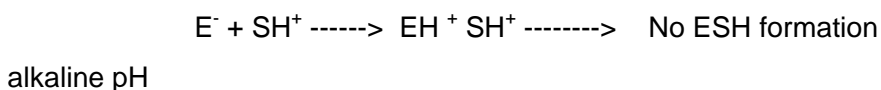
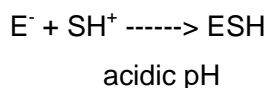
- When compared to substrate concentration, the concentration of enzyme is always **very very low** on molar basis.
- Hence, **increasing the enzyme concentration will always increase the reaction rate**

Temperature

- The **velocity of enzyme-catalysed reactions** roughly **doubles with a 10°C** rise in temperature over a limited range of temperature
- Enzymes, being proteins, are **denatured by heat** and become **inactive** as the temperature increases beyond a certain point.
- Most of the enzymes are inactivated at temperatures **above 60°C**.
- The temperature at which the reaction rate is maximum is known as **optimum temperature**

pH

- Most enzymes have a **characteristic pH** at which their activity is maximum; above or below this pH, the activity declines
- The pH affects the ionic state of the enzyme and frequently that of the substrate also.
- If a negatively charged enzyme (E^-) reacts with a positively charged substrate (SH^+), ESH is formed.
- At low pH values, E^- will be protonated and ESH is not formed.
- Similarly, at very high pH values SH^+ will ionize and lose its positive charge.



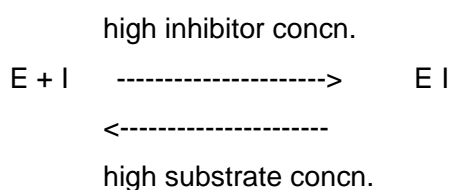
- Another important factor is the **change in conformation (denaturation) of enzyme at extreme pH values.**

Inhibitors

- Compounds that have the **ability to combine with certain enzymes but do not serve as substrates** and therefore **block catalysis** are called **inhibitors.**
- The important type of inhibitors are **competitive** and **noncompetitive inhibitors.**

Competitive inhibitor

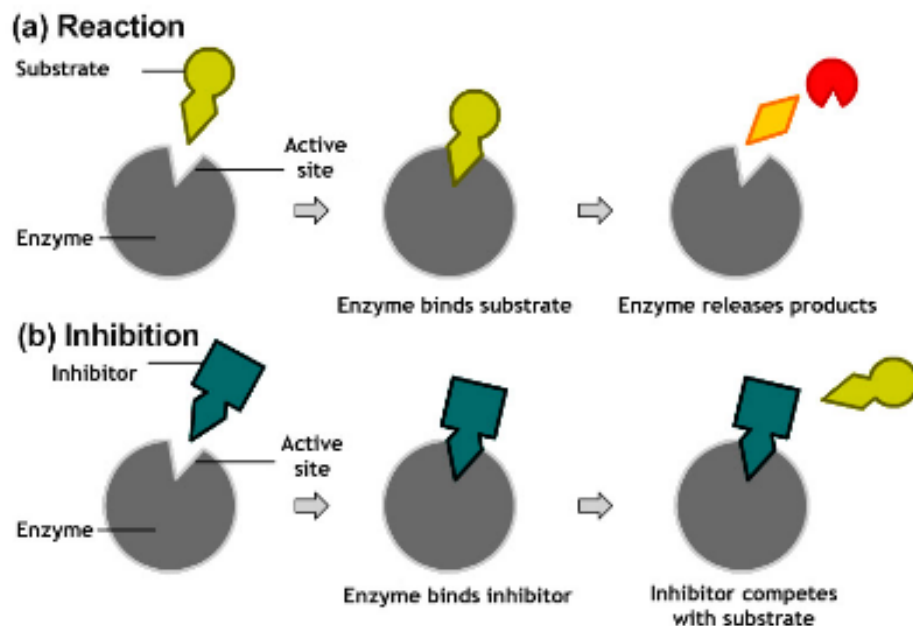
- Any compound which **possesses a close structural resemblance to a particular substrate** and which **competes with that of substrate for the same active site on the enzyme** is called as **competitive inhibitor.**
- The inhibitor is not acted upon by the enzyme and so remains bound to the enzyme preventing the substrate to bind.
- This is a **reversible process.**
- It **depends upon the relative concentration of substrate and inhibitor.**
- Competitive inhibition can be completely reversed by addition of large excess of substrate



Eg. the enzyme, succinate dehydrogenase converts succinate to fumarate.

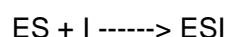
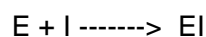
For this reaction, **malonic acid** is a **competitive inhibitor** as it structurally resembles that of succinate

- In case of competitive inhibition, **K_m is increased** but **V_{max} is not altered.**



Non-competitive inhibitor

- Non-competitive inhibitors **bind to a site other than the active site on the enzyme** often to **deform the enzyme**, so that, it does not form the ES complex at its normal rate.
- Once formed, the ES complex does not decompose at the normal rate to yield products.
- These **effects are not reversed** by increasing the substrate concentration.



- Some enzymes possessing an essential -SH group are non-competitively inhibited by heavy metal ions (Hg^{2+} , Pb^{2+}).
- Some **metalloenzymes** are inhibited **non competitively by metal chelating agents like ethylene diamine tetraacetic acid(EDTA)**.
- Inhibitors are used as **tools to probe the mechanism of enzyme - catalysed reactions** and as **therapeutic agents**.
- In case of noncompetitive inhibition, V_{max} is lowered but K_m is not altered

Uncompetitive inhibitor

- In case of uncompetitive inhibition, the inhibitor binds only to free enzyme and not to the enzyme substrate [ES] complex

MID TERM EXAMINATION

(All the Best)

Lecture 18

APOENZYMES, COENZYMES AND COFACTORS, ISOZYMES

A complete, catalytically active enzyme together with its coenzyme and/or metal ions is called holoenzyme.

- The **protein part of an enzyme** is called **apoenzyme or apoprotein**.
- Enzymes require an additional non-protein component to carry out its catalytic functions.
- Generally these **non-protein components** are called as **cofactors**.
- The cofactors may be either one or more **inorganic ions such as Fe^{2+} , Mg^{2+} , Mn^{2+} and Zn^{2+}** or a complex **organic molecules called coenzymes**.
- A coenzyme or metal ion that is covalently bound to the enzyme protein is called **prosthetic group**.
- Some enzymes require both coenzyme and one or more metal ions for their activity
- Coenzymes function as transient carriers of specific functional groups

Cofactors

- Metals are required as cofactors in approximately two thirds of all enzymes.
- **Metalloenzymes** contain a definite quantity of functional metal ion that is retained throughout whereas metal-activated enzymes bind metals less tightly but require added metals.
- The distinction between metalloenzymes and metal activated enzymes thus rests on the **affinity of a particular enzyme for its metal ion**.
- The mechanisms whereby metal ions perform their function appear to be **similar** both in metalloenzymes and metal activated enzymes.
- Metals participate through their **ability to act as Lewis acids and through chelate formation**. Eg. For metal functioning as a Lewis acid is the **zinc** in **carbonic anhydrase**.
- The metal can also **promote catalysis by binding substrate at the site of bond cleavage**. In **carboxypeptidase**, the carbonyl oxygen is chelated to the zinc.

The **iron-sulfur enzymes** are unique class of metalloenzymes in which the active centre consists of one or more clusters of **sulfur-bridged iron chelates**. These are of greater importance in plant systems

Isoenzymes

- **Enzymes which exist in multiple forms within a single species of organism or even in a single cell are called isoenzymes or isozymes.**
- Such multiple forms can be detected and separated by gel electrophoresis of cell extracts.
- Since they are **coded by different genes**, they **differ in amino acid composition and thus in their isoelectric pH values.**
- **Lactate dehydrogenase** is an example for the isoenzymes which occur as five different forms in the tissues of the human and other vertebrates.
- All the five isozymes catalyze the same reaction.
$$\text{Lactate} + \text{NAD}^+ \text{ ----- } \text{Pyruvate} + \text{NADH} + \text{H}^+$$
- They have the molecular weight of about 134,000 and contain four polypeptides.
- The five isozymes consist of five different combinations of two different kinds of polypeptides **M and H.**
- Kinetic study of lactate dehydrogenase isozymes has revealed that although they catalyze the same reaction, they **differ significantly in their Km values for their substrates as well as Vmax values.**
- The two polypeptide chains in LDH are coded by **two different genes.**
- Skeletal muscle contains four identical M chains and designated as M4; whereas heart muscle contains four identical H chains and designated as H4.

- LDH of other tissues are a mixture of the five possible forms H₄, H₃M, H₂M₂, H₁M₃ and M₄.
- A **determination of the relative amounts of the five LDH isozymes** and the total concentration of LDH in a serum sample can provide valuable **diagnostic information about which tissues have been damaged and the extent of the damage.**

Lecture 19 -24

METABOLISM OF CARBOHYDRATE

Introduction

- ❖ Carbohydrates are major sources of energy for living organisms.
- ❖ The **chief source of carbohydrate** in human food is **starch**, which is the storage form of glucose in plants.
- ❖ Plants may store relatively large amounts of starch within their own cells in time of abundant supply, to be used later by the plant itself when there is a **demand for energy production**.
- ❖ **Glycogen** is the glucose storage polysaccharide of animals.
- ❖ It accounts for upto 10% of the mass of the liver and one percent of the mass of the muscle.
- ❖ Glycogen is larger and highly branched than amylopectin.
- ❖ By the action of several enzymes, such as **α -amylase, β -amylase, amylo $\alpha(1\rightarrow6)$ glucosidase and $\alpha(1\rightarrow4)$ glucosidase**, starch and glycogen from dietary intake are degraded finally to glucose.
- ❖ Carbohydrate is utilized by cells mainly in the form of glucose.
- ❖ The three principal monosaccharides resulting from the digestive processes are **glucose, fructose and galactose**.
- ❖ Both fructose and galactose are readily converted to glucose by the liver.
- ❖ Pentose sugars such as xylose, arabinose and ribose may be present in the diet, but their fate after absorption is obscure.
- ❖ Since glucose is the compound formed from starch and glycogen, the carbohydrate metabolism commences with this monosaccharide.

The major metabolic processes in carbohydrates are:

i. Glycolysis:

Glycolysis is the sequence of reactions that convert **glucose into pyruvate** with the concomitant trapping of the energy as ATP.

ii. The citric acid cycle:

It is the final **common oxidative pathway for carbohydrates, fats and proteins**. It is also a source of precursors for biosynthesis of various biomolecules. The **acetyl CoA** that enters in this pathway is completely oxidised to **carbon dioxide and water** with concomitant production of reducing equivalents, namely **NADH and FADH₂**.

iii. The hexose monophosphate shunt:

It is an **alternative pathway** to the glycolytic pathway and the citric acid cycle for the oxidation of glucose to carbon dioxide and water with the **generation of reduced nicotinamide adenine dinucleotide phosphate (NADPH) molecules and ribose 5-phosphate.**

iv. Gluconeogenesis:

It is a biosynthetic pathway that generates **glucose from non-carbohydrate precursors.**

v. Glycogenesis:

It is a pathway by which **glycogen is synthesised** from glucose.

vi. Glycogenolysis:

Glycolysis

- ❖ Glycolysis, also called as **Embden-Meyerhof-Parnas pathway (EMP pathway)**, consists of a series of reactions through which glucose is converted to pyruvate with the concomitant production of relatively small amounts of adenosine triphosphate (ATP).
- ❖ It is derived from the Greek stem '**glykys**' meaning sweet and '**lysis**' meaning splitting.
- ❖ It is the primary pathway occurring in the cytoplasm of all the tissues of biological systems.
- ❖ All the enzymes responsible for the catalysis are found in the **extra-mitochondrial soluble fraction of the cells (cytoplasm).**

In plants, glucose and fructose are the main monosaccharides catabolised by glycolysis although others are also converted into these sugars.

- ❖ Glucose entering the glycolysis is derived from **starch or sucrose**, and fructose is derived from **sucrose.**
- ❖ The starch is either from seeds or chloroplasts of matured plants.
- ❖ Glycolysis normally takes place in the **presence of O₂** in higher plant cells.

The enzymes in the cytoplasm catalyse the reactions involved in the conversion of **glucose to pyruvate .**

The series of reactions indicated take place in 3 stages.

Stage 1: Conversion of glucose to fructose 1,6-bisphosphate

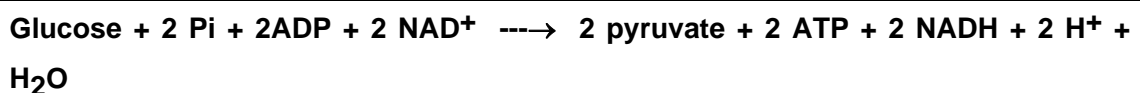
- ❖ The formation of fructose 1,6-bisphosphate takes place in three steps catalysed by enzymes.

- ❖ The purpose of these reactions is to form a compound that can be readily cleaved into phosphorylated three carbon units from which, through a series of reactions, ATP is formed.
 - ❖ After the **first phosphorylation** reaction to form glucose 6-phosphate, isomerisation of glucose 6-phosphate to **fructose-6-phosphate** occurs which is conversion of an aldose into a ketose.
 - ❖ A second phosphorylation reaction follows the isomerization, catalysed by **phosphofructokinase** resulting in the formation of fructose 1,6-bisphosphate.
 - ❖ **Phosphofructokinase** is the key enzyme in the control of glycolysis.
- Stage 2: Conversion of fructose 1,6-bisphosphate to 3-phosphoglycerate.**
- ❖ The **splitting of fructose 1,6-bisphosphate** occurs in the second stage of glycolysis resulting in the formation of a molecule of glyceraldehyde 3-phosphate and a molecule of dihydroxyacetone phosphate catalysed by **aldolase**.
 - ❖ The dihydroxyacetone phosphate is isomerised to glyceraldehyde 3-phosphate by **phosphotriose isomerase**. The isomerisation reaction is rapid and reversible.
 - ❖ In the next step, glyceraldehyde 3-phosphate is oxidised to 1,3-bisphosphoglycerate catalyzed by **glyceraldehyde 3-phosphate dehydrogenase**.
 - ❖ The product is further converted into 3-phosphoglycerate and a molecule of ATP is formed. The phosphorylation of ADP to ATP is called **substrate level phosphorylation** since the phosphate group from a substrate molecule is transferred to ADP.

Stage 3: Formation of pyruvate

- ❖ An intramolecular rearrangement of the phosphoryl group occurs resulting in the formation of **2-phosphoglycerate from 3-phosphoglycerate catalyzed by phosphoglycerate mutase**.
- ❖ The 2-phosphoglycerate formed undergoes **dehydration** forming phosphoenolpyruvate which gives rise to pyruvate and a molecule of ATP (substrate level phosphorylation).
- ❖ The reaction is irreversible and catalyzed by **pyruvate kinase**.

The net reaction in the transformation of glucose to pyruvate is



Once pyruvate is formed, further degradation is determined by the **presence or absence of oxygen**.

Under anaerobic conditions, in one of the pathways, pyruvate undergoes reduction yielding **lactic acid**.

The formation of lactic acid is very rare in plants with exception of potato tubers maintained under anaerobic condition and some green algae.

In the second pathway, pyruvate is converted to **ethyl alcohol and carbon dioxide**. The **alcoholic fermentation** is the basis of the beer and wine-making industries.

Under **aerobic conditions**, pyruvate is **oxidatively decarboxylated to acetyl CoA** which is then completely oxidised to CO_2 and water through the **citric acid cycle**

Energetics of glycolysis

From glucose, two molecules of glyceraldehyde 3-phosphate are formed in the second stage of glycolysis from which two molecules of pyruvate are obtained as end products of glycolysis. Hence energetic of glycolysis is calculated by taking into account two molecules of glyceraldehyde 3-phosphate.

Energetics of glycolysis

Stages/steps	Enzyme	Method of high energy bond formation	No. of ATP formed
Stage 1			
Formation of 1,3-bisphosphoglycerate from glyceraldehydes 3-phosphate	Glyceraldehyde3-phosphate dehydrogenase	Respiratory chain oxidation of 2 NADH	5
Stage 2			
Formation of 3 phosphoglycerate from 1,3 bisphosphoglycerate	Phosphoglycerate kinase	Phosphorylation at substrate level	2
Stage 3			
Formation of pyruvate from phosphoenol pyruvate	Pyruvate kinase	Phosphorylation at substrate level	2
Allowance for consumption of ATP by reactions catalysed by hexokinase and phosphofructokinase.			2
Number of ATP molecules generated by the catabolism of one molecule of glucose under aerobic conditions.			7
Number of ATP molecules generated by the catabolism of one molecule of glucose under anaerobic conditions.			2

Significance of glycolysis

- ❖ Glycolysis is an almost **universal central pathway** of glucose catabolism occurring in the cytoplasm of all the tissues of biological systems leading to generation of energy in the form of ATP for vital activities.
- ❖ It is the pathway through which the **largest flux of carbon** occurs in most cells.
- ❖ Some plant tissues which are modified for the storage of starch such as potato tubers and some plants adapted to growth in inundated water such as water cress derive most of their energy from glycolysis.

- ❖ In plants, glycolysis is the **key metabolic component of the respiratory process**, which generates energy in the form of ATP in cells where photosynthesis is not taking place.
- ❖ Many types of **anaerobic microorganisms** are entirely dependent on glycolysis.
- ❖ Mammalian tissues such as renal medulla and brain solely dependent on glycolysis for major sources of metabolic energy.

The tricarboxylic acid cycle

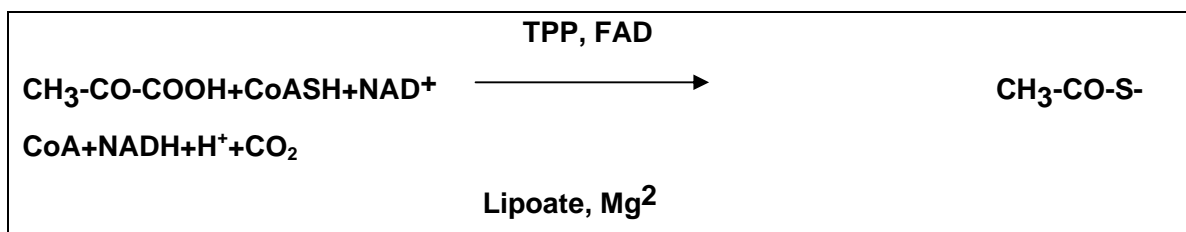
- ❖ In 1937, Sir Hans Krebs, an English biochemist proposed a pathway consisting of a cycle of reactions through which acetyl CoA is converted to carbon dioxide and water and hence the cycle was named as Krebs's cycle.
- ❖ All the enzymes catalyzing the reactions of this cycle occur inside **mitochondria (mitochondrial matrix)** in contrast with those of glycolysis, which occur in the cytosol.

Before pyruvate can enter the citric acid cycle, it must be oxidatively decarboxylated to acetyl CoA (active acetate).

Three different enzymes working sequentially in a multienzyme complex catalyse this reaction.

This formation of acetyl CoA from pyruvate **by alpha-oxidative decarboxylation** occurs in the mitochondrion following the formation of pyruvate in the cytosol during glycolysis.

The reaction involves six cofactors: **coenzyme A, NAD⁺, lipoic acid, FAD, thiamine pyrophosphate (TPP) and Mg²⁺**.



Reactions of the TCA cycle

Acetyl CoA, derived mainly from the oxidation of carbohydrates, lipids and proteins, combines with oxaloacetate to form **citrate** which is the first reaction of the citric acid cycle. Subsequently, citrate is oxidised in a series of reactions liberating carbon dioxide and reducing equivalents (NADH, FADH₂).

The oxaloacetate is regenerated and functions therefore in a catalytic manner in the oxidation of acetyl CoA to two molecules of carbon dioxide.

The citric acid cycle has eight steps as described below:

i. Formation of citrate

The first step is the reaction between the four-carbon unit, oxaloacetate and the two-carbon unit, acetyl CoA resulting in the formation of citrate and coenzyme A catalysed **by citrate synthase**. The coenzyme A formed in this reaction is recycled.

ii. Formation of isocitrate via cis-aconitate

The isomerization of citrate to isocitrate catalysed by **aconitase** occurs in two steps with the formation of cis-aconitate as an intermediate. This formation of isocitrate involves both dehydration and hydration. The result is an interchange of hydrogen and a hydroxyl group. In this reaction, **fluoroacetate** acts as an inhibitor to the enzyme, aconitase.

iii. Oxidation of isocitrate to α -ketoglutarate

The enzyme, **isocitrate dehydrogenase** oxidatively decarboxylates isocitrate to α -ketoglutarate with simultaneous liberation of carbon dioxide. The intermediate in this reaction is oxalosuccinate, an unstable β -ketoacid. While bound to the enzyme, it loses carbon dioxide to form α -ketoglutarate. There are two different forms of isocitrate dehydrogenase (isozymes), one requiring NAD^+ and other requiring NADP^+ .

iv. Oxidation of α -ketoglutarate to succinyl CoA

α -Ketoglutarate, undergoes oxidative decarboxylation forming succinyl-CoA and carbon dioxide in the presence of **α -ketoglutarate dehydrogenase complex**, an assembly consisting of three kinds of enzymes. The mechanism of this reaction is very similar to the reaction catalyzed by **pyruvate dehydrogenase complex**. This reaction is irreversible. **Arsenite** acts as an inhibitor of TCA cycle by inhibiting the action of α -ketoglutarate dehydrogenase complex.

v. Conversion of succinyl CoA to succinate

Succinate is formed in a reversible reaction from succinyl CoA catalysed by the enzyme, **succinyl CoA synthetase or succinate thiokinase** with the simultaneous formation of GTP and coenzyme A. Succinate thiokinase utilises GDP in animal tissues whereas it uses ADP predominantly in plants and bacteria. The **formation of GTP** in this reaction is a **substrate level phosphorylation reaction**.

vi. Formation of fumarate by oxidation of succinate

The succinate formed from succinyl CoA is oxidised to fumarate by **succinate dehydrogenase** with the participation of FAD. **Malonate**, an analogue of succinate being a strong competitive inhibitor of succinate dehydrogenase, blocks the citric acid cycle.

vii. Formation of malate by hydration of fumarate

The reversible hydration of fumarate to L-malate is catalysed by **fumarase**.

viii. Oxidation of malate to oxaloacetate

This reaction forms the last reaction of the citric acid cycle. NAD-linked malate dehydrogenase catalyses the oxidation of L-malate to oxaloacetate.

Energetics of tricarboxylic acid cycle

From one molecule of glucose, two molecules of pyruvate are formed which in turn give rise to two molecules of acetyl CoA. When two molecules of acetyl-CoA undergo oxidation through TCA cycle, the following number of high-energy bonds (ATPs) are produced.

Significance of the TCA cycle

- i) The major significance of the citric acid cycle is to act as the **final common pathway for the oxidation of carbohydrates, lipids and proteins**, since glucose, fatty acids and many amino acids are all metabolised to acetyl CoA.
- ii) This cycle serves as the mechanism by which much of **the free energy liberated during the oxidation of carbohydrate, lipids and amino acids is made available**.
- iii) TCA cycle is of further significance since it has **dual or amphibolic role thus providing precursor compounds for biosynthesis of other biomolecules** (amino acids, fatty acids, and glucose).

Glyoxylate cycle

- ❖ Plants, especially seedlings, can use acetate as the only source of carbon for all carbon compounds they produce.
- ❖ Acetyl CoA, which enters the TCA cycle, is completely oxidised to two molecules of CO₂. Thus it would not be possible for the cycle to produce the massive amounts biosynthetic precursors needed for acetate based growth unless alternative reactions were possible.
- ❖ Plants and bacteria employ a **modification of the TCA cycle** called the glyoxylate cycle to produce four **carbon dicarboxylic acids from acetyl CoA**. The glyoxylate cycle bypasses the decarboxylations of the TCA cycle.

- ❖ The enzymes of the glyoxylate cycle in plants are present in **glyoxysomes**. **Isocitrate lyase and malate synthase** are the additional enzymes required for this cycle in addition to TCA cycle enzymes.
- ❖ Glyoxysomes do not contain all the enzymes needed for the glyoxylate cycle. The enzymes succinate dehydrogenase, fumarase and malate dehydrogenase are absent.
- ❖ Hence glyoxysomes, with the help of mitochondria run their cycle Succinate molecules formed in glyoxysomes are transported to mitochondria where it is converted to oxaloacetate with the help of TCA cycle enzymes. The oxaloacetate is then converted to aspartate and transported to glyoxysomes where it is transaminated to oxaloacetate.
- ❖ The oxaloacetate is converted to malate through glyoxylate cycle. The malate then enters the cytosol and converted into glucose via gluconeogenesis pathway.

The existence of glyoxylate cycle is important for the **germinating seeds** where photosynthesis is not possible. Triacylglycerols rich in oilseeds are degraded to acetyl CoA. Glyoxysomes formed during germination convert the acetyl CoA to oxaloacetate, which is then utilised for the conversion to glucose through gluconeogenesis. Once the growing seedling begins their photosynthesis to produce carbohydrates, the glyoxysomes disappear.

Electron transport chain and oxidative phosphorylation

- ❖ The mitochondrion is the aerobic organelle in which the final stage of the oxidation of food occurs.
- ❖ It is the site of the citric acid cycle, fatty acid oxidation and oxidative phosphorylation, processes that are responsible for the formation of ATP under aerobic condition.
- ❖ The two most important energy transductions in the biological systems are the **oxidative phosphorylation (ATP synthesis driven by electron transfer to oxygen)** and photophosphorylation (ATP synthesis driven by light).
- ❖ Oxidative phosphorylation is the process in which ATP molecules are formed as a result of the transfer of electrons from the reducing equivalents, NADH or FADH₂ (produced by glycolysis, the citric acid cycle and fatty acid oxidation) to oxygen by a series of electron carriers in the form of a chain located in the inner membrane of mitochondria. This is the final reaction sequence of respiration.

- ❖ Since the electrons are transferred by a series of electron carriers in the form of a chain, it is known as electron transport chain (ETC).
- ❖ In plants, ATP is mainly derived through photosynthesis utilizing the energy derived from the sun. In non-photosynthetic tissues, ATPs are derived through respiration.

The electrons are transferred along a set of cytochromes in the form of a chain in steps from the **more electronegative components (NADH/FADH₂) to the more electropositive oxygen.**

The respiratory chain consists of a number of protein complexes that are remarkably complicated in nature. They are known as **NADH- ubiquinone reductase, succinate-ubiquinone reductase, ubiquinone-cytochrome c reductase and cytochrome c oxidase**. These complexes are also called as **NADH dehydrogenase, succinate dehydrogenase, cytochrome b-c complex and cytochrome c oxidase respectively or as complexes I - IV.**

All the three reductases are also known as iron-sulphur proteins since they contain Fe-S centres as their critical components. Iron in these enzyme complexes can exist in two forms as Fe²⁺ and Fe³⁺. Each cytochrome in its oxidised form (Fe³⁺) accepts one electron and becomes reduced to Fe²⁺ form. Fe²⁺ donates electron to the next carrier.

Oxidation of one molecule of NADH results in generation of 2.5 molecules of ATP whereas oxidation of one molecule of FADH₂ generates 1.5 molecules of ATP.

Sites of ATP formation

When electrons are transported along the respiratory chain, due to high amount of energy released, ATP molecules are synthesised at the following three sites.

- transfer of electrons from NADH to ubiquinone via flavoprotein (FMN).**
- transfer of electrons from cyt b to cyt c.**
- transfer of electrons from cyt a to cyt a₃.**

Mechanism of ATP formation

Two principal hypotheses have been proposed for the mechanism of oxidative phosphorylation.

i. Chemical hypothesis

ii. Chemiosmotic theory

Chemical hypothesis

Many attempts have been made since 1920 to identify an energy-rich metabolite linking oxidation and phosphorylation. No such intermediates was isolated and in 1960, Peter Mitchell suggested that no possibility of existence of such an intermediate compound. So, the chemical hypothesis has become discredited.

Chemiosmotic theory

The chemiosmotic theory states that the coupling of oxidation to phosphorylation is indirect. According to this, the hydrogen ions (protons) generated by the oxidation of components in the respiratory chain are ejected to the outside (matrix) of the inner membrane. The electrochemical potential difference resulting from the asymmetric distribution of the hydrogen ions (protons or H^+) is used to drive a membrane-located ATP synthase which in the presence of $P_i + ADP$ forms ATP.

Inhibitors of respiratory chain

Inhibitors, which inhibit respiratory chain, may be grouped as follows:

i. Inhibitors of electron transfer

ii. Inhibitors of ATP synthase

iii. Uncouplers of oxidative phosphorylation

Inhibitors that arrest respiration by blocking the respiratory chain act at three sites.

Compounds such as barbiturates, amytal, rotenone prevent the transfer of electron from FeS centre to ubiquinone. Carboxin specifically inhibits transfer of reducing equivalents from succinate dehydrogenase to ubiquinone.

Antimycin A blocks electron transfer from cytochrome b to cytochrome c_1 .

Substances such as cyanide (CN^-), azide (N_3^-) and carbon monoxide inhibit cytochrome c oxidase by binding to heme group and are extremely poisonous. Oligomycin inhibits ATP synthase.

In the presence of the uncouplers such as dicoumarol and 2,4-dinitrophenol, oxidation proceeds without phosphorylation (dissociation of oxidation in the respiratory

chain from phosphorylation) releasing energy in the form of heat rather than in the form of ATP.

The hexose monophosphate shunt

The hexose monophosphate shunt (HMP shunt), also called as pentose phosphate pathway (PPP) and phosphogluconate pathway is an alternate pathway for the oxidation of glucose. In 1930, Otto Warburg discovered the first evidence for the existence of this pathway, which was later, elucidated in 1950 by Frank Dickens group.

The pathway is important during the hours of darkness and in non-photosynthetic tissues such as differentiating tissues and germinating seeds. In animal system, it occurs in certain tissues, notably liver, lactating mammary gland and adipose tissue in addition to the Embden - Meyerhof pathway. The enzymes of the shunt pathway are found in the extra mitochondrial soluble portion of the cell. It is in effect, a multicyclic process whereby three molecules of glucose 6-phosphate give rise to three molecules of CO₂ and three 5-carbon residues. The latter are rearranged to regenerate two molecules of glucose 6-phosphate and one molecule of glyceraldehyde-3-phosphate. Since two molecules of glyceraldehyde 3-phosphate can regenerate a molecule of glucose 6-phosphate by reactions, which are essentially a reversal of glycolysis, the pathway can account for the complete oxidation of glucose. Here oxidation is achieved by dehydrogenation using NADP and not NAD as in Embden-Meyerhof's glycolytic pathway. This pathway consists of a series of reactions taking place in three stages

Stage I. Formation of NADPH and ribulose 5-phosphate

The first three reactions of the pathway, catalysed by glucose-6-phosphate dehydrogenase, phosphogluconolactonase and phosphogluconate dehydrogenase ultimately result in **the formation of ribulose 5-phosphate and NADPH.**

Stage II.

In this stage, the ribulose 5-phosphate is converted to ribose 5-phosphate by ribulose 5-phosphate isomerase and then to xylulose-5 phosphate by ribulose 5-phosphate epimerase. The ribose 5-phosphate is essential precursor in the biosynthesis of nucleotides.

Stage III.

In the third stage, three molecules of the 5-carbon sugars are converted to two molecules of 6-carbon sugars and one molecule of 3-carbon sugar, glyceraldehyde 3-phosphate catalysed **by two enzymes, transaldolase and transketolase.**

Transketolase catalyses the transfer of a C₂ unit from xylulose 5-phosphate to ribose 5-phosphate yielding glyceraldehyde 3-phosphate and sedoheptulose 7-phosphate.

Transaldolase catalyses the transfer of a three carbon unit from sedoheptulose 7-phosphate to glyceraldehyde 3-phosphate yielding erythrose 4-phosphate and fructose 6-phosphate.

Control of the HMP shunt

Ribose 5-phosphate and NADPH are the principal products of the HMP shunt. In this pathway, excess amount of ribose 5-phosphate is converted into glycolytic intermediates when the need for NADPH exceeds that of ribose 5-phosphate in nucleotide biosynthesis.

If ribose 5-phosphate is needed more than NADPH, fructose 6-phosphate and glyceraldehyde 3-phosphate are used for the synthesis of ribose 5-phosphate by reversal of the transaldolase and transketolase reactions.

The rate of NADPH formation in the pathway is controlled by the rate of the glucose 6-phosphate dehydrogenase reaction.

Metabolic significance of the HMP Shunt

- i. Major function of HMP shunt appears to be the production of reduced NADP (NADPH) required by anabolic (synthetic) processes such as fatty acid synthesis outside the mitochondria .
- ii. The pathway provides ribose for nucleotide and nucleic acid synthesis.
- iii. It also provides erythrose required for the synthesis of phenolics and other aromatic compounds through shikimate pathway.

Glucose 6-phosphate can be used as a substrate either for glycolysis or for the pentose phosphate pathway. On the basis of the cell's needs, it makes this choice for biosynthesis and for energy from catabolism. If glucose 6-phosphate is channeled into glycolysis, ATP is produced in abundance; but if it is channeled into pentose phosphate pathway. NADPH and ribose 5-phosphate are produced. The fate of glucose 6-phosphate is determined to a large extent of phosphofructokinase and glucose-6 P. There are four principal possibilities in which, depending upon the cell's need, HMP shunt operates.

- i. More ribose 5-phosphate than NADPH is required

Most of the glucose 6-phosphate is converted into fructose 6-phosphate and glyceraldehyde 3-phosphate by the glycolytic pathway. Two molecules of fructose 6-

phosphate and one molecule of glyceraldehyde 3-phosphate are converted into three molecules of ribose 5-phosphate by a reversal of reactions catalysed by transaldolase and transketolase reactions.

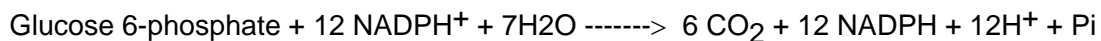
ii. Both ribose 5-phosphate and NADPH are needed by the cell

In this, the first four reactions of the pentose phosphate pathway predominate. Ribose 5-phosphate is the principal product of the metabolism and NADPH is also produced. The net reaction for these processes is



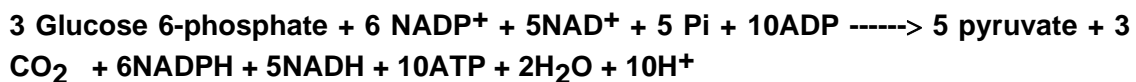
3. More NADPH than ribose 5-phosphate is needed by the cell

Under this situation, glucose 6-phosphate is completely oxidized to carbon dioxide. Three reactions are active. First, two NADPH and one ribose 5-phosphate are formed by the oxidative branch of the pentose phosphate pathway. Then, ribose 5-phosphate is converted into fructose 6-phosphate and glyceraldehyde 3-phosphate by transketolase and transaldolase. In the final reaction, glucose 6-phosphate is resynthesised from fructose 6-phosphate and glyceraldehyde 3-phosphate by the gluconeogenic pathway. The sum of these reactions is



iv. Both NADPH and ATP are needed by the cell.

In this, fructose 6-phosphate and glyceraldehyde 3-phosphate derived from ribose 5-phosphate enter the glycolytic pathway and form pyruvate. ATP and NADPH are concomitantly generated and five of the six carbons of glucose 6-phosphate emerge in pyruvate.



Comparative account of glycolysis and HMP shunt

These two major pathways are meant for the catabolism of glucose. They have little in common, e.g. the presence of metabolites like glucose 6-phosphate. The major differences are

- i. ATP is not generated in the HMP pathway, whereas in glycolysis, ATP molecules are generated.
- ii. Pentose phosphates are generated in the HMP pathway but not in glycolysis.
- iii. NADH is produced in glycolytic pathway whereas NADPH is produced in HMP shunt.

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LIPASES AND PHOSPHOLIPASES

Lipids constitute one of the four major classes of compounds that are found in living systems. The lipids of metabolic significance include triacylglycerol, phospholipids and the products of lipid metabolism such as free fatty acids and glycerol.

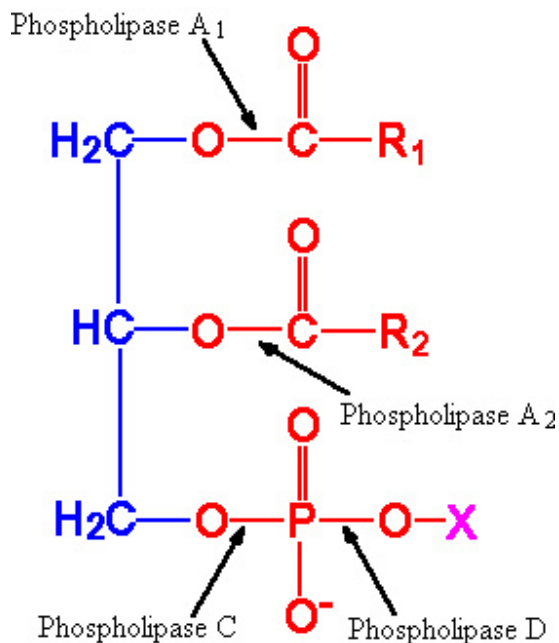
Lipases

- ❖ Triacylglycerols or triglycerides undergo hydrolysis by **lipases** to form glycerol and fatty acids, which undergo further oxidation generating energy.
- ❖ Lipases have been reported to be present in **dry seeds of some species, e.g. castor bean, Scots pine and Douglas fir** but at a low level, or absent in others e.g. apple.
- ❖ In most cases of seeds, **following imbibitions**, there appears to be a **rise in lipase activity** but whether this increase is due to the *de novo* synthesis of the enzyme or activation of existing lipases has not been determined.
- ❖ A **decline in lipase activity** is always associated with decline in acylglycerol reserves.
- ❖ In castor bean, as in many other fat-storing seeds, free fatty acids do not accumulate, but are rapidly degraded and converted to carbohydrate within the endosperm.
- ❖ In other seeds such as **germinating seeds of oil palm (*Elaeis guineensis*)**, a different pattern of fat mobilization can be observed.
- ❖ The products of lipid catabolism are transported via specialized structures called **haustorium** through its vascular system.
- ❖ Lipases are generally **non-specific** and can hydrolyse a wide variety of triacylglycerols
- ❖ They initiate digestion by hydrolyzing triacylglycerols to form free fatty acids and 1,2-diacylglycerols.
- ❖ Complete hydrolysis of triacylglycerols produces **glycerol and fatty acids**.
- ❖ Lipase hydrolyses easily the terminal fatty acids to produce 2-monoacyl glycerol as major

Phospholipases

- ❖ Phospholipases are the hydrolytic enzymes acting on phospholipids and splitting into different products.

- ❖ There are four types of phospholipases known as **phospholipase A₁**, **phospholipase A₂ or B₁**, **phospholipase C** and **phospholipase D**.



Phospholipase A

- ❖ Phospholipase A is present in large amounts in **snake venom and human pancreas**.
- ❖ It is also designated as **phospholipase A₁**.
- ❖ It catalyses the hydrolysis of the fatty acids in the 2 or β-position of the phospholipids.
- ❖ Though this enzyme attacks on glycerophosphatides, it is fairly specific for phosphatidyl choline (lecithin).
- ❖ The enzyme is relatively stable to heat (below pH 7.0).
- ❖ The product of the hydrolysis, a **lysolecithin**, (monoacylphosphoryl choline) has a powerful **hemolytic activity**.

Phospholipase B (A₂)

- ❖ It is otherwise termed as **lysophospholipase** and widely distributed in nature often in association with phospholipase A.
- ❖ Phospholipase B is also designated as **phospholipase A₂** since it acts on the lysolecithin (the product obtained from phospholipid by the action of phospholipase A₁).

- ❖ The action of this enzyme following that of phospholipase A yields **glycerophosphorylcholine** as the final product.

Phospholipase C

- ❖ Phospholipase C is mostly found in the plant kingdom but it may also be present in some animal tissues and venoms.
- ❖ It catalyses the liberation of a 1,2-diacylglycerol and phosphorylcholine from phosphatidylcholine.
- ❖ Phosphorylcholine is also liberated from sphingomyelin by this enzyme.

Phospholipase D

- ❖ Phospholipase D, an enzyme described mainly in plants catalyses the **hydrolysis of choline** from phosphatidylcholine leaving phosphatidic acid.

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OXIDATION OF FATTY ACIDS

Fatty acids obtained by hydrolysis of fats undergo different oxidative pathways designated as alpha (α), beta (β) and omega (ω) pathways.

α -oxidation

- ❖ α -Oxidation of fatty acids has been found in certain tissues especially in **brain tissue of mammals and plant systems**.
- ❖ It does not require CoA intermediates and no high-energy phosphates are generated.
- ❖ This type of oxidation results in the **removal of one carbon** at a time from the **carboxyl end of the fatty acid**.
- ❖ The physiological role of α -oxidation in plants is not yet fully established but it has been suggested that it may be **involved in the degradation of long chain fatty acids** as observed in many animal tissues.
- ❖ α -Oxidation is clearly the **main source of the odd-carbon fatty acids** and their derivatives that occur in some plant lipids.
- ❖ In this process, sequential removal of one carbon at a time from free fatty acids of chain length ranging from C₁₃ to C₁₈ occur.

ω -Oxidation

- ❖ ω -Oxidation is normally a very minor pathway brought about by **hydroxylase enzymes** involving **cytochrome P-450** in the **endoplasmic reticulum**.
- ❖ Fatty acids with oxygen function (alcoholic or carboxyl) at the methyl terminal end (ω -end) are formed by ω -oxidation and frequently occur as constituents of **cutin and suberin**.
- ❖ The requirements for the oxygenase-mediated conversion of a ω -methyl fatty acyl CoA into a ω -hydroxymethyl fatty acyl CoA are **molecular oxygen**, reduced pyridine nucleotide and a **non-heme iron protein** in higher plants.

β -Oxidation of fatty acids

In 1904, Franz Knoop made a critical contribution to the elucidation of the mechanism of fatty acid oxidation and demonstrated that most of the fatty acids are degraded by oxidation at the **β -carbon**.

- ❖ β -Oxidation of fatty acids takes place in **mitochondria**.

- ❖ Fatty acids are activated before they enter into mitochondria for oxidation.

Activation of fatty acids

- ❖ Fatty acids are converted into active intermediate in a reaction with **ATP and coenzyme A**.
- ❖ A **thioester linkage** between the carboxyl group of a fatty acid and the sulfhydryl group of coenzyme A is formed with the hydrolysis of ATP.
- ❖ This activation reaction takes place on the **outer mitochondrial membrane** catalysed by **acyl CoA synthetase**.
- ❖ Several **acyl CoA synthetases** each specific for fatty acids of different chain length are present in the membrane of mitochondria.

Penetration of long chain fatty acids into mitochondria

- ❖ Long chain acyl-CoA molecules do not readily get into the inner mitochondrial membrane and are carried across the inner membrane by conjugating with **carnitine** (β -hydroxy γ -trimethyl ammonium butyrate), a zwitterionic compound formed from lysine.
- ❖ Activation of lower fatty acids and their oxidation within the mitochondria occur independently of carnitine, but long-chain acyl CoA will become oxidised unless they form acylcarnitines.
- ❖ The acyl CoA combines with carnitine in the presence of **carnitine acyltransferase I**, which is bound to the outer mitochondrial membrane.
- ❖ **Acylcarnitine** is transported in, coupled with the transport out of one molecule of carnitine.
- ❖ The acylcarnitine then reacts with coenzyme A catalyzed by **carnitine palmitoyl transferase II**, located on the inside of the inner membrane.
- ❖ Acyl CoA is reformed in the mitochondrial matrix and carnitine is liberated.

Oxidation

A saturated acyl CoA is oxidised by a **recurring sequence of four reactions**

- ❖ Oxidation in presence of FAD, hydration, oxidation in presence of NAD^+ , and thiolysis by CoASH.
- ❖ In β -oxidation, **2 carbons are cleaved** at a time from acyl CoA molecules, starting from the carboxyl end.
- ❖ The chain is **broken** between the α -and β -carbon atoms.
- ❖ The two-carbon units formed are acetyl CoA.

i) The first reaction in β -oxidation of acyl CoA is the formation of *trans* Δ^2 - enoyl CoA or α , β -unsaturated acyl CoA in presence of acyl-CoA dehydrogenase and the coenzyme, FAD.

ii) The next step is the **hydration of the double bond** between C-2 and C-3 by enoyl CoA hydratase with the formation of β -hydroxy acyl CoA.

iii) In the third step, the β -hydroxy acyl CoA is **dehydrogenated** in the presence of **β -hydroxy acyl CoA dehydrogenase** and NAD^+ forming β -ketoacyl CoA.

iv) In the last step of β -oxidation, β -ketoacyl CoA reacts with coenzyme A in the presence of the enzyme, **thiolase**.

The products of this reaction are acetyl CoA and an acyl CoA containing **two carbons less than the original acyl CoA molecule** that underwent oxidation.

By the above steps of β -oxidation fatty acids are completely degraded to acetyl CoA units. The acetyl CoA formed from fatty acids can be oxidised to carbon dioxide and water via citric acid cycle.

Energetics of β oxidation

The energetics or the energy conserved in terms of ATP by oxidation of a molecule of palmitic acid is given below:

- ❖ Palmitic acid (16 carbons) undergoes β -oxidation forming eight molecules of acetyl CoA by undergoing **seven β -oxidation spirals**.
- ❖ When one cycle of β -oxidation takes place, one molecule of FADH_2 , one molecule of NADH and one molecule of acetyl CoA are produced.
- ❖ Electrons from these reducing equivalents (FADH_2 and NADH) are transported through the **respiratory chain in mitochondria** with simultaneous regeneration of high-energy phosphate bonds.
- ❖ Mitochondrial oxidation of FADH_2 eventually results in the net formation of about 1.5 ATP.
- ❖ Likewise, oxidation of electrons from NADH yields 2.5 molecules of ATP. Hence, a total of **four ATP molecules** are formed per cycle and **ten molecules of ATP** are formed through Krebs's cycle from each molecule of acetyl CoA.

8 Acetyl CoA through TCA cycle yield (8x10)	= 80 ATP
7 β -oxidation spiral reactions yield (7x4)	= 28 ATP

Total	108 ATP

ATP utilized in the initial step	= 2 ATP
Hence, complete oxidation of palmitic acid yields 106 ATP.	

Oxidation of monounsaturated fatty acids

❖ Oxidation of monounsaturated fatty acids follows many of the reactions of saturated fatty acids except the requirement of **two additional enzymes, an isomerase and a novel reductase.**

❖ Reactions of monounsaturated fatty acid are explained by considering the oxidation of a C-16 unsaturated fatty acid, palmitoleic acid, having a single double bond between C-9 and C-10 .

❖ Palmitoleic acid is activated and transported across the inner mitochondrial membrane in the same way as saturated fatty acids.

❖ Palmitoleoyl CoA undergoes three cycles of degradation as in β oxidation. But the *cis* Δ^3 decenoyl CoA formed after the third cycle does not serve as a substrate for acyl CoA dehydrogenase.

❖ The presence of a double bond between C-3 and C-4 prevents the formation of another double bond between C-2 and C-3.

❖ **An isomerase** converts the *cis* double bond into a *trans* double bond and shifts the position of double bond between C-2 and C-3.

❖ The subsequent or follow up reactions are those of the β oxidation pathway in which the *trans* Δ^2 decenoyl CoA is a regular substrate.

Oxidation of polyunsaturated fatty acids

The oxidation of a polyunsaturated fatty acid, linoleic acid, with *cis*- Δ^9 and *cis*- Δ^{12} double bonds, is considered.

❖ The *cis*- Δ^3 double bond formed after three rounds of β -oxidation is converted into a *trans* double bond by the **isomerase**.

❖ This permits one more round of β -oxidation.

- ❖ The acyl CoA produced by four rounds of β -oxidation of linoleic acid contains a *cis*- Δ^4 double bond, which undergoes dehydrogenation by **acyl CoA dehydrogenase** yielding *trans* Δ^2 , *cis*- Δ^4 dienoyl intermediate.
- ❖ This intermediate is not a substrate for the next enzyme in the β -oxidation pathway.
- ❖ This intermediate is converted into a ***trans* Δ^3 enoyl CoA** to the *trans* Δ^2 form, an intermediate generally found in β -oxidation pathway and results in complete oxidation of the fatty acid.

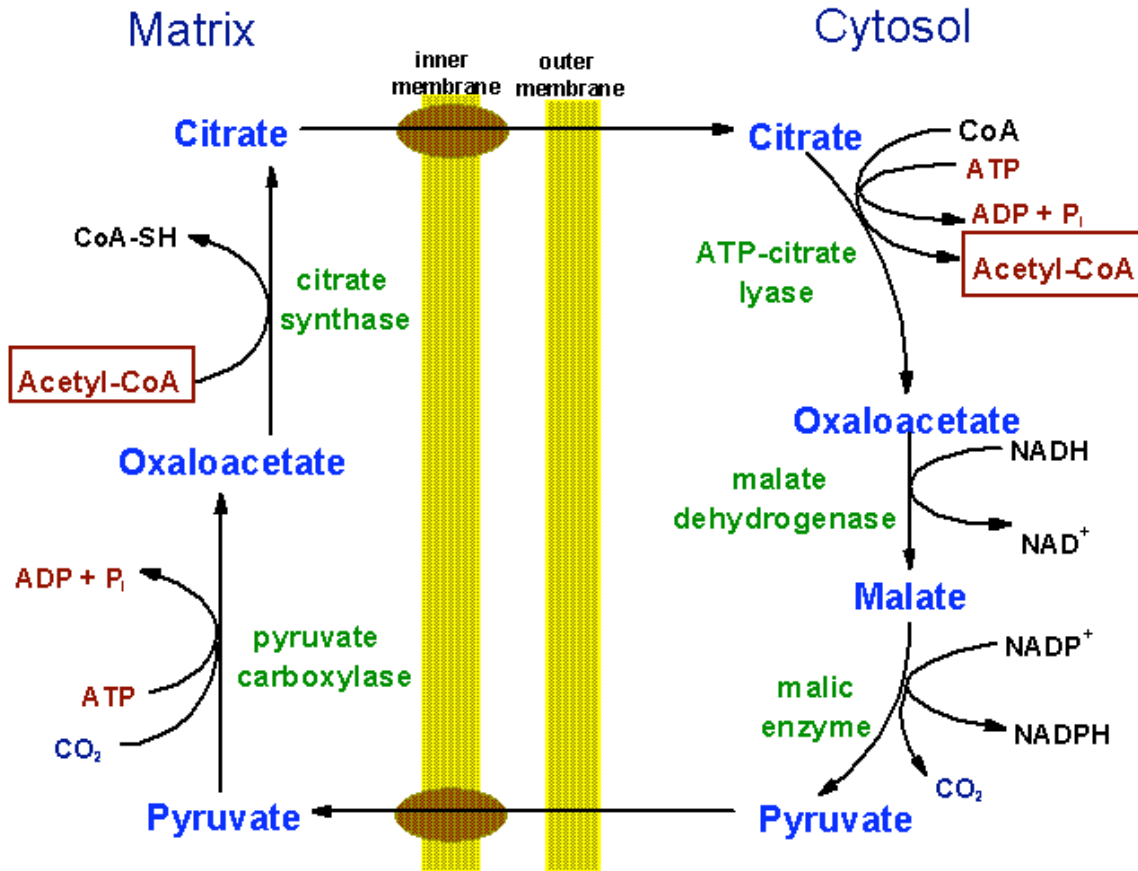
Lecture: 27

Fatty acid and triacyl glycerol biosynthesis

Biosynthesis of fatty acids

- ❖ It was thought that fatty acid biosynthesis occurred by **reversal of the β -oxidation pathway**.
- ❖ On the contrary, it occurs by a separate pathway that differs from β -oxidation in several ways.
 - i. Synthesis takes place in the **cytosol**, in contrast with degradation or oxidation, which occurs in the **mitochondrial matrix**.
 - ii. Intermediates in fatty acid synthesis are covalently linked to the sulfhydryl group of an **acyl carrier protein (ACP)** whereas intermediates in fatty acid breakdown are bonded to coenzyme A.
 - iii. The enzymes of fatty acid synthesis in animals are **joined in a single polypeptide chain called fatty acid synthase**. In contrast, the degradative enzymes do not seem to be associated. Plants employ separate enzymes to carry out the biosynthetic reactions.
 - iv. The reductant in fatty acid synthesis is **NADPH**, whereas the oxidants in fatty acid oxidation are NAD^+ and FAD .

Pathway for the movement of acetyl-CoA units from within the mitochondrion to the cytoplasm for use in lipid and cholesterol biosynthesis.

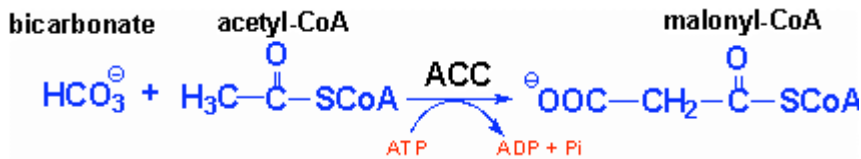


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The following seven steps are involved in fatty acid biosynthesis.

Formation of malonyl CoA

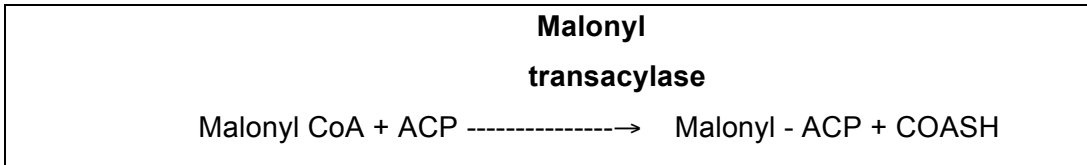
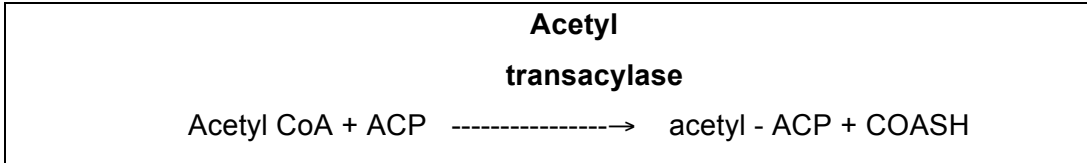
The synthesis of malonyl CoA from acetyl CoA is catalyzed by acetyl CoA carboxylase having biotin as prosthetic group. The production of malonyl CoA is the initial and controlling step in fatty acid synthesis. In this reaction, bicarbonate serves as a source of CO₂. The reaction takes place in two steps, namely carboxylation of biotin involving ATP and transfer of the carboxyl group to acetyl CoA resulting in malonyl CoA.



- **Acetyl CoA carboxylase** plays a key role in regulating fatty acid metabolism and the same is inactivated by phosphorylation.

ii) Formation acetyl and malonyl ACP

Acetyl transacylase and malonyl transacylase catalyze the formation of acetyl ACP and malonyl ACP respectively. Acetyl transacylase can transfer acetyl as well acyl groups whereas malonyl transacylase is highly specific.



iii) Formation of acetoacetyl - ACP (β -ketoacyl ACP)

- ❖ Acetyl ACP condenses with malonyl ACP to form acetoacetyl ACP.
- ❖ Carbondioxide is eliminated from malonyl ACP.

iv) Reduction of β -ketoacyl ACP to β -hydroxyl acyl ACP.

- ❖ The β - keto group in acetoacetyl ACP is reduced by **NADPH- dependent β -ketoacyl reductase**.

v) Formation of unsaturated acyl ACP.

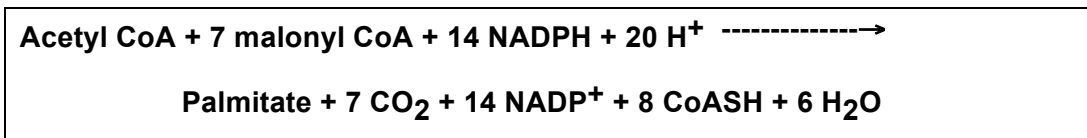
The β -hydroxyl group combines with the hydrogen atom attached to the γ -carbon and a water molecule is removed to form α, β -unsaturated acyl ACP.

vi) Formation of Acyl ACP

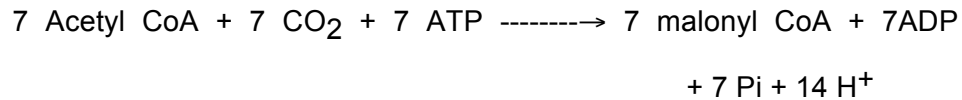
- ❖ The unsaturated acyl ACP is converted in the next step to a saturated acyl ACP by the enzyme **α, β -unsaturated acyl ACP reductase** using NADPH as the coenzyme.
- ❖ The resultant product contains two carbon atoms more than the starting material.
- ❖ Addition of subsequent acetyl units through malonyl ACP leads to the formation of 16-carbon palmitate.

Stoichiometry of fatty acid synthesis

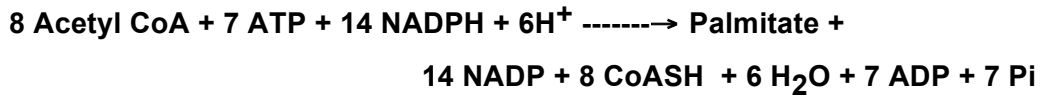
The stoichiometry of the synthesis of palmitate is given below:



The equation for the synthesis of the malonyl CoA used in the above reaction is



The overall stoichiometry for the synthesis of palmitate is



Fatty acid synthesis and degradation are reciprocally regulated so that both are not simultaneously active.

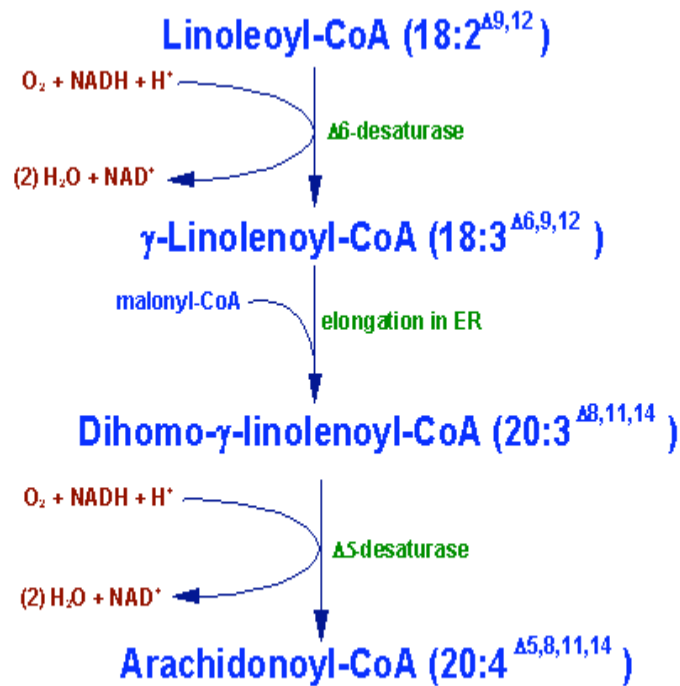
Elongation of fatty acids or synthesis of long chain fatty acids

- ❖ Elongation by the **fatty acid synthase complex** stops upon formation of palmitate (16 C).
- ❖ Further elongation and the formation of double bonds are carried out by other enzyme systems.
- ❖ The major product of fatty acid biosynthesis is the 16-carbon fatty acid, palmitate.
- ❖ Additional enzymes are required to synthesise longer chain fatty acids.
- ❖ Chain elongation reactions occur both in **mitochondria** and in **microsomes**. Microsomes are small membrane-enclosed vesicles derived from the endoplasmic reticulum of cells.
- ❖ Mitochondria and microsomes carry out chain elongation by adding two-carbon units to fatty acids.
- ❖ The microsomal system has great physiological significance in that it provides the long chain fatty acids (18-24C) required for the **myelination of nerve cells in animal system**.
- ❖ Chain elongation occurs by a cycle of **condensation, reduction, dehydration followed by another reduction** that parallels cytosolic fatty acid biosynthesis.
- ❖ The more active elongation system adds **two carbons to palmitoyl-CoA to make it steroyl CoA**.
- ❖ The mechanism of elongation is identical with that known in the synthesis of palmitate except the enzyme systems and the acyl carrier protein.

Biosynthesis of unsaturated fatty acids

- ❖ Palmitate and stearate serve as precursors of the two most common monounsaturated fatty acids, **palmitoleate, 16:1, (Δ^9)** and **oleate, 18:1 (Δ^9)** respectively.

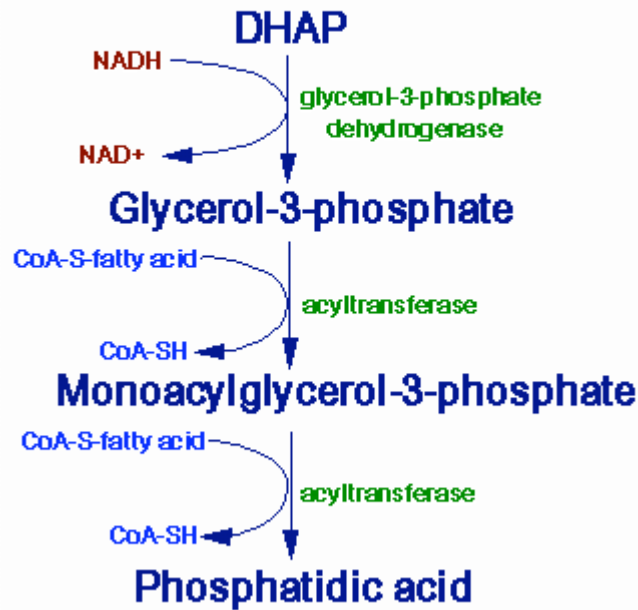
- ❖ Each of these fatty acids has a single double bond between C-9 and C-10.
- ❖ The **double bond is introduced into the fatty acid chain** by an oxidative reaction catalysed by **fatty acyl-CoA desaturase**, which is **NADPH-dependent enzyme**.
- ❖ The unsaturated fatty acids, linoleate, 18:2 ($\Delta^{9,12}$) and α -linolenate, 18:3 ($\Delta^{9,12,15}$) cannot be synthesised by mammals; but plants can synthesise both.
- ❖ The **desaturases** responsible for synthesis of both the above fatty acids are present in **endoplasmic reticulum of plants**.
- ❖ The plant **desaturases** oxidise phosphatidylcholine-bound oleate and produce polyunsaturated fatty acids and do not directly add double bonds to the fatty acids.
- ❖ Once ingested, the linoleate are readily converted to other **polyunsaturated fatty acids** like γ -linolenate, **arachidonic acid** etc. in animals and human beings.



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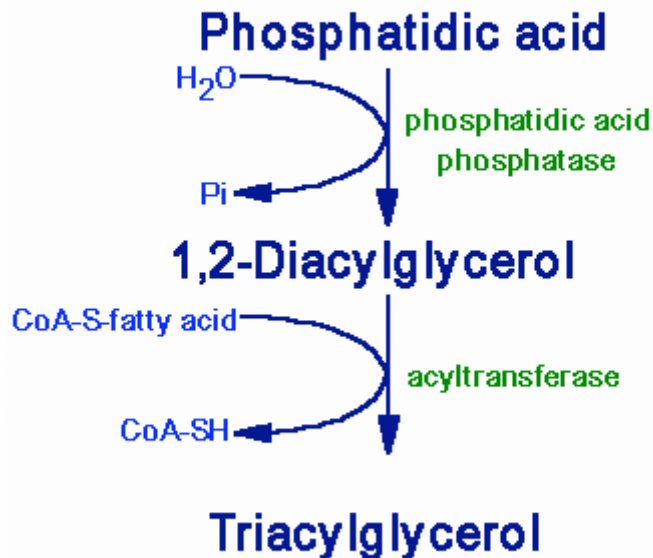
Biosynthesis of triacylglycerols

Phosphatidic Acid Synthesis



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Triacylglycerol Synthesis



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- Triacylglycerols are not synthesised by reversal of lipolysis.
- They are synthesised by a different mechanism in which both glycerol and fatty acids are activated by ATP before they are incorporated into acylglycerols.

i) Activation of glycerol

- *Glycerol kinase* catalyses the activation of glycerol to glycerol 3-phosphate.
- If glycerol kinase is found in low quantity or absent, glycerol 3-phosphate will be formed from dihydroxyacetone phosphate obtained from glycolysis and this reaction is catalysed by the enzyme **glycerol 3-phosphate dehydrogenase**.

ii) Activation of fatty acids

- Fatty acids are activated to acyl CoA by the enzyme **acyl CoA synthetase**, utilizing ATP and CoASH.
- Two molecules of acyl CoA combine with glycerol 3-phosphate to form 1,2-diacylglycerol phosphate.
- Formation of 1,2-diacyl glycerol phosphate takes place in two stages, catalysed by **glycerol 3-phosphate acyl transferase** and then by **1-acyl glycerol 3-phosphate acyl transferase**.
- The phosphate group is removed from 1,2-diacyl glycerol phosphate by **phosphatidate phosphatase** to form 1,2-diacyl glycerol.
- Triacylglycerols are finally formed by esterification of one or more molecule of acyl CoA with the diacylglycerol.

Alternative pathway for triacylglycerol biosynthesis

- In this pathway, dihydroxyacetone phosphate from glycolysis is reduced by NADPH, acylated and converted to lysophosphatidate.

This pathway accounts for less than 10% of total triacylglycerol synthesis.

Lecture: 28

TRANSAMINATION, DEAMINATION AND DECARBOXYLATION

- Protein metabolism is a key physiological process in all forms of life.
- Proteins are converted to amino acids and then catabolised.
- The complete hydrolysis of a polypeptide requires mixture of peptidases because individual peptidases do not cleave all peptide bonds.
- Both **exopeptidases and endopeptidases** are required for complete conversion of protein to amino acids.

Amino acid metabolism

- The amino acids not only function as **energy metabolites** but also used as **precursors** of many physiologically important compounds such as **heme, bioactive amines, small peptides, nucleotides and nucleotide coenzymes**.
- In normal human beings about 90% of the energy requirement is met by oxidation of carbohydrates and fats. The remaining 10% comes from oxidation of the carbon skeleton of amino acids.
- Since the 20 common protein amino acids are distinctive in terms of their carbon skeletons, amino acids require unique degradative pathway.
- The degradation of the carbon skeletons of 20 amino acids converges to just **seven metabolic intermediates** namely.

i. Pyruvate

ii. Acetyl CoA

iii. Acetoacetyl CoA

iv. α -Ketoglutarate

v. Succinyl CoA

vi. Fumarate

vii. Oxaloacetate

- Pyruvate, α -ketoglutarate, succinyl CoA, fumarate and oxaloacetate can serve as **precursors for glucose synthesis** through gluconeogenesis. Amino acids giving rise to these intermediates are termed as **glucogenic**.
- Those amino acids degraded to yield **acetyl CoA** or acetoacetate are termed **ketogenic** since these compounds are used to synthesize ketone bodies.
- Some amino acids are **both glucogenic and ketogenic** (For example, phenylalanine, tyrosine, tryptophan and threonine).

Catabolism of amino acids

The **important reaction** commonly employed in the breakdown of an amino acid is always the **removal of its α -amino group**. The product **ammonia** is excreted after conversion to **urea** or other products and the carbon skeleton is degraded to CO_2 releasing energy. The important reaction involved in the deamination of amino acids is

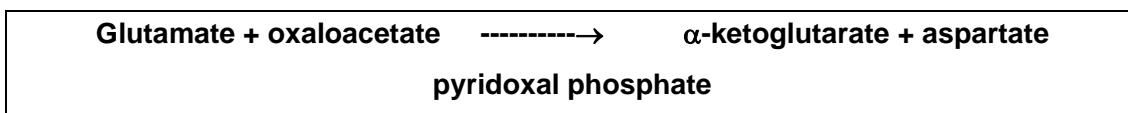
i. Transamination

ii. Oxidative deamination

iii. Non oxidative deamination

Transamination

- Most amino acids are deaminated by transamination reaction catalysed by **aminotransferases or transaminases**.
- The **α -amino group** present in an amino acid is transferred to an α -keto acid to yield a new amino acid and the α -keto acid of the original amino acid.
- The predominant amino group acceptor is **α -keto glutarate**. Glutamate's amino group is then transferred to oxaloacetate in a second transamination reaction yielding aspartate.



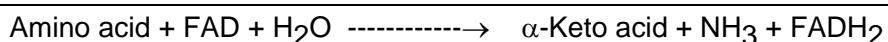
- **Pyridoxal phosphate**, the coenzyme of pyridoxine (vitamin B6) plays an important role in these reactions.
- Amino transferase reactions occur in two stages.
 - Pyridoxal phosphate is covalently attached to the amino transferases via a **Schiff's base linkage** formed between the aldehyde group of pyridoxal phosphate and the **epsilon amino group of lysine** residue of the enzyme. Pyridoxal phosphate is converted to pyridoxamine phosphate.
 - In the second stage, the amino group attached to pyridoxamine phosphate is transferred to a different keto acid to yield a new amino acid and releases pyridoxal phosphate

Oxidative deamination

- Transamination does not result in net deamination, since one amino acid is replaced by another amino acid.

- The **function of transamination is to funnel the amino nitrogen** into one or a few amino acids.
- For glutamate to play a role in the net conversion of amino groups to ammonia, a mechanism for glutamate deamination is needed so that α -ketoglutarate can be regenerated for further transamination.
- The generation is accomplished by the oxidative deamination of glutamate by glutamate dehydrogenase.
- Glutamate is oxidatively deaminated in the mitochondrion by glutamate dehydrogenase. **NAD⁺ or NADP⁺** functions as the coenzyme.
- Oxidation is thought to occur with the transfer of a hydride ion from glutamate's α carbon to NAD(P)⁺ to form α -iminoglutarate, which is then hydrolysed to α -ketoglutarate and ammonia.
- The ammonia produced is then converted to urea in mammals

Two non-specific amino acid oxidases namely, **L-amino acid and D-amino acid oxidases** catalyse the oxidation of L and D-amino acids utilizing **FAD as their coenzymes**.



Non-oxidative deamination

- Amino acids such as serine and histidine are deaminated non-oxidatively
- The other reactions involved in the catabolism of amino acids are decarboxylation, transulfuration, desulfuration, dehydration etc.

Decarboxylation

- The decarboxylation process is important since the products of decarboxylation reactions give rise to physiologically active amines.
- The enzymes, **amino acid decarboxylases** are **pyridoxal phosphate-dependent enzymes**.
- Pyridoxal phosphate forms a Schiff's base with the amino acid so as to stabilise the α -carbanion formed by the cleavage of bond between carboxyl and α -carbon atom.

- The physiologically active amines epinephrine, **nor-epinephrine**, **dopamine**, **serotonin**, **γ-amino butyrate** and **histamine** are formed through decarboxylation of the corresponding precursor amino acids.

Lecture 29

Ammonia assimilating enzymes, GDH, GS and GOGAT

Biosynthesis of ammonia

Ammonia is produced from **the catabolic pathways of amino acids**. Some of the ammonia that is generated is recycled and used in a variety of biosynthetic processes. The excess ammonia is excreted directly or converted to **uric acid or urea** for excretion depending on the organism.

- Many aquatic organisms simply excrete ammonia as NH_4^+ into the surrounding medium.
- Most terrestrial vertebrates convert the ammonia into urea (humans, other mammals and adult amphibians) or uric acid (birds, reptiles).
- In plants **ammonia is also derived from nitrate absorbed from the soil**. Nitrate is first converted to nitrite and then to ammonia.
- The major route for the **assimilation of ammonia into organic nitrogen** is the result of the **collaborative activity of glutamine synthetase (GS) and glutamate synthase** (also called as Glutamine oxoglutarate aminotransferase or GOGAT).
- Ammonia is fixed with the help of **glutamine synthetase** which catalyses the joining of ammonia to glutamic acid.
- The enzyme **GOGAT** is dependent either on NADPH (bacteria, roots and developing seeds but not in leaves) or ferredoxin (leaves, legume nodules, roots and legume seeds) to transfer the amino nitrogen from glutamine to oxoglutarate.
- The **net reaction** is the production of one molecule of glutamate from one molecule of oxoglutarate and one molecule of NH_4^+
- An additional enzyme **glutamate dehydrogenase(GDH)** is widely distributed but is not significantly involved in ammonia assimilation because of high K_m value.
- All the 20 protein amino acids are synthesised by plants and microorganisms.
- Human beings are able to synthesise only 10 amino acids, which are called as **non-essential amino acids**.

- The synthesis of non essential amino acids require only one or two step reactions whereas the synthesis of essential amino acids require multi step reactions.
- The synthesis of 20 amino acids is grouped into families where the precursor compounds are same for one family .

Lecture: 31

SECONDARY METABOLITES - OCCURRENCE, CLASSIFICATION AND FUNCTIONS OF PHENOLICS

Secondary metabolites

- ❖ **Organic compounds** produced by the plants which have **no direct role in the growth and development** are called as **secondary metabolites**.
- ❖ There are about 100,000 secondary compounds that are produced by the plants and the structures of more than 15000 alkaloids, 30000 terpenes, several thousand phenyl propanoids, 1000 flavonoids, 500 quinones, 700 polyacetylenes and 800 non-protein amino acids have already been characterised.
- ❖ These secondary compounds produced by plants are grouped into **five** major groups.
 1. **Phenolics**
 2. **Terpenoids**
 3. **Alkaloids**
 4. **Special nitrogen metabolites**
 5. **Cuticular compounds**

Phenolics

- ❖ Phenolics are a group of compounds characterized by at least **one aromatic ring bearing one or more hydroxyl groups**.
- ❖ Most of the thousands of phenolics known to date are of plant origin.
- ❖ These phenolic compounds are biosynthesised through **shikimate pathway**.

Shikimate pathway
- ❖ Shikimate pathway is an important pathway in plants through which many secondary plant products are synthesised.
- ❖ The **key starting materials** are **phosphoenolpyruvate (PEP) and erythrose 4P** derived from glycolysis and pentose phosphate pathways, respectively.
- ❖ These two compounds condense to produce a six carbon cyclic compound with one carbon (COOH) side chain namely **shikimate**.
- ❖ Then shikimate is phosphorylated and condensed with another molecule of PEP to produce a cyclic compound containing a three carbon and one carbon side chains.
- ❖ This is finally converted to aromatic amino acids **phenylalanine and tyrosine**.
- ❖ These amino acids are **deaminated** followed by **hydroxylation** at different carbon atoms in the aromatic ring to form **cinnamic acid derivatives**.

- ❖ These cinnamic acid derivatives are utilised for the synthesis of different phenolic compounds.

Functions of phenolics

- Phenolics are of great importance as **cell wall components**.
- They form **part of cell wall structures** such as **lignins, cutins and suberins**, which provide **mechanical support and function as barriers against microbial attack**.
- The **flavonoids and anthocyanins** contribute to flower and fruit colours. This is important for attracting insects and animals to the plant for pollination and seed dispersal.
- Phenolics also play a **defensive role** in plants by protecting against predators.
- Simple phenolic acids, polyphenolics like tannins and phenolic resins at the plant surface are **effective feeding deterrents**.
- Phenolics are accumulated as **post-infectious low molecular compounds** called **phytoalexins** as a result of microbial attack.
- Among the phenolic phytoalexins, hydroxycoumarins and hydroxycinnamate conjugates contribute to **disease resistance mechanism** in plants.
- Phenolic compounds also produce **allelopathic effect**. A well known compound from Juglans species is juglone which is highly toxic for a wide range of plants. It occurs in the plant as a non-toxic glucoside and is made active by deglucosylation and oxidation after leaching from the leaves into the soil.
- Phenolics also function as **signal molecules** in the interaction between **nitrogen fixing bacteria and leguminous plants**.
- These plants exude **flavonoids** which act selectively in Rhizobia as **inducers of nodulation gene transcription**.
- Salicylic acid is strongly implicated as a **signal molecule** which induces active defense responses in several plant species against many types of pathogens.
- Recently, it has been shown that phenolic compounds function as **effective antioxidants**.
- Polyphenolics are important in **foodstuffs, wines and herbal teas** because of their **astringent taste**.
- Plants rich in polyphenolics were used as **tanning agents** in leather industries.
- **Phenolic pigments** (anthocyanins, flavones etc) of fruits are most widespread food colours occurring in fruit juices, wines and jams.
- Anthocyanins have considerable potential in the food industry as **safe and effective food additives**.



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