Structure, Classification, and Functions of Carbohydrates

Introduction

Carbohydrates are necessary for all living things, including people, plants, and microbes. They are essential to our diet and may be found in many different foods, such as fruits, grains, vegetables including potatoes, milk, honey, and table sugar.

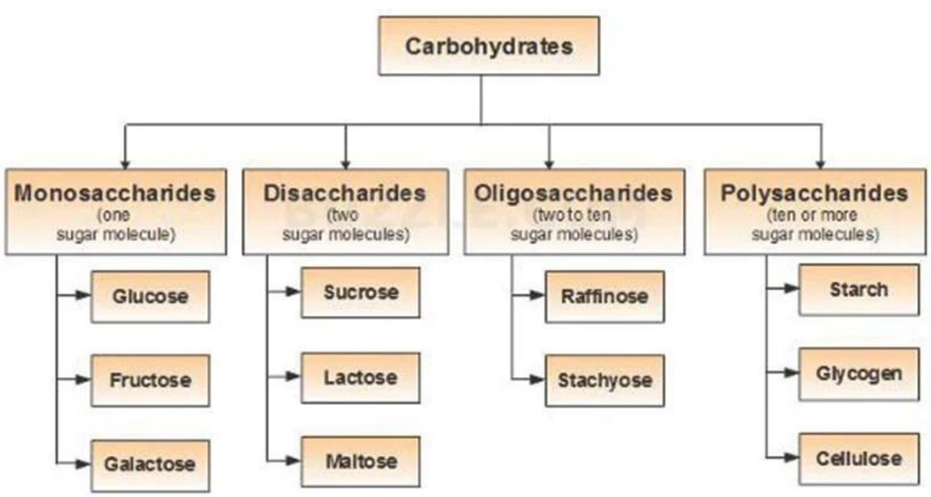
Out of the four macromolecules—proteins, fats, and nucleic acids—carbohydrates were the last to catch scientists' interest for investigation and further study.

What are Carbohydrates?

Carbohydrates are defined as biomolecules containing a group of naturally occurring carbonyl compounds (aldehydes or ketones) and several hydroxyl groups. It consists of carbon (C), hydrogen (H), and oxygen (O) atoms, usually with a hydrogen-oxygen atom ratio of 2:1 (as in water). It's represented with the empirical formula $C_m(H_2O)_n$ (where m and n may or may not be different) or $(CH_2O)_n$.

But some compounds do not follow this precise stoichiometric definition, such as uronic acids. And there are others that, despite having groups similar to carbohydrates, are not classified as one of them, e.g., formaldehyde and acetic acid.

Classification of Carbohydrates



Carbohydrates are divided into four major groups based on the degree of polymerization: monosaccharides, disaccharides, oligosaccharides, and polysaccharides. Given below is a brief account of the structure and functions of carbohydrate groups.

1. Monosaccharides

Monosaccharides are the simplest carbohydrates and cannot be hydrolyzed into other smaller carbohydrates. The “mono” in monosaccharides means one, which shows the presence of only one sugar unit.

They are the building blocks of disaccharides and polysaccharides. For this reason, they are also known as simple sugars. These simple sugars are colorless, crystalline solids that are soluble in water and insoluble in a nonpolar solvent.

The general formula representing monosaccharide structure is $Cn(H_2O)n$ or CnH_2nOn. Dihydroxyacetone and D- and L-glyceraldehydes are the smallest monosaccharides – here, n=3.

The monosaccharides containing the aldehyde group (the functional group with the structure, R-CHO) are known as aldolases and the one containing ketone groups is called ketoses (the functional group with the structure RC(=O)R′). Some examples of monosaccharides are glucose, fructose, erythrulose, and ribulose.

D-glucose is the most common, widely distributed, and abundant carbohydrate. It’s commonly known as dextrose and it’s an aldehyde containing six carbon atoms, called aldohexose. It’s present in both, open-chain and cyclic structures.

Most monosaccharide names end with the suffix -ose. And based on the number of carbons, which typically ranges from three to seven, they may be known as trioses (three carbons), tetroses (four carbons), pentoses (five carbons), hexoses (six carbons), and heptoses (seven carbons)

Although glucose, galactose, and fructose all have the chemical formula of $C_6H_{12}O_6$, they differ at the structural and chemical levels because of the different arrangement of functional groups around their asymmetric carbon.

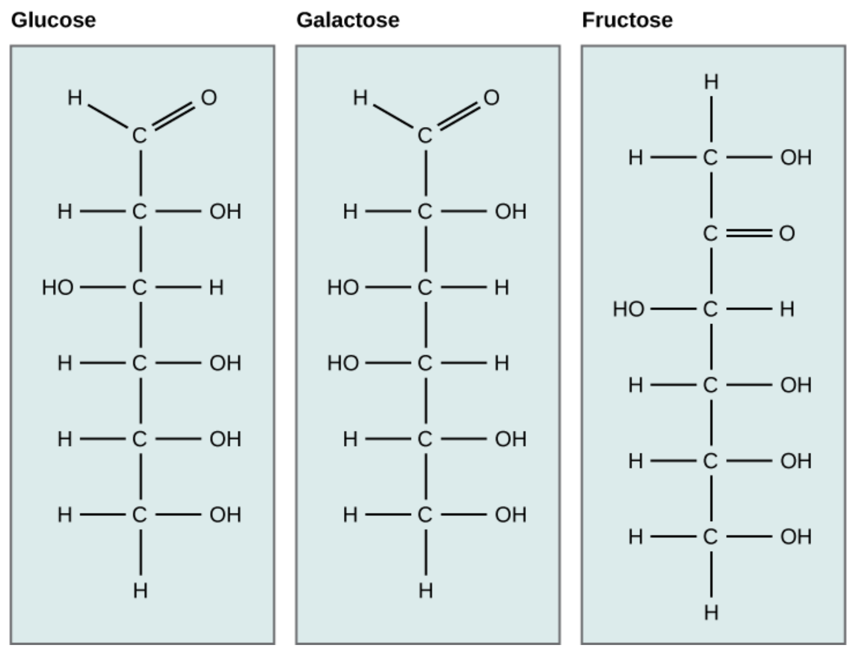


Figure: A structural representation of glucose, fructose, and galactose.

Structure of Monosaccharides

Monosaccharides are either present as linear chains or ring-shaped molecules. In a ring form, glucose's hydroxyl group (-OH) can have two different arrangements around the anomeric carbon (carbon-1 that becomes asymmetric in the process of ring formation).

If the hydroxyl group is below carbon number 1 in the sugar, it is said to be in the alpha (α) position, and if it is above the plane, it is said to be in the beta (β) position.

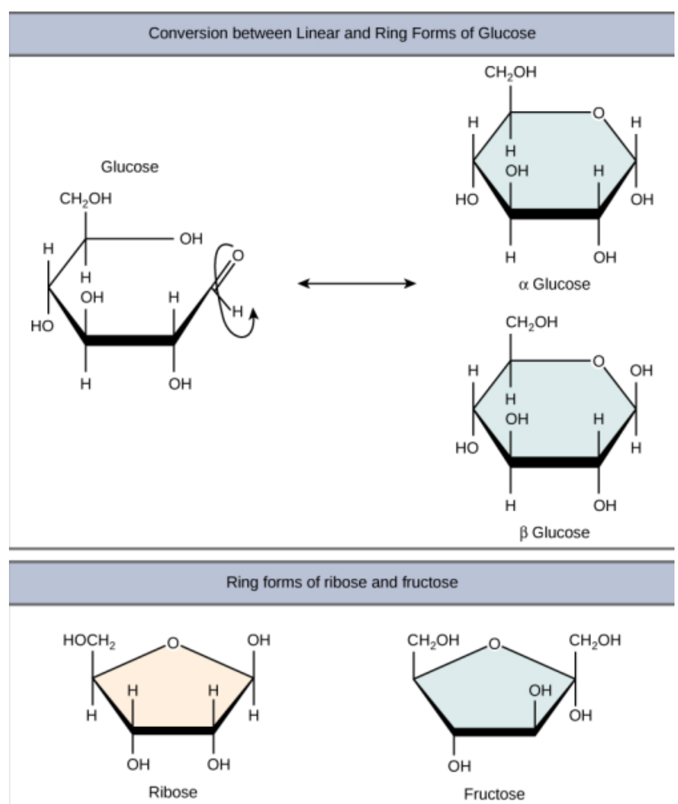


Figure: A structural representation of ring forms of glucose and fructose.

Functions of Monosaccharides

- Glucose ($C_6H_{12}O_6$) is an important source of energy in humans and plants. Plants synthesize glucose using carbon dioxide and water, which in turn is used for their energy requirements. They store the excess glucose as starch which humans and herbivores consume.
- The presence of galactose is in milk sugar (lactose), and fructose in fruits and honey makes these foods sweet.
- Ribose is a structural element of nucleic acids and some coenzymes.
- Mannose is a constituent of mucoproteins and glycoproteins required for the proper functioning of the body.

2. Disaccharides

Disaccharides consist of two sugar units. When subjected to a dehydration reaction (condensation reaction or dehydration synthesis), they release two monosaccharide units.

In this process, the hydroxyl group of one monosaccharide combines with the hydrogen of another monosaccharide through a covalent bond, releasing a molecule of water. The covalent bond formed between the two sugar molecules is known as a **glycosidic bond**.

The glycosidic bond or glycosidic linkage can be alpha or beta type. The alpha bond is formed when the OH group on the carbon-1 of the first glucose is below the ring plane, and a beta bond is formed when the OH group on the carbon-1 is above the ring plane.

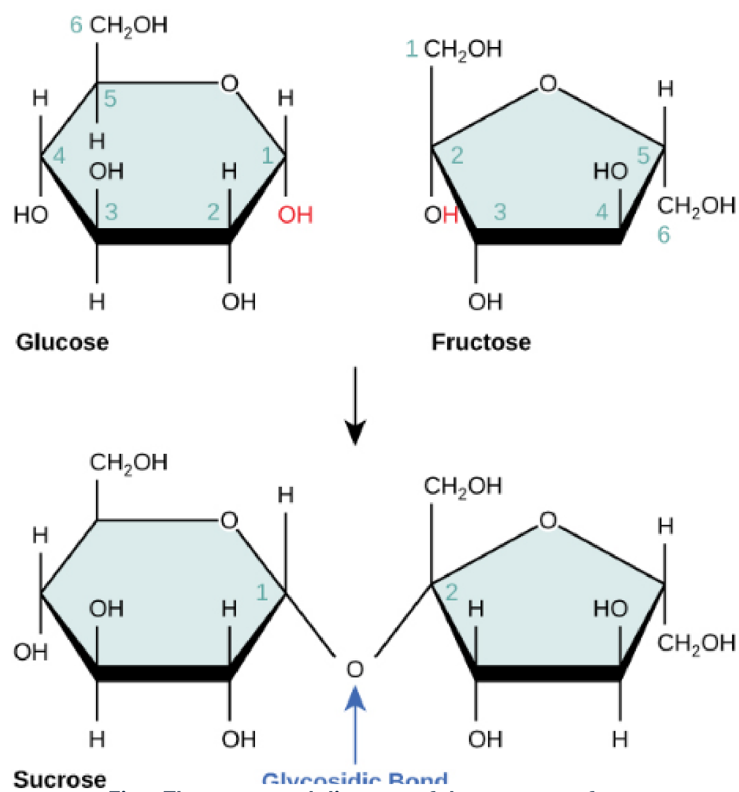


Fig. : The structural diagram of the process of glycosidic bond formation between two sugar units (glucose and fructose) forming a disaccharide (sucrose).

Some examples of disaccharides are lactose, maltose, and sucrose. Sucrose is the most abundant disaccharide of all and is composed of one D-glucose molecule and one D-fructose molecule. The systematic name for sucrose is O-α-D-glucopyranosyl-(1→2)-D-fructofuranoside.

Lactose occurs naturally in mammalian milk and is composed of one D-galactose molecule and one D-glucose molecule. The systematic name for lactose is O-β-D-galactopyranosyl-(1→4)-D-glucopyranose.

Disaccharides can be classified into two groups based on their ability to undergo oxidation-reduction reactions.

- **Reducing sugar:** A disaccharide in which the reducing sugar has a free hemiacetal unit serving as a reducing aldehyde group. Examples include maltose and cellobiose.
- **Non-reducing Sugar:** Disaccharides that do not have a free hemiacetal because they bond through an acetal linkage between their anomeric centers. Examples are sucrose and trehalose.

Some other examples of disaccharides include lactulose, chitobiose, kojibiose, nigerose, isomaltose, sophorose, laminaribiose, gentiobiose, turanose, maltulose, trehalose, palatinose, gentiobiulose, mannobiose, melibiose, melibiulose, rutinose, rutinulose, and xylobiose.

A list of disaccharides with their monomer units is given below:

Disaccharide	Monomer Units
Sucrose	**Glucose and Fructose**
Lactose	**Galactose and Glucose**
Maltose	**Glucose and Glucose (alpha-1,4 linkage)**
Trehalose	**Glucose and Glucose (alpha-1, alpha-1 linkage)**
Cellobiose	**Glucose and Glucose (beta-1,4 linkage)**
Gentiobiose	**Glucose and Glucose (beta-1,6 linkage)**

Functions of Disaccharides

- Sucrose is a product of photosynthesis, which functions as a major source of carbon and energy in plants.
- Lactose is a major source of energy in animals.

- Maltose is an important intermediate in starch and glycogen digestion.
- Trehalose is an essential energy source for insects.
- Cellobiose is essential in carbohydrate metabolism.
- Gentiobiose is a constituent of plant glycosides and some polysaccharides.

3. Oligosaccharides

Oligosaccharides are compounds that yield 3 to 10 molecules of the same or different monosaccharides on hydrolysis. All the monosaccharides are joined through glycosidic linkage. And based on the number of monosaccharides attached, the oligosaccharides are classified as trisaccharides, tetrasaccharides, pentasaccharides, and so on.

The general formula of trisaccharides is $C_n(H_2O)_{n-2}$, and that of tetrasaccharides is $Cn(H_2O)n-3$, and so on. The oligosaccharides are normally present as glycans. They are linked to either lipids or amino acid side chains in proteins by N- or O-glycosidic bonds known as glycolipids or glycoproteins.

The glycosidic bonds are formed in the process of glycosylation, in which a carbohydrate is covalently attached to an organic molecule, creating structures such as glycoproteins and glycolipids.

- **N-Linked Oligosaccharides:** It involves the attachment of oligosaccharides to asparagine via a beta linkage to the amine nitrogen of the side chain. In eukaryotes, this process occurs at the membrane of the endoplasmic reticulum. Whereas in prokaryotes, it occurs at the plasma membrane.
- **O-Linked Oligosaccharides:** It involves the attachment of oligosaccharides to threonine or serine on the hydroxyl group of the side chain. It occurs in the Golgi apparatus, where monosaccharide units are added to a complete polypeptide chain.

Functions of Oligosaccharides

- Glycoproteins are carbohydrates attached to proteins involved in critical functions such as antigenicity, solubility, and resistance to proteases. Glycoproteins are relevant as cell-surface receptors, cell-adhesion molecules, immunoglobulins, and tumor antigens.

- Glycolipids are carbohydrates attached to lipids that are important for cell recognition and modulate membrane proteins that act as receptors.
- Cells produce specific carbohydrate-binding proteins known as lectins, which mediate cell adhesion with oligosaccharides.
- Oligosaccharides are a component of fiber from plant tissues.

4. Polysaccharides

Polysaccharides are a chain of more than 10 carbohydrates joined together through glycosidic bond formation. They are ubiquitous and mainly involved in the structural or storage functions of organisms. They are also known as glycans.

These compounds' physical and biological properties depend on the components & the architecture of their binding or reacting molecules and their interaction with the enzymatic machinery.

Polysaccharides are classified based on their functions, the type of monosaccharide units they contain, or their origin.

Based on the type of monosaccharides involved in the formation of polysaccharide structures, they are classified into two groups: homopolysaccharides and heteropolysaccharides.

Homopolysaccharides:

They are composed of repeating units of only one type of monomer. A few examples of homopolysaccharides include cellulose, chitin, starches (amylose and amylopectin), glycogen, and xylans. And based on their functional roles, these compounds are classified into structural polysaccharides and storage polysaccharides.

- Cellulose is a linear, unbranched polymer of glucose units joined by beta 1-4 linkages. It's one of the most abundant organic compounds in the biosphere.

Cellulose structure

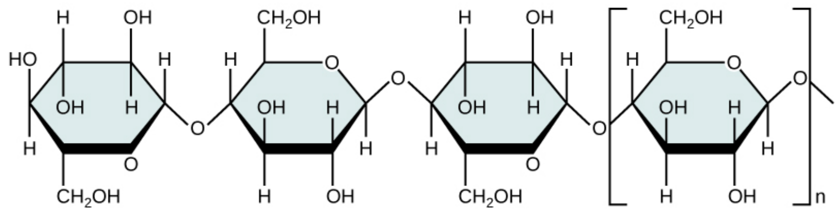


Figure: A structural representation of cellulose.

- Chitin is a linear, long-chain polymer of N-acetyl-D-glucosamine (a derivative of glucose) residues/units, joined by beta 1-4 glycosidic linkages. It's the second most abundant natural biopolymer after cellulose.
- Starch is made of repeating units of D-glucose that are joined together by alpha-linkages. It's one of the most abundant polysaccharides found in plants and is composed of a mixture of amylose (15-20%) and amylopectin (80-85%).

Heteropolysaccharides:

They are composed of two or more repeating units of different types of monomers. Examples include glycosaminoglycans, agarose, and peptidoglycans. In natural systems, they are linked to proteins, lipids, and peptides.

- Glycosaminoglycans (GAG) are negatively charged unbranched heteropolysaccharides. They are composed of repeating units of disaccharides with the general structural formula n. Amino acids like N-acetylglucosamine or N-acetylgalactosamine and uronic acid (like glucuronic acid) are normally present in the GAG structure.
- **A list containing major GAGs is mentioned below:**

GAGs	Acidic sugar	Amino sugar
Hyaluronic acid	D-Glucuronic acid	N-acetylglucosamine
Chondroitin sulfate	D-Glucuronic acid	N-acetylgalactosamine
Heparan sulfate	D-Glucuronic acid or L-iduronic acid	N-acetylglucosamine
Heparin	D-Glucuronic acid or L-iduronic acid	N-acetylglucosamine
Dermatan sulfate	D-Glucuronic acid or L-iduronic acid	N-acetylgalactosamine

Keratan sulfate	**D-Galactose**	**N-acetylglucosamine**

- Peptidoglycan is a heteropolymer of alternating units of N-acetylglucosamine (NAG) and N-acetylmuramic acids (NAM), linked together by beta-1,4-glycosidic linkage.
- Agarose is a polysaccharide composed of repeating units of a disaccharide, agarobiose, consisting of D-galactose and 3,6-anhydro-L-galactopyranose.

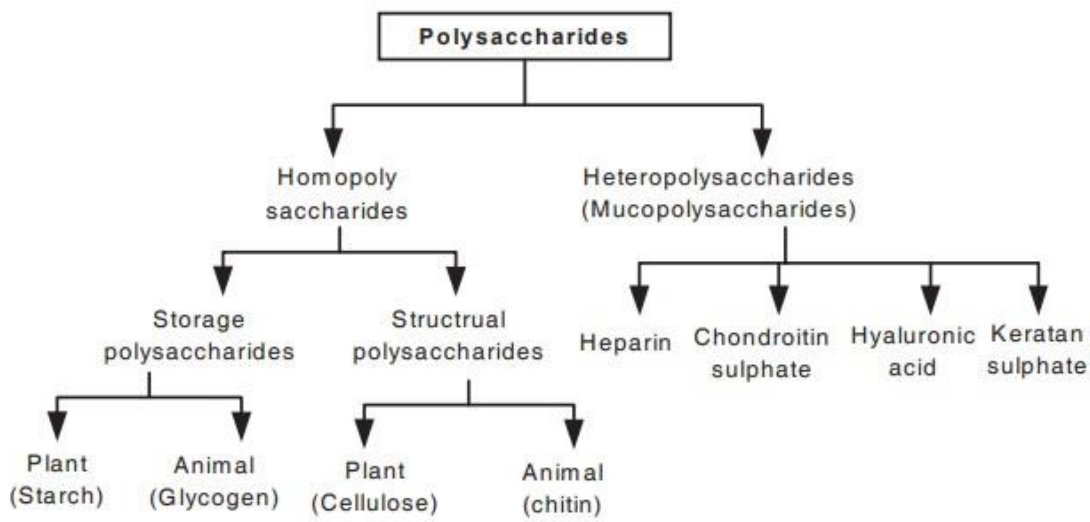


Figure: A classification summary of polysaccharides into different sub-groups.

Functions of Polysaccharides

- **Structural polysaccharide:** They provide mechanical stability to cells, organs, and organisms. Examples include chitin and cellulose. Chitin is involved in the synthesis of fungal cell walls, while cellulose is an important constituent of diet for ruminants.
- **Storage polysaccharides:** They are carbohydrate storage reserves that release sugar monomers when required by the body. Examples include starch, glycogen, and inulin. Starch stores energy for plants, and in animals, it is catalyzed by the enzyme amylase (found in saliva) to fulfill the energy requirement. Glycogen is a polysaccharide food reserve of animals, bacteria, and fungi, while inulin is a storage reserve in plants.

- Agarose provides a supporting structure in the cell wall of marine algae.
- Peptidoglycan is an essential component of bacterial cell walls. It provides strength to the cell wall and participates in binary fission during bacterial reproduction.
- Peptidoglycan protects bacterial cells from bursting by counteracting the osmotic pressure of the cytoplasm.
- Hyaluronic acids are an essential component of the vitreous humor in the eye and synovial fluid (a lubricant fluid present in the body's joints). It's also involved in other developmental processes like tumor metastasis, angiogenesis, and blood coagulation.
- Heparin acts as a natural anticoagulant that prevents blood from clotting.
- Keratan sulfate is present in the cornea, cartilage, and bones. In joints, it acts as a cushion to absorb mechanical shocks.
- Chondroitin is an essential component of cartilage that provides resistance against compression.
- Dermatan sulfate is involved in wound repair, blood coagulation regulation, infection responses, and cardiovascular diseases.

Conclusion

One of the four main necessary macromolecules needed by living things is carbohydrates. They are consumed by organisms in a variety of ways and are divided into four groups according to the quantity of monomer units in their structure. Polysaccharides, oligosaccharides, disaccharides, and monosaccharides are among them.

Glucose, fructose, cellulose, starch, glycoproteins, and chitin are among the components found in all carbohydrates and are essential to many bodily processes. They serve a variety of purposes, including supplying the cells with energy and maintaining the structural integrity of the cells as well as promoting the growth and development of the organism.

Scientists have learned important lessons about conformational changes, molecular dynamics, and a host of other topics by studying carbohydrates. Additionally, there are still a number of activities that these molecules' researchers are working to uncover.