

Carbohydrates: Definition, Classification, Structure and Functions

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Carbohydrates are sugars, sugar polymers, and chemically modified sugar derivatives that organisms use for energy, storage, structure, and cell recognition. Their behavior depends on molecular structure, especially the position of the carbonyl group, the configuration of a sugar ring, and the type of glycosidic linkage.

A carbohydrate's linkage can change its digestibility and function even when it uses the same monosaccharide building block.

The easiest way to learn carbohydrates is to follow one chain of reasoning: identify the monosaccharide unit, locate its anomeric carbon, read the linkage, and then predict the molecule's properties. That approach explains why glucose fuels cells, why starch stores energy, why cellulose forms strong fibers, and why sucrose is nonreducing.

What Are Carbohydrates?

Carbohydrate is a broad chemical term. It includes monosaccharides, oligosaccharides, polysaccharides, and compounds derived from monosaccharides by reactions such as oxidation, reduction, deoxygenation, or replacement of a hydroxyl group. The word **saccharide** is often used for the sugar part of this family.

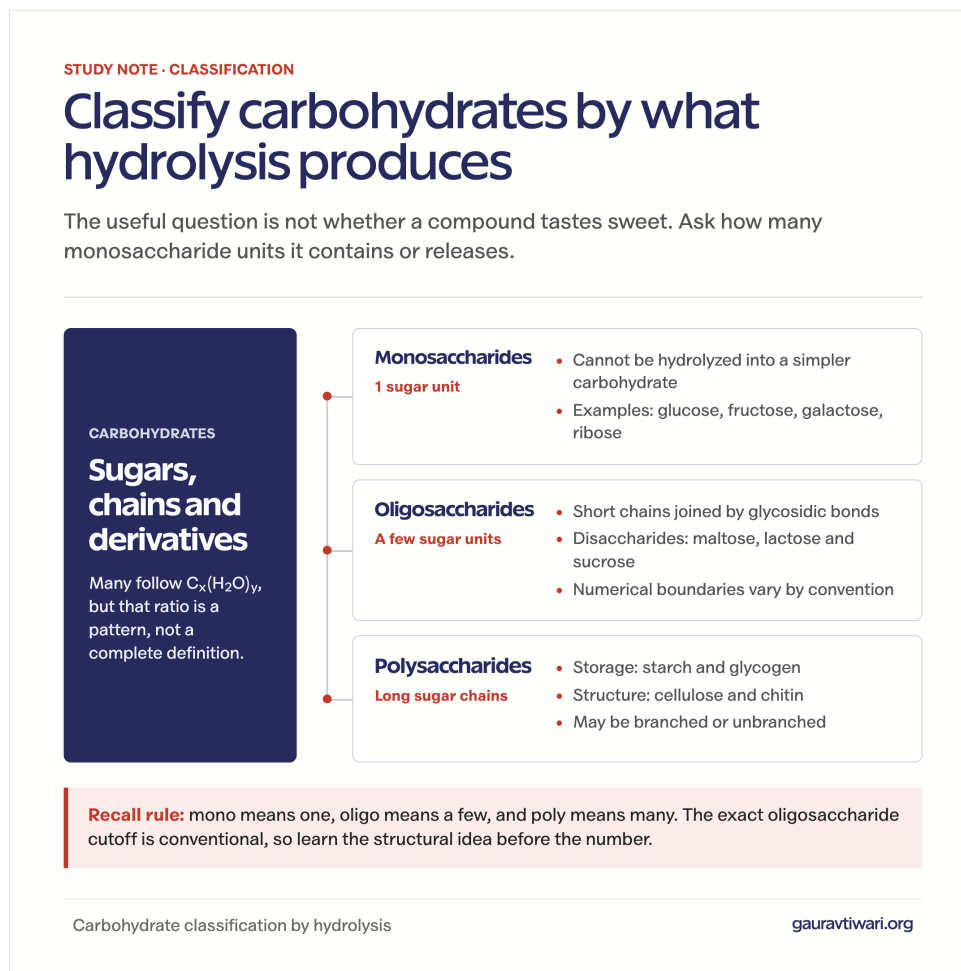
Many common carbohydrates follow the empirical pattern $C_x(H_2O)_y$. Glucose, $C_6H_{12}O_6$, fits it neatly. The pattern explains the old name "hydrate of carbon," but it cannot define the group by itself:

- **Some carbohydrates do not fit it:** deoxyribose is $C_5H_{10}O_4$.
- **Some non-carbohydrates do fit it:** acetic acid, $C_2H_4O_2$, has the same 1:2:1 atomic ratio.
- **Structure decides the class:** functional groups, stereochemistry, and linkages matter more than the ratio alone.

Treat $C_x(H_2O)_y$ as a useful pattern, not a chemical test for carbohydrates.

Classification of Carbohydrates

Carbohydrates are commonly classified by the number of monosaccharide units they contain or yield on hydrolysis. Taste is unreliable: some sugars are sweet, while major polysaccharides such as starch and cellulose are not.



Carbohydrate classification map showing monosaccharides, oligosaccharides, and polysaccharides with hydrolysis behavior and examples

Class	Structural idea	Hydrolysis	Examples
Monosaccharide	One sugar unit	Cannot be hydrolyzed into a simpler carbohydrate	Glucose, fructose, galactose, ribose
Oligosaccharide	A short chain of sugar units	Yields a few monosaccharides	Maltose, lactose, sucrose, raffinose
Polysaccharide	A long chain, branched or unbranched	Yields many monosaccharides or derivatives	Starch, glycogen, cellulose, chitin

The numerical boundary for an oligosaccharide varies across textbooks. Some use 2-10 units; others reserve the word for 3-10 and list disaccharides separately. The stable idea is a *short, defined chain* between a single monosaccharide and a large polysaccharide.

Monosaccharides: the Units Carbohydrates Are Built from

In its open-chain form, a typical monosaccharide has one carbonyl group and several hydroxyl groups. Two features classify it: the position of the carbonyl group and the number of carbon atoms.

- An **aldose** has an aldehyde carbonyl at the end of its open chain.
- A **ketose** has a ketone carbonyl within the chain.
- A **triose**, **pentose**, or **hexose** has three, five, or six carbon atoms.
- The two labels combine. Glucose is an **aldohexose**; fructose is a **ketohexose**.

Carbon atoms	Class name	Aldose example	Ketose example
3	Triose	Glyceraldehyde	Dihydroxyacetone
4	Tetrose	Erythrose	Erythrulose
5	Pentose	Ribose	Ribulose
6	Hexose	Glucose, galactose	Fructose
7	Heptose	Glucoheptose	Sedoheptulose

Important monosaccharides

The most useful examples are the ones that reappear in larger biomolecules:

- **Glucose:** an aldohexose and a central cellular fuel. It is the monomer of starch, glycogen, and cellulose.
- **Fructose:** a ketohexose found free in many fruits and joined to glucose in sucrose.
- **Galactose:** an aldohexose that differs from glucose at C4. It joins glucose to form lactose.
- **Ribose:** an aldopentose in RNA, ATP, and several coenzymes.
- **2-deoxyribose:** a ribose derivative in DNA. It lacks the hydroxyl group at C2.

Ribose and deoxyribose connect carbohydrate chemistry to **nucleic acids**. Amino sugars, sugar acids, and sugar alcohols show why the carbohydrate family is broader than ordinary dietary sugar.

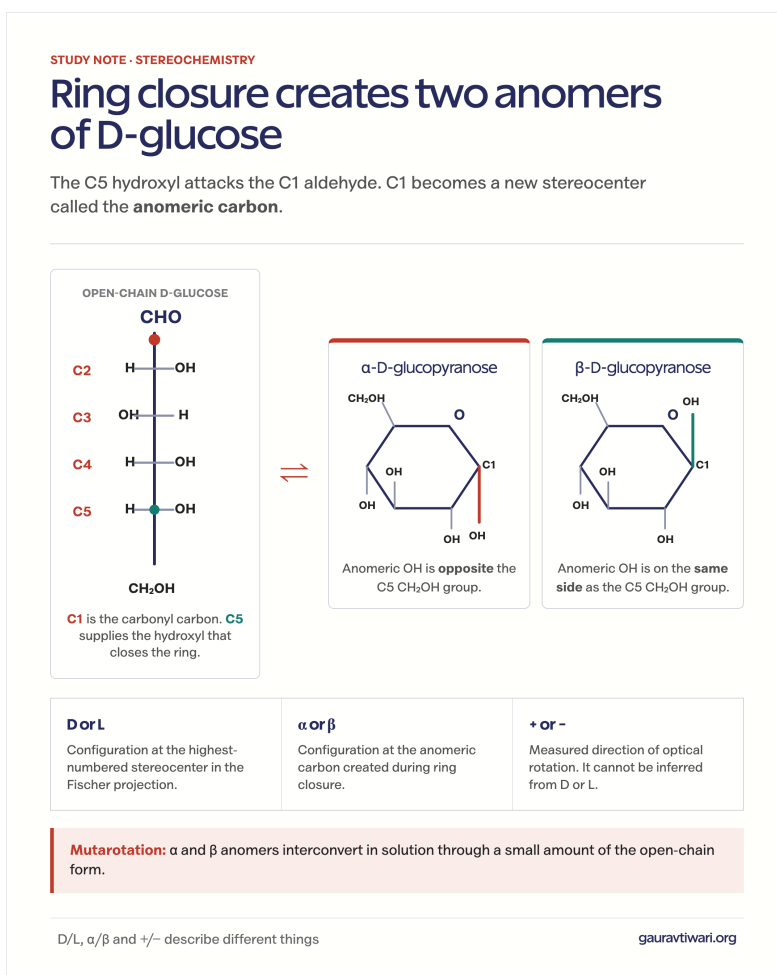
D/L configuration is not optical rotation

In a Fischer projection, D or L is assigned from the stereocenter farthest from the carbonyl group. If its hydroxyl group points right, the sugar belongs to the D series; if it points left, it belongs to the L series.

This label does not predict whether the compound rotates plane-polarized light clockwise (+) or counterclockwise (-). Optical rotation must be measured. D-fructose, for example, is levorotatory under standard conditions.

Ring formation, anomers, and mutarotation

Five- and six-carbon monosaccharides exist mainly as rings in aqueous solution. In glucose, the C5 hydroxyl reacts with the C1 aldehyde to form a six-membered cyclic hemiacetal. The former carbonyl carbon, C1, becomes the **anomeric carbon**.



Glucose ring formation comparing open-chain D-glucose with alpha and beta D-glucopyranose anomers

- **Alpha and beta anomers** differ only at the anomeric carbon.
- For a D-sugar in a Haworth projection, the alpha anomer has its anomeric OH opposite the CH₂OH group; the beta anomer has them on the same side.

- **Mutarotation** is the change in optical rotation as alpha and beta forms interconvert through the open-chain form in solution.
- In fructose, the carbonyl carbon is C2, so C2 becomes the anomeric carbon. Fructose can form both five-membered and six-membered rings.

Glycosidic Bonds and Oligosaccharides

A glycosidic bond joins the anomeric carbon of a sugar to an oxygen or another atom in a second molecule. When two monosaccharides form an O-glycosidic bond, the shorthand states both the anomeric configuration and the carbon positions involved.

- $\alpha(1\rightarrow4)$ means the first sugar contributes its alpha-configured C1, which joins C4 of the second sugar.
- $\beta(1\rightarrow4)$ uses the beta configuration at the first sugar's C1.
- $\alpha(1\rightarrow6)$ commonly marks a branch point because C1 of one glucose joins C6 of another.
- Bond formation is a condensation reaction; hydrolysis adds water to split the bond.

- **Disaccharide: Maltose**

- **Components:** Glucose + glucose
- **Linkage:** $\alpha(1\rightarrow4)$
- **Reducing?:** Yes
- **Common context:** Produced during starch digestion

- **Disaccharide: Lactose**

- **Components:** Galactose + glucose
- **Linkage:** $\beta(1\rightarrow4)$
- **Reducing?:** Yes
- **Common context:** Milk sugar

- **Disaccharide: Sucrose**

- **Components:** Glucose + fructose
- **Linkage:** $\alpha(1\leftrightarrow2)\beta$
- **Reducing?:** No
- **Common context:** Table sugar and plant transport sugar

STUDY NOTE - GLYCOSIDIC BONDS

A free anomeric carbon makes a sugar reducing

The linkage name records the anomeric configuration and the carbon numbers joined. A green dot marks an anomeric carbon still free to open.

Maltose glucose + glucose		Reducing Second glucose keeps a free anomeric carbon.
Lactose galactose + glucose		Reducing Glucose keeps a free anomeric carbon.
Sucrose glucose + fructose		Nonreducing No free anomeric carbon remains.
First symbol α or β describes the configuration at the first sugar's anomeric carbon.	Two numbers They identify the carbon atoms connected through oxygen.	Reducing test Look for a free hemiacetal or hemiketal anomeric carbon, not just an -OH group.

Fructose exception: fructose is a ketose but still reduces Benedict's or Fehling's reagent in alkaline solution because it can rearrange to aldose forms.

Green dot = free anomeric carbon

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Glycosidic bond comparison of maltose, lactose, and sucrose by linkage and free anomeric carbon

Reducing and nonreducing sugars

A reducing sugar has a free anomeric carbon that can return to a reactive open-chain form. This structural test is more reliable than memorizing a list.

- All common monosaccharides are reducing sugars under Benedict's or Fehling's alkaline test conditions.
- Maltose and lactose are reducing because one anomeric carbon remains free.
- Sucrose is nonreducing because its glycosidic bond uses the anomeric carbon of both glucose and fructose.
- Fructose is a ketose, but it can rearrange to aldose forms in alkaline solution and therefore reduces these reagents.

Benedict's and Fehling's tests detect reducing substances. They are not specific tests for glucose and should not be treated as modern clinical diagnostic methods.

Polysaccharides: Storage Versus Structure

Polysaccharides contain many monosaccharide residues linked into long chains. A homopolysaccharide uses one main monomer; a heteropolysaccharide uses two or more. Function depends on the linkage, branching pattern, and interactions between neighboring chains.

STUDY NOTE · POLYSACCHARIDES

The same glucose monomer can build storage or structure

The decisive variables are bond orientation and branching. Human amylases recognize many α linkages, but not cellulose's β (1 $\rightarrow$ 4) chain.

Amylose part of plant starch	 α (1 $\rightarrow$ 4), mostly unbranched; chain tends to coil.	Plant energy storage Digestible by human starch-degrading enzymes.
Amylopectin part of plant starch	 α (1 $\rightarrow$ 4) chains with α (1 $\rightarrow$ 6) branch points.	Branched plant storage Many chain ends allow faster enzyme access than one long chain.
Glycogen animal and fungal storage	 α (1 $\rightarrow$ 4) chains, with more frequent α (1 $\rightarrow$ 6) branching.	Rapidly mobilized reserve Stored mainly in liver and skeletal muscle in humans.
Cellulose plant cell-wall structure	 β (1 $\rightarrow$ 4), unbranched; alternate glucose units are flipped.	Strong structural fibers Humans lack cellulase, so cellulose acts as dietary fiber.

Mechanism: linkage geometry changes the three-dimensional chain, which changes hydrogen bonding, packing, and whether an enzyme can bind the bond correctly.

Linkage $\rightarrow$ shape $\rightarrow$ enzyme access $\rightarrow$ biological role

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Polysaccharide comparison showing linkages, branching, roles, and human digestibility of amylose, amylopectin, glycogen, and cellulose

- **Polysaccharide: Amylose**
- **Main building unit:** Glucose
- **Key linkage or pattern:** α (1 $\rightarrow$ 4), mostly unbranched
- **Role:** Part of plant starch
- **Human digestion:** Digestible
- **Polysaccharide: Amylopectin**
- **Main building unit:** Glucose
- **Key linkage or pattern:** α (1 $\rightarrow$ 4) with α (1 $\rightarrow$ 6) branches

- **Role:** Part of plant starch
- **Human digestion:** Digestible
- **Polysaccharide: Glycogen**
- **Main building unit:** Glucose
- **Key linkage or pattern:** $\alpha(1\rightarrow4)$, frequently branched by $\alpha(1\rightarrow6)$
- **Role:** Animal and fungal glucose reserve
- **Human digestion:** Digestible
- **Polysaccharide: Cellulose**
- **Main building unit:** Glucose
- **Key linkage or pattern:** $\beta(1\rightarrow4)$, unbranched
- **Role:** Plant cell-wall structure
- **Human digestion:** Not digested by human enzymes
- **Polysaccharide: Chitin**
- **Main building unit:** N-acetylglucosamine
- **Key linkage or pattern:** $\beta(1\rightarrow4)$
- **Role:** Arthropod exoskeletons and fungal cell walls
- **Human digestion:** Not substantially digested
- **Polysaccharide: Inulin**
- **Main building unit:** Mostly fructose units
- **Key linkage or pattern:** Usually $\beta(2\rightarrow1)$ fructan
- **Role:** Plant storage carbohydrate and dietary fiber
- **Human digestion:** Not digested in the small intestine; can be fermented by gut microbes

Why starch, glycogen, and cellulose differ

Starch and glycogen contain alpha-linked glucose. Their chains can coil or branch, and human starch-degrading **enzymes** can position these bonds in their active sites. Cellulose contains beta(1→4)-linked glucose. Alternate units are flipped, producing extended chains that hydrogen-bond into strong fibers. Humans lack cellulase, so cellulose passes through the small intestine as dietary fiber.

The difference is not the monomer. All three use glucose. The difference is how glucose units are connected and how the resulting chain interacts with enzymes and neighboring chains.

Carbohydrate Digestion and Absorption

Digestible carbohydrates must be reduced to monosaccharides before intestinal cells can absorb them. Starch digestion and disaccharide digestion use different enzyme steps:

1. **Mouth:** salivary alpha-amylase begins hydrolyzing internal $\alpha(1\rightarrow4)$ bonds in starch.
2. **Stomach:** low pH greatly reduces salivary amylase activity.
3. **Small-intestinal lumen:** pancreatic alpha-amylase produces maltose, maltotriose, and branched alpha-limit dextrins. It does not simply convert starch directly into glucose.
4. **Brush border:** maltase-glucoamylase, sucrase-isomaltase, and lactase complete digestion to glucose, galactose, and fructose.
5. **Absorption:** glucose and galactose enter through SGLT1, fructose mainly through GLUT5, and the monosaccharides leave the enterocyte through GLUT2.

Absorbed glucose can enter **cellular respiration** to support ATP production or be stored as glycogen. Non-digestible carbohydrates continue to the colon, where some, including inulin, can be fermented by microbes into short-chain fatty acids.

Functions of Carbohydrates

Carbohydrates do far more than supply dietary energy. Across the major classes of **biomolecules**, they contribute to six recurring biological jobs:

- **Immediate fuel:** glucose is a central substrate for ATP-producing pathways.
- **Energy storage:** starch stores glucose in plants; glycogen stores it in animals and fungi.
- **Structural support:** cellulose strengthens plant cell walls, while chitin strengthens fungal walls and arthropod exoskeletons.
- **Nucleic-acid structure:** ribose forms part of RNA and ATP; deoxyribose forms part of DNA.
- **Cell recognition:** short oligosaccharides on **glycoproteins** and **glycolipids** act as molecular labels. ABO blood-group antigens are familiar examples.
- **Extracellular protection and signaling:** glycosaminoglycans help organize hydrated extracellular matrices and cell surfaces.
- **Dietary fiber:** non-digestible carbohydrates add bulk or feed gut microbes, depending on their structure and fermentability.

These functions make carbohydrates central to **cell structure and function**, not merely a synonym for bread, rice, or sugar.

Fast Revision: Distinctions That Prevent Mistakes

Most carbohydrate errors come from mixing labels that answer different questions. Keep these pairs separate:

Do not confuse	Correct distinction
D/L and +/–	D/L describes relative configuration; +/– is measured optical rotation.
Aldose/ketose and alpha/beta	Aldose/ketose locates the open-chain carbonyl; alpha/beta describes the anomeric carbon in a ring or glycosidic bond.
Sweetness and carbohydrate class	Classification depends on structure and hydrolysis, not taste.
Free -OH and reducing behavior	A reducing sugar needs a free anomeric carbon that can access a reactive open-chain form.
Starch and cellulose monomers	Both use glucose; alpha versus beta linkage geometry creates different shapes and digestibility.
Amylase and complete glucose release	Amylase produces smaller carbohydrates; brush-border enzymes complete digestion to monosaccharides.

Test Your Recall

Try to answer each question before opening it. Retrieval is more useful than rereading the same paragraph.

Why does the formula $C_x(H_2O)_y$ not define a carbohydrate?

Some carbohydrates, including deoxyribose, do not fit the ratio, while some non-carbohydrates do. Functional groups, stereochemistry, and chemical relationships define the family more reliably.

How can you decide whether a disaccharide is reducing?

Look for a free anomeric carbon. If one sugar unit retains a hemiacetal or hemiketal anomeric carbon that can open, the disaccharide is reducing. Sucrose is nonreducing because both anomeric carbons form the glycosidic bond.

What is the difference between D/L and alpha/beta?

D/L describes configuration relative to glyceraldehyde at the stereocenter farthest from the carbonyl group. Alpha/beta describes configuration at the anomeric carbon created during ring formation.

Why can humans digest starch but not cellulose?

Starch contains alpha-linked glucose that human amylases can hydrolyze. Cellulose contains beta(1-to-4)-linked glucose and humans lack cellulase. The linkage changes chain shape and enzyme recognition.

Does amylase convert starch directly into glucose?

No. Alpha-amylase first produces smaller carbohydrates such as maltose, maltotriose, and alpha-limit dextrans. Brush-border enzymes then release absorbable monosaccharides.

Further Reading

For deeper chemical definitions and mechanisms, use the [IUPAC Gold Book carbohydrate entry](#), [OpenStax Biology 2e on carbohydrates](#), [OpenStax Organic Chemistry on disaccharides](#), and the [NCBI overview of nutrient absorption](#).

Starch and Cellulose

Starch and cellulose both contain glucose units. Their different glycosidic arrangements produce different structures and biological roles. Human digestive enzymes can hydrolyze the relevant starch linkages but do not directly digest cellulose with cellulase.

The reducing-sugar question also depends on structure. A free anomeric carbon can open into a reactive carbonyl form; tying the relevant anomeric centers into a glycosidic linkage can remove that behavior. Counting carbon, hydrogen and oxygen alone cannot decide whether a sugar is reducing.

The points to check in this example are:

- Monosaccharide identity and linkage arrangement both matter.
- A reducing end is a structural feature, not a synonym for sweetness.
- Storage and structural polysaccharides can use closely related building blocks.

Check Your Understanding

Try the questions before reading the answers.

Question 1. Does sharing glucose units make starch and cellulose nutritionally equivalent for humans?

Answer. No. Their linkages and digestive handling differ.

Question 2. Is every disaccharide nonreducing?

Answer. No. The anomeric-carbon arrangement determines the answer.