CARBOHYDRATES

Introduction

Carbohydrates (CHO) are a large group of organic compounds common in plants which include simple sugars, starches, celluloses, gums, and related substances. They contain C, H, and O with a ratio of hydrogen to oxygen of 2:1 which is similar to H_20 hence the name "carbohydrate". However the ratio of 2:1 is not always true. The general formula is $C_n(H_20)_n$. Carbohydrates are generally composed of carbon, hydrogen, and oxygen and sometimes nitrogen and sulfur. Chemically, carbohydrates on hydrolysis yield polyhydroxy aldehydes (the aldoses) and ketones (the ketoses). They form the largest part of the animal's food supply and make up 75 percent of the dry weight of plants.

Carbohydrates are a cheap source of energy and can spare the more expensive protein as an energy source. The protein sparing effects of carbohydrates and lipids should be maximized in order to reduce feed costs. Since carbohydrate is the most economical dietary energy source, as much digestible carbohydrate as the fish can utilize is used in fish diets. Carbohydrates such as starch, flour, alginates, agar, carrageenan, and guar gum are also used as feed binders to improve the water stability of fish and shrimp diets.

After studying this section, the reader should be able to differentiate among the various forms of carbohydrate and their significance in fish nutrition; distinguish between utilization of carbohydrates by warmwater and coldwater fishes and know how dietary carbohydrates are made available to fish.

Classification of Carbohydrates

Carbohydrates are classified as monosaccharides, disaccharides or oligosaccharides, and polysaccharides depending on whether the molecule is made up of one, two or many simple sugar units (Table 2.10). They are classified according to digestibility as digestible, partially digestible, and indigestible. Sugars, starches, dextrin, and glycogen are digestible carbohydrates whereas, cellulose, dietary fibers, and hemicellulose are indigestible carbohydrates. Galactogens, mannosans, inulin, and pentosans are considered partially digestible carbohydrates.

Table 2.10 Classification of carbohydrates

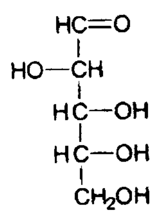
Monosaccharides (single glycose units)	
Pentoses ($C_5H_{10}O_5$)	Hexoses ($C_6H_{12}O_6$)
Arabinose	Glucose
Ribose	Galactose
Xylose	Fructose
Xylulose	Mannose
Disaccharides (2 glycose units) and oligosaccharides (2 to 10 glycose units)	
Sucrose	Raffinose
Maltose	Stachyose
Lactose	Verbascose
Polysaccharides (Glycan, >10 glycose units)	
Starch	
Dextrin	
Glycogen	
Cellulose	
Hemicellulose	
Lignin	
Chitin	
Pectin	
Gums and mucilages	
Alginates, agar, carrageenan (extracts from seaweeds)	

A. Monosaccharides

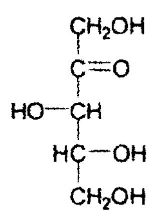
The monosaccharide is the fundamental unit from which all carbohydrates are derived. They are characterized by the number of carbon atoms they contain, C3, C4, C5, etc., and by their structural configuration either as aldose or ketose. The carbohydrate glucose is an aldose because of the presence of an aldehyde group while fructose is a ketose because of the presence of a ketone group. Most common sugars are aldoses rather than ketoses. Their structure includes a carbonyl group and several hydroxyl groups.

Most monosacharides are obtained by hydrolysis of more complex plant substances. Hydrolysis is a chemical reaction whereby a complex substance is broken into smaller units by the addition of water in the presence of a catalyst. The monosaccharides are often referred to as simple sugars. Two series of simple sugars are commercially important: the pentoses or five-carbon-atom sugars and the hexoses or six-carbon-atom sugars. The hexoses are abundant in nature, but the pentoses, ribose and deoxyribose, occur in the structures of RNA and DNA, respectively.

Pentoses The pentoses have the general formula $C_5H_{10}O_5$. Two pentoses are of commercial importance and both are aldopentoses: xylose and arabinose. Xylose is formed by the hydrolysis of pentosans. Considerable amount of xylose are formed in the pulping of wood through hydrolysis of hemicellulose. Arabinose is produced by the hydrolysis of gum arabic or wheat bran.



D-arabinose
(an aldose)

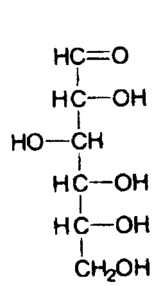


D-xylulose
(a ketose)

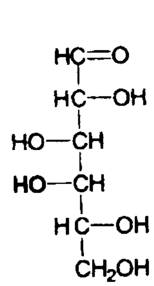
Hexoses The hexoses have the general formula $C_6H_{12}O_6$. The hexose sugars: galactose, and glucose are aldoses, while fructose is a ketose. The most abundant carbohydrates in plants and animals are either hexoses or complex molecules which form hexoses on hydrolysis.

Glucose is the most common of the aldohexose sugars and is commercially produced from the hydrolysis of cornstarch. It is the basic molecule for the synthesis of starch and cellulose. Glucose is of great importance in nutrition, as it is the major end product of the digestion of carbohydrates by nonruminants. Glucose, oxidized to carbon dioxide and water, is the primary energy source of humans.

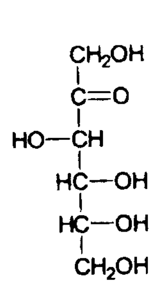
Fructose is the only important ketohexose in nature and is the sweetest of the carbohydrates. When cane or beet sugar (sucrose) is hydrolyzed, one molecule of fructose and one molecule of glucose are formed.



D-glucose
(an aldose)



D-galactose
(an aldose)



D-fructose
(a ketose)

Galactose does not occur in the free form in nature.

The hydrolysis of lactose or milk sugar produces galactose and glucose.

Isomerism. Glucose, fructose, and galactose have the same molecular formula but their structural formulas differ in the arrangement of their atoms within a molecule. These sugars are optical isomers because when placed in a polariscope, glucose and galactose rotate the plane of polarized light to the right, while fructose rotates the light to the left. Thus, although they have the same molecular formulas they differ in their individual properties.

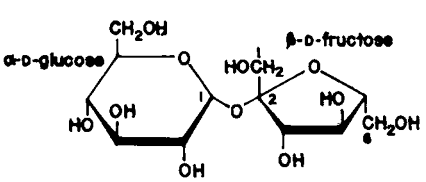
B. Disaccharides and Oligosaccharides

The oligomers of sugars are made up of two to ten monosaccharide units and frequently occur as disaccharides. Disaccharides are a combination of two molecules of monosaccharide. The formula, $C_{12}H_{22}O_{11}$, shows that one molecule of water was removed as two monosaccharides are combined. Hydrolysis results in cleavage of the molecule and formation of the hexoses. The three important disaccharides are sucrose, lactose and maltose.

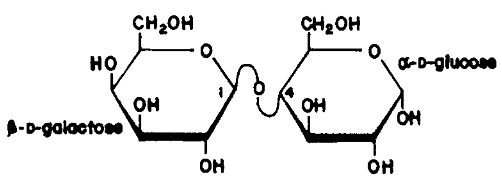
Sucrose, the common table sugar, is made up of a combination of one molecule of glucose and one molecule of fructose. It is derived largely from sugar cane and sugar beets which are sources of commercial sugar. When sucrose is consumed by animals, it is hydrolyzed to glucose and fructose, which are degraded by metabolic processes to provide energy.

Lactose, or milk sugar, is found only in the milk of all mammals. Nearly half of the milk solids is lactose hence hydrolysis of lactose will give a molecule of glucose and a molecule of galactose. Lactose is of special interest in human nutrition.

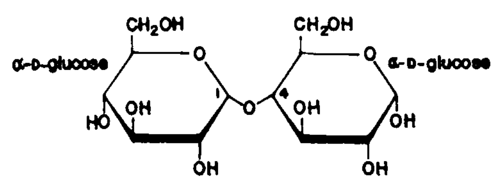
Maltose occurs naturally in seeds of starch-producing plants. It is formed by hydrolyzing starch with the enzyme α-amylase. When maltose is further hydrolyzed by the enzyme α-glucosidase, two molecules of glucose are produced.



Sucrose



Lactose (α form)



Maltose (α form)

C. Polysaccharides

The polysaccharides are formed by the combination of hexoses or other monosaccharides. They are of high molecular weight and mostly insoluble in water and are considered the most important nutrients of plant origin. Upon hydrolysis by acids or enzymes, they are broken down into various intermediate products and finally into their simple sugars (Figure 2.6). The polysaccharides have the general formula $(C_6H_{10}O_5)_n$.

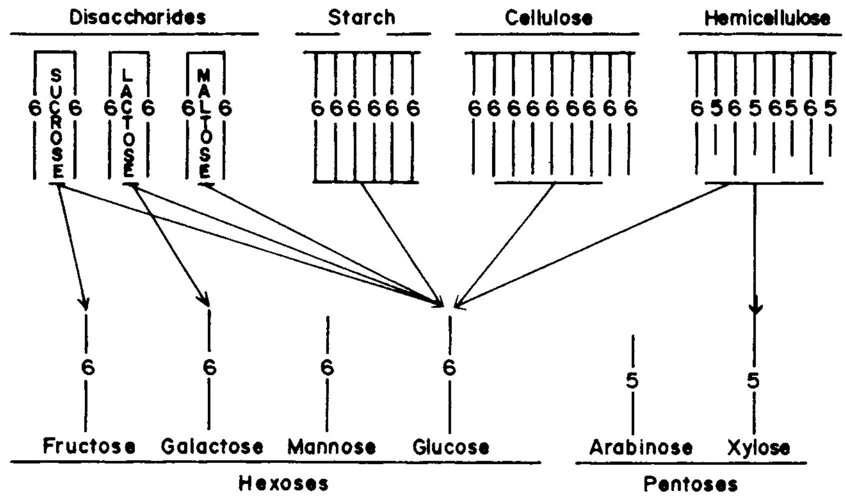
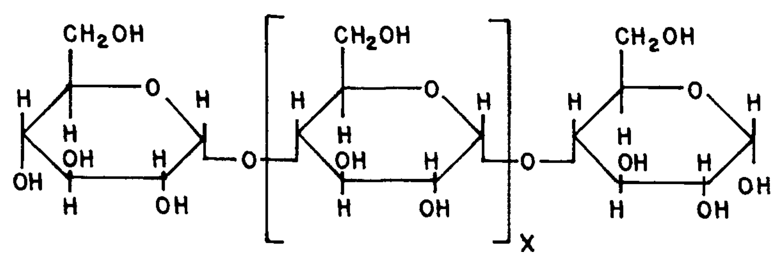


Figure 2.6
Summary of hydrolysis of carbohydrates.

Starch is the principal storage form of carbohydrates in plants and is found in the tuber, rhizomes, and seeds. It is the cheapest foodstuff and serves mainly in human and animal nutrition as a source of energy. Starch is hydrolyzed by either acids or enzymes into dextrin, maltose, and finally glucose. Both plants and animals contain enzymes, alpha- and beta- amylase, that hydrolyze starch. About 20 to 26 molecules of glucose are produced from each molecule of starch.



Starch (X = about 20 to 26)

Glycogen is manufactured by mammals and other animals from glucose in the blood and is found in the muscle tissue and liver. It is the storage form of carbohydrate in animals, as starch is in plants.

Cellulose is the major structural component of plant cell wall and is the most abundant substance in the plant kingdom. Cellulose is essentially insoluble and extremely resistant to degradation by enzyme action. It consists of several glucose units and can be hydrolyzed to glucose by strong acids. Animals lack enzymes called cellulase that hydrolyze cellulose to glucose.

Hemicelluloses are composed of a mixture of hexose and pentose units. Hydrolysis of hemicellulose yields glucose and a pentose, usually xylose. It is the principal component of plant cell wall. Unlike cellulose, it is less resistant to chemical degradation and can be hydrolyzed by a relatively mild acid treatment.

Lignin is found in the cobs and hulls and the fibrous portion of roots, stems, and leaves of plants. It has a complex structure consisting of carbon to carbon bonds and ether linkages which is resistant to acid and alkali.

Chitin is the major structural component of the rigid exoskeleton of invertebrates such as insects, crustacea, and also occurs in cell walls of algae, fungi, and yeasts. It is a polysaccharide with nitrogen atoms as well as C, H, and O and is composed of N-acetyl D-glucosamine. Like cellulose, chitin has a structural role and a fair amount of mechanical strength because the individual strands are held together by hydrogen bonds.

Pectin is found primarily on the spaces between plant cell walls and may also infiltrate the cell wall itself. Pectin cannot be hydrolyzed by mammalian enzyme pectinase but is digested by microbial action. It can be extracted with hot or cold water and forms a gel.

Plant gums are formed at the site of injury or by an incision on the bark. They are complex, highly branched residues containing D-glucuronic and D-galacturonic acids along with other simple sugars such as arabinose and shammose. They are viscous fluids which become hard when dry and are used commercially as thickening agents or stabilizers for emulsions. Gum arabic is a well-known commercial gum.

Alginates, agar, and carrageenan are extracts from seaweeds, the giant kelp, *Gracilaria* sp. and *Kappaphycus* sp., respectively. These are important binders in fish and crustacean diets.

Utilization of Carbohydrates

Aquatic animals do not have a specific dietary requirement for carbohydrates but their presence in diets may provide an inexpensive source of energy. The ability of fish to utilize dietary carbohydrates for energy varies considerably. Most carnivorous species have more limited ability compared with omnivorous and herbivorous species. Amylase is an enzyme that digests starches into sugars in the intestine of fishes. The activity of intestinal amylase is higher in omnivorous fishes, like milkfish, tilapia, and carp, than in carnivorous fishes, such as rainbow trout and yellow tail. Fibrous carbohydrates in the form of cellulose is essentially indigestible by some fish species and does not make a positive contribution to their nutrition. Thus, the level of crude fiber in fish feeds is typically restricted to less than 7% of the diet to limit the amount of undigested material that enters the culture system.

The availability of various forms of carbohydrates to fish and their nutritive value remains unclear. The highly digestible carbohydrates (carbohydrate with small molecular weight and shorter chain length such as glucose) have high nutritive value for coldwater fishes but are not effectively utilized by other fishes. Warmwater fishes such as red seabream and carp utilize starch more effectively than dextrin and glucose. Figure 2.7 shows the growth and feed efficiency of carp fed diets containing starch, dextrin or glucose at 42% level. The chain length of various carbohydrates and frequency of feeding affects their utilization by fingerling carp. The starch diet results in best weight gain and feed efficiency compared with other carbohydrates with shorter chain length such as dextrin and glucose.

The type and levels of carbohydrate in the diet have also been shown to affect the growth of penaeid shrimps. Tiger shrimp utilizes starch

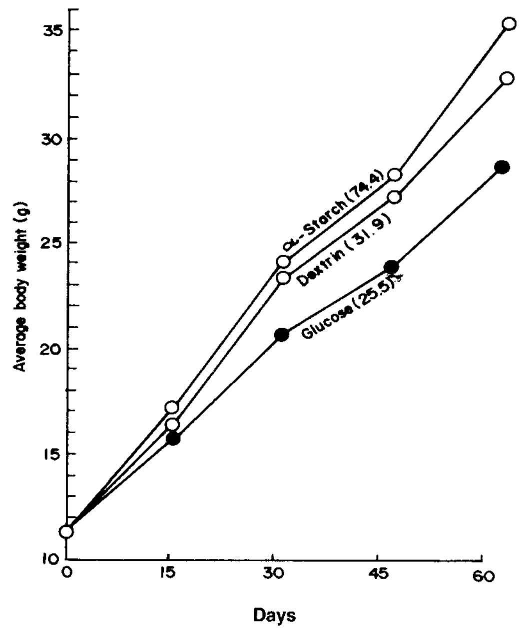


Figure 2.7
Growth and feed efficiency (in parenthesis) of carp fed diets containing 42% of α-starch, dextrin or glucose.
Source: Watanabe et al. 1988

better than dextrin and glucose. When the dietary starch level is increased from 20 to 30%, and the dietary protein is decreased from 40 to 30%, weight gain and feed efficiency are not affected but protein efficiency ratio is increased (Table 2.11). Other studies show that tiger shrimp can utilize trehalose and sucrose better than glucose. Glucose is also poorly utilized by other species of penaeids such as kuruma shrimp. Furthermore, different types and levels of carbohydrate in the diet significantly influences survival of juvenile tiger shrimp.

Table 2.11 Means for weight gain, feed efficiency ratio (FER), protein efficiency ratio (PER), and survival rate of tiger shrimp fed diets with different carbohydrate sources and levels

Carbohydrate source	Weight gain (%)	FER	PER	Survival (%)
40% protein				
20% glucose	207.52^{d}	0.38^{d}	0.71^{c}	55.77^{c}
20% dextrin	370.99^{ab}	0.47^{bc}	1.05^{bc}	65.39^{b}
20% starch	408.17^{a}	0.50^{ab}	1.11^{b}	64.42^{b}
35% protein				
25% glucose	232.38^{d}	0.35^{d}	0.91^{cd}	47.29^{c}
25% dextrin	328.99^{bc}	0.44^{bc}	1.06^{b}	75.00^{ab}
25% starch	388.71^{ab}	0.48^{ab}	1.25^{b}	80.81^{a}
30% protein				
30% glucose	152.44^{c}	0.26^{c}	0.76^{cd}	55.94^{c}
30% dextrin	272.68^{cd}	0.40^{cd}	1.20^{b}	71.55^{ab}
30% starch	387.36^{ab}	0.54^{a}	1.51^{a}	74.36^{ab}

Column means having a common superscript are not significantly different ($P>0.05$).
Source: Shiau 1992

Guide Questions

1. What does the term "carbohydrate" mean?
2. What are the functions of carbohydrates?
3. Distinguish between lipid and carbohydrates.
4. What are carbohydrates chemically? Why is glucose called an aldose, fructose a ketose?
5. Give three classifications of carbohydrates and give one example of each.
6. What is isomerism? Why are glucose, fructose, and galactose optical isomers?
7. What is the major end product of carbohydrate digestion?
8. Show by means of chemical equation how glucose is made from starch.
9. What carbohydrate type is the principal component of the exoskeleton of insects and crustaceans?
10. Name the important binders for aquaculture feeds obtained from seaweeds.
11. If lipid gives twice as much energy as carbohydrates, why then should carbohydrates be included in the diet?
12. Name some good carbohydrate sources in fish diets.