Plant-Based Sweeteners and Their Applications in Modern Lifestyle

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Contents

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Abbreviations

CAGR	Compound annual growth rate
CSDs	Carbonated soft drinks
FOS	Fructooligosaccharides
GRAS	Generally recognized as safe
HFCS	High fructose corn syrup
HSH	Hydrogenated starch hydrolysates
IMO	Isomalto-oligosaccharide
JECFA	Joint FAO/WHO Expert Committee on Food Additives
LCS	Low-calorie sweeteners
USFDA	United States Food and Drug Administration

1 Introduction

The history of sugar is relatively new (500 BC) as it was discovered that grass with bamboo-like stem contains a sweet juice (Eggleston 2019). This grass (sugarcane) was soon cultivated around the world in warm damp climates. Its juice was initially used in concentrated form and later (about 1400 AD) used in refined form (brown sugar) throughout Europe (Kinghorn et al. 1986). Later in the 1800s, a new source of sugar was discovered (sugar beet) with root tubers containing more sucrose per kilogram than sugar. This new source gradually replaced sugarcane in Europe. In the 1950s, sugar syrup from corn starch was discovered (now known as high fructose corn syrup), which gradually replaced sucrose in the United States (Bode et al. 2014).

The market size of natural sweeteners also exceeded by 9.2 million dollars USD in 2019 and expecting an estimated growth of 4.3% compound annual growth rate (CAGR) between 2020 and 2026. Increased consumer awareness of eating natural ingredients will further help this market grow.

The classification of sweeteners is incredibly vivid such as natural versus artificial sweeteners, nutritive versus non-nutritive sweeteners, caloric versus low-caloric or zero-caloric sweeteners, and carbohydrate vs non-carbohydrate sweeteners. Here classifying sweeteners alone is not the main objective of discussion but also to present a picture of sweeteners from natural sources, especially from plants with their general introduction.

2 Carbohydrate and Non-carbohydrate Sweeteners

Starting with the carbohydrates such as sugars, starches and fibers are naturally occurring organic substances with varying sweetness. They are found in healthy as well as unhealthy foods. The most common and important sugar is sucrose found in various fruits and vegetables. It is also found in some grasses such as *Saccharum officinarum*. Sugar is produced in plants due to photosynthesis and stored in different parts such as stalk (*Saccharum officinarum*) or root (*Beta vulgaris*). A country like Brazil uses most of its sugarcane to produce alcohol through fermentation. It is further converted as alcohol fuel to run vehicles. Worldwide approximately 179.66 million metric tons of sugar were produced in 2018–2019. The consumption was 172.6 million metric tons which are further expected to increase to about 177.8 million metric tons by 2020–2021. The other sources of sucrose (sugar maple and carob) are not very significant in terms of their commercial value. Due to its universal availability and versatility, sucrose production is growing in the developing world and gained prominence in the food.

Moving toward the non-sucrose carbohydrates, honey is one of the oldest known mixtures of such monosaccharides or disaccharides. The US Food and Drug Administration described honey as the assimilated nectar and saccharide exudate of plants modified (inversion) and stored by the honeybees (*Apis mellifera* and *Apis dorsata*) (Food and Drug Administration 2014). The color, composition, and flavor of honey depend upon the nectar-yielding flower. It also exhibits a similar result of the chemical test as for other carbohydrate sweeteners (Hasam et al. 2020). Honey has wide applications in baked goods, confectionery, and dairy products. Another natural sweetener is maple syrup (the first man-made sweeteners in America) obtained from the sugar maple tree *Acer saccharum*. It is costlier than sucrose and other starch-based sweeteners. Consequently, adulteration in maple syrup and related products is commonly seen in the marketplace (Paradkar et al. 2003). The physical properties of maple syrup are also similar to sucrose syrups which make it a perfect fit for confectionery and baking. The concentrated juice of sugar cane or sugar beet, called molasses, is generally used as animal feed and to produce alcohol through fermentation. Now with the help of technological advancements, molasses is also being transformed into food products. Cane syrup is another sweetener used in baked goods and candy products. This product is made at sugar cane plants or refineries and is well known in the United States. The composition of some popular sweeteners is given in Table 1.

Table 1 Chemical composition of sweeteners

	Honey	Maple syrup	Cane molasses
Component	Average (weight %)		
Calcium		0.07	
Citric acid	0.010		
Fructose	38.5		5–12
Fumaric acid		0.004	
Glucose	31.0		4–9
Hexoses		0.0–7.9	
Insoluble ash		0.08–0.67	
Malic acid		0.093	
Maltose	7.2		
Manganese		0.005	
Nitrogenous compounds			2.5–4.5
Proteins	0.3		0.5–1.5
Silica		0.02	
Sodium		0.003	
Soluble ash		0.30–0.81	
Succinic acid		0.008	
Sucrose	1.5	58.2–65.5	30–40
Vitamins	0.2[a]		
Water	17.1	34.0	

[a]Along with minerals

3 The Quest for an Ideal Sweetener

From the foregoing note, it is clear that sugar or caloric sweeteners are the most popular among consumers because of its properties. Sugar has become an indispensable part of our food diet, and thus progressively its overconsumption has been linked to various health issues (Lustig et al. 2012; Willett and Ludwig 2013). There is another category of sweeteners called intense sweeteners that are very diverse, from "amino acid" to "halogenated sugars." The sweetness of these compounds ranges from 30 (e.g., cyclamate) to 2000 (e.g., alitame) times than sucrose. Most of the intense sweeteners are discovered accidentally such as saccharin. Sweetness is subjective to and dependent on several factors, including temperature, pH, the medium used, the concentration of the sweetener, and the taster's sensitivity. Sucrose is the typical standard and is assigned a sweetness of "1." According to scientists, the ideal sweetener does not exist. It is said that an ideal sweetener should be as sweet as sucrose, it should be colorless, odorless, non-cariogenic, pleasant in taste, and economically viable. Further, the applications of such sweeteners should also be very versatile. On a common note, the different type of sweeteners are compiled in Fig. 1.

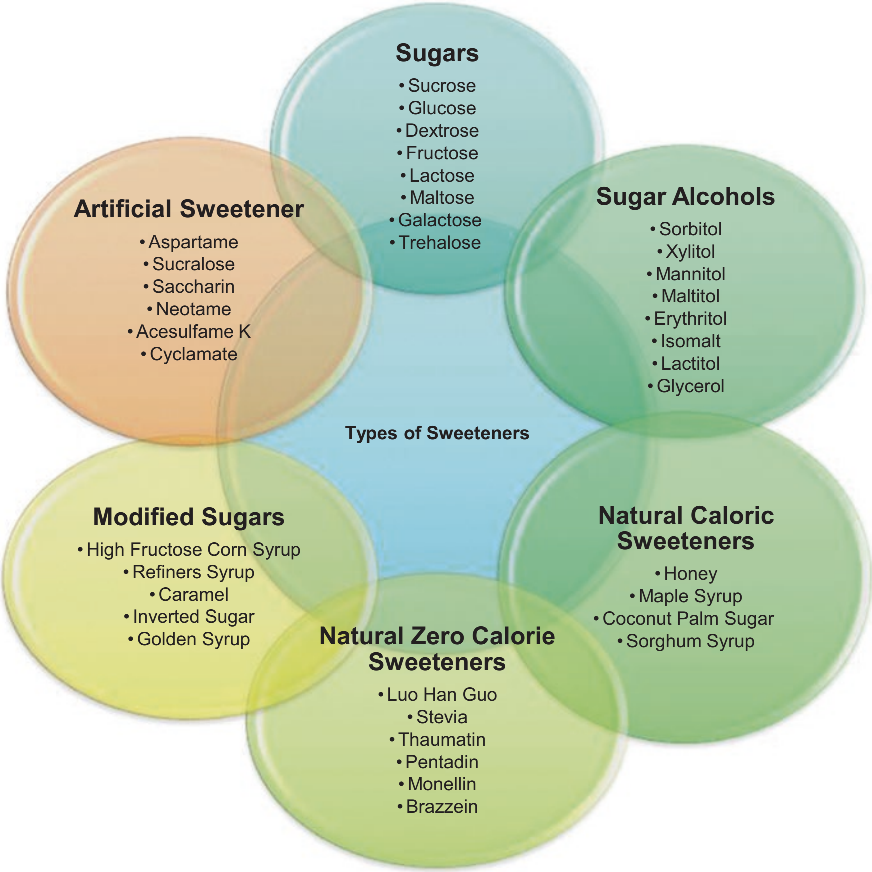


Fig. 1 Types of sweeteners

The search for ideal sweeteners led to the discovery of artificial sweeteners (Chattopadhyay et al. 2014). There are many low-calorie, or no-calorie popularly called zero-calorie, sweeteners available on the market as sugar substitutes (de Samaniego-Vaesken et al. 2020). Saccharin was the first discovered no-calorie or low-calorie sweetener. After that, many sweeteners were synthesized in laboratories and isolated from natural sources. Majority of these sweet compounds are organic and superior over saccharine. Aspartame and saccharine are called "high-intensity" or "intense" sweeteners. However, more term further proposed for such sweeteners was artificial sweeteners and natural sweeteners. However, due to the inappropriateness of these terms, the sweeteners are now termed nutritive and or non-nutritive sweeteners. The commercial viability of the non-nutritive sweeteners depends upon the factors as follows:

3.1 Taste Quality

The consumers do not readily accept the new sweeteners with changes in taste quality despite having other advantages such as low-calorie content. Beverages and carbonated soft drinks (CSDs) were the food products sweetened with the non-nutritive sweeteners. Several efforts were made to improve the taste quality of these sweeteners. The taste quality largely depends upon the type of food product in which the sweeteners are being used. However, its best measure of taste quality depends only on the consumer study.

3.2 Safety

Natural sweeteners are seeming to have no toxicity unless studies regarding their adverse effects on human health were undertaken. The research regarding the adversity of natural sweeteners led to the formulation of legislation over the use of these sweeteners and other additives. Except a few sweeteners, not all the sweeteners are listed in generally recognized as safe (GRAS) list.

3.3 Solubility and Stability

Solubility of sweeteners is the prime requirement in many manufacturing processes. The sweeteners with high solubility and dissolution rates are preferred for general utility. The second parameter is the stability of sweeteners under intended conditions of use. The stability ensures long-term usage of stored food products and their sweetening property.

3.4 Cost

Compared to sucrose, which is one of the most cost-effective sweeteners, the other alternatives must be either low cost or should have sufficient advantages to match their costs. The sweetening potency (P) generally expressed on a weight basis (Pw) is not constant for different sweeteners. Pw for a sweetener changes according to the reference sucrose concentration. For example, Pw for aspartame [Pw (0.34) = 400] is about 0.34% sucrose reference, while at 10% sucrose reference it is Pw (10) = 100. The sweetening potency P also gets affected by food system and temperature.

4 Plant-Derived Sweeteners

There has been an increased demand of low-calorie or no-calorie sweeteners in the market. Many alternatives are available to the consumers. But there is always a question in their minds that which one of the alternative sweeteners is good for health. Therefore, the demand for natural sweeteners has profoundly increased over artificial sweeteners (Tandel 2011). Plant-based sweeteners are natural and, apparently, have no side effects (Kinghorn et al. 1986). Among the many plant-based sweeteners, the difference is in their flavor profile (Philippe et al. 2014). The search for plant-based natural sweeteners also geared up in the last decades (Grembecka 2015). Despite being natural, the plant-derived sweeteners also need to be researched for their effect on human health and safety. The chemical/ molecular structure of different plant-derived sweeteners is compiled in Fig. 2. Following is a discussion on natural plant-derived sweeteners.

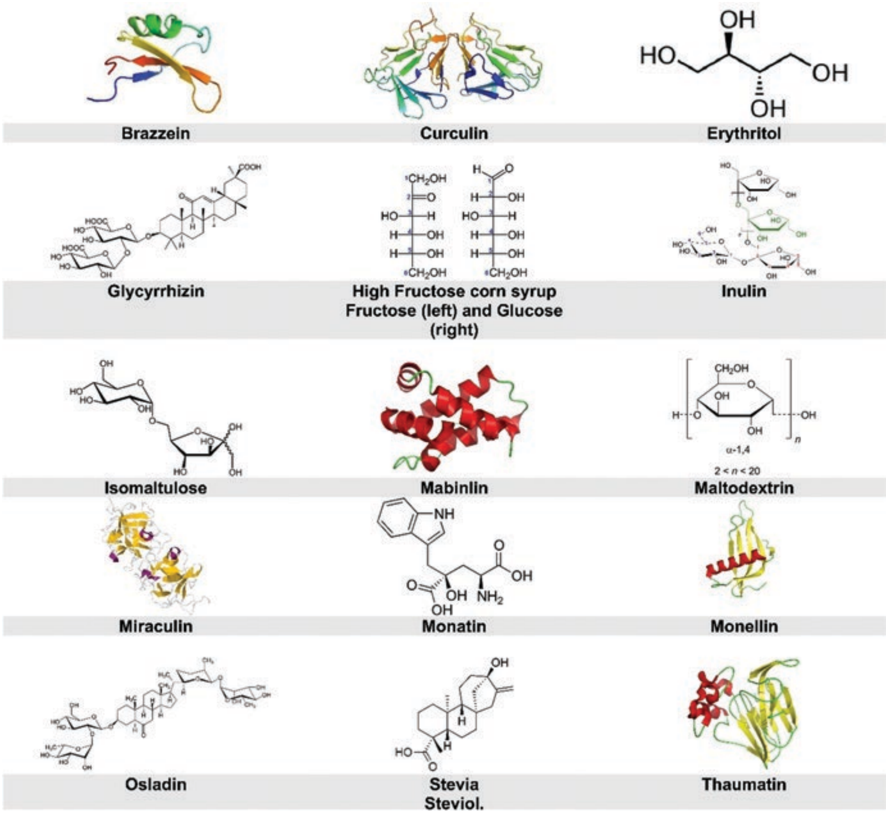


Fig. 2 Chemical and molecular structure of plant-derived sweeteners

4.1 Brazzein

Brazzein is a protein with sweet taste obtain from Oubli (*Pentadiplandra brazzeana* Baillon) which is an evergreen shrub that belongs to the family Pentadiplandraceae. For the protein brazzein, there is a taste receptor protein (TAS1R3) found in primates (Nishi et al. 2016). Wild animals usually get attracted toward this plant's sweet berries and help disperse its seeds. The plant parts, namely, leaves, roots, tubers, and berries are used in traditional culture in many ways. The roots hung are used to repel snakes, while root bark powder is used as an ingredient in African whiskey. Root is also used as vegetable, and its syrup is also marketed throughout the Congo basin (Ming and Hellekant 1994).

This plant is a monoecious shrub of 5 m (as a shrub) to 20 m (in the form of liana high in the trees) (Ming and Hellekant 1994; Bayer and Appel 2003). This plant is found in West Africa and is known to produce red berries with this sweet protein brazzein. Despite its sweetening property, this sugar alternative is not yet approved as a food additive in the United States and European Union.

Due to expensiveness of berries, the newer biofermentation technology is being used to produce brazzein from the food-grade bacteria (Berlec et al. 2008). The process is very cost-effective and more standardized compared to the traditional farming methods.

4.2 Curculin

Curculin is also a sweet protein obtained from the fruits of *Curculigo latifolia* (belongs to the family Hypoxidaceae) found in Malaysia. Curculin is a taste modifier, makes water, and sour solution taste sweet after its consumption. The protein curculin is a heterodimer consisting of two monomeric units (12.5 kDa and 12.7 kDa) connected through disulfide bridge (Yamashita et al. 1995).

Curculin is a high-intensity sweetener that is 430–2070 times sweeter than sucrose. Its taste-modifying property gets affected in the presence of divalent cations (Suzuki et al. 2004). Like most other proteins, it is also susceptive to heat and loses its sweetening and taste-modifying property at 50 °C. Because of its heat sensitivity, it is not a good candidate for hot or processed food (Yamashita et al. 1995).

Curcumin is not readily available from its natural source; therefore, alternative methods for its manufacture are being studied. The recombinant curculin protein initially produced in *E. coli* and yeast was lacking the sweet-tasting property. Later in 2004, the efforts yielded the recombinant curculin from *E. coli* with its distinct sweetening property (Suzuki et al. 2004). The challenges related to regulatory and legal issues in commercializing the recombinant curculin also need to be resolved before marketing it as a sweetener.

4.3 Erythritol

John Stenhouse a Scottish chemist discovered erythritol in 1848, and it was first isolated in 1852. Erythritol is naturally found in some fruits and fermented food (Jeya et al. 2009). At the industrial level, it is produced by fermenting glucose with yeast (Moon et al. 2010). Erythritol has been used in many food and drink products as a sweetener and flavor enhancer with approval in more than 60 countries.

Erythritol readily gets absorbed in the blood and attains peak within two hours followed by its extraction in the urine with almost 90% unchanged form (Rakicka-Pustułka et al. 2020). The scientist found some mild gastrointestinal upset with abdominal bloating and stool frequency associated with different doses of erythritol (Munro et al. 1998). The European Food Safety Authority came up with the recommended doses as 0.6 gm per kg body weight.

The caloric amount of erythritol is 0.2 kilocalories per gram which is 95% less than sugar and other carbohydrates. Erythritol is not metabolized by oral microbes and thus no risk of tooth decay. It also has an antibacterial effect on oral bacteria and helps reduce dental plaques.

4.4 Fructooligosaccharide

Fructooligosaccharides (FOS) (oligosaccharide fructans) are an alternative sweetener generally obtained from blue agave plants. Fruits, vegetables, grains, and cereals are also the source of FOS, and it is also referred to as oligofructose or oligofructan (Campbell et al. 1997). Among the cultured plants, the Jerusalem artichoke together with the blue agave has maximum concentrations of FOS.

Because of its prebiotic property, the FOS is now becoming a popular sweetener in Western countries. It acts as a substrate for intestinal microflora, thereby improving the overall intestinal health (Sabater-Molina et al. 2009). FOS is also reported to encourage calcium absorption in lab animals and also in human intestine (Morohashi et al. 1998; Ohta et al. 1998). By reducing gut pH, it improves calcium availability in the bloodstream from ingested food (Morohashi et al. 1998).

At the commercial level, FOS is produced by inulin degradation or transfructosylation (Sangeetha et al. 2005; Mutanda et al. 2014; Wang et al. 2016). According to reports, the FOS may also be fermented by other pathogenic bacteria, such as *Klebsiella*, *E. coli*, and *Clostridium*, that results in gas formation in the intestines (Mao et al. 2015). The FOS is listed in GRAS, although many countries have their own regulations to use it.

4.5 Glycyrrhizin

Glycyrrhizin is obtained from the roots of licorice (Hayashi and Sudo 2009). Glycyrrhizin is 50 times sweeter than sucrose and has a low glycemic index. Because of the strong licorice flavor, it is not used as a sweetener on its own but for sweets, chewing gum, lozenges, and medicine. Glycyrrhizin has its main application in the treatment of ulcers and in the manufacture of cough mixtures and toothpastes (Gao et al. 2009; Fu et al. 2013). The admissible limit of its intake is 100 mg/day, but excessive intake may imbalance sodium and potassium in the body.

4.6 High Fructose Corn Syrup

High fructose corn syrup (HFCS) is obtained from corn and contains both glucose and fructose. In the United States, it is used in processed food and drinks as a replacement for regular sugar. A syrup is made from genetically modified corn followed by converting its glucose into fructose by enzymatic treatment (Skryabin and Tutelyan 2013). The HFCS includes varying amounts of fructose, such as HFCS 90 contains 90% fructose and it is the most concentrated form, while the HFCS 55 is like sucrose as it contains almost 50% glucose and 50% fructose. Difference between an HFCS and regular sugar is that its liquid contains 24% water compared to dry and granulated sugar. Chemically glucose and fructose are not bounded in HFCS as in regular sugar. In our body, liver metabolizes significant amounts of fructose and turns the overdose into fat that may contribute to fatty liver (Collison et al. 2009). High fructose is also linked to body ailments, namely, insulin resistance, obesity, and type 2 diabetes (Basciano et al. 2005). All these problems arise due to excessive sugars, not because of fruit consumption that also contain other nutrient fibers and antioxidants.

4.7 Inulin

Inulin is a fiber (soluble) extract from a root vegetable primarily chicory. It has low sweetness and is used as low-calorie sugar substitutes mainly to add bulk to products. Inulin has zero glycemic index and is good for diabetes (Kalyani Nair et al. 2010). It is also prebiotic, known to promote the growth of bacteria in the colon, and improves nutrient absorption (Struck et al. 2014). The excess intake of insulin is associated with cramps, and it also demonstrates the laxative effects (Den Hond et al. 2000).

4.8 Isomalto-Oligosaccharide

Isomalto-oligosaccharide (IMO) occurs naturally in honey (in small quantities) and in fermented foods (miso and soy sauce) (Park et al. 2016). It is a moderately sweet carbohydrate consisting of 3 to 6 glucose molecules with indigestible glycosidic bonds. IMO is generally used to make protein bars and health bars. It contains half the calories of sugar and has a very low glycemic index. Like inulin, IMO also adds fiber to the diet and acts as prebiotic (Oku and Nakamura 2003). It also helps the body to absorb minerals from food.

4.9 Isomaltulose

Isomaltulose is a disaccharide carbohydrate made up of glucose and fructose. It is naturally found in honey and sugarcane extracts (Eggleston and Grisham 2003). In taste, it is like table sugar but with half sweeteners. Commercially, it is produced from isomerization of sucrose from beet sugar by enzyme treatment. Isomaltulose is approved to be used as sweetener in many countries including Japan, United States, and European Union. Because of its physical property and similarity to sucrose, it can easily be used as a replacement for sucrose in different recipes and processes. Isomaltulose is a reducing sugar and has low glycemic index compared to sucrose.

4.10 Luo Han Guo

Luo Han Guo popularly known as monk fruit or Luohan guo (*Siraitia grosvenorii*) is native to Guangxi province in Southwest China (Kasal et al. 1989). The plant is cultivated mainly for its fruit. In China, it has been known for more than 800 years. It is being used for medicinal purposes and as a major antioxidant. The sweetening taste is due to mogrosides which is 300 times sweeter than sucrose. Monk fruit has a zero glycemic index, has no calories, and thus suitable for diabetics. This sweetener is used as a bulking agent and appropriate for cooking and baking.

4.11 Mabinlin

Mabinlins (Sweet tasting proteins) are obtained from the seeds of a Chinese plant mabinlang (*Capparis masaikai* Levi.). It has four homologs of which mabinlin–2 (Mol wt. 10.4 kDa) was first isolated in 1983 (Hu and He 1983). Mabinlin–2 has the highest thermostability due to the four disulfide bridges (Guan et al. 2000).

Mabinlins are 100–400 times sweeter than sucrose on a molar basis and 10 times sucrose on a weight basis. Heat stability and solubility in water make it a good choice as a sweetener. Attempts are also made to produce mabinlin–2 at the industrial level (Kohmura and Ariyoshi 1998). Efforts were also made to produce Mabinlin–2 through a transgenic approach. (Sun et al. 2000; Hu et al. 2009).

4.12 Maltodextrin

Maltodextrin is a group of complex sugars produced enzymatically from starch. Its complexity depends on the method of production. Maltodextrin is not suitable for diabetics due to the high glycemic index (85–105) (Sardarian et al. 2020). It is used in the food industry for various purposes, such as thickening the sauces and broth, soup powder, coffee whiteners, and in pharmaceutical industry as binders. Maltodextrin is hugely popular among bodybuilders as it helps in quick recovery after workout.

4.13 Maple Syrup

Maple syrup, a popular natural sweetener, is made from sap or fluid of sugar maple trees (Lebedev 2010). Eastern Canada is the world's largest producer of maple syrup. It is available in different grades based on color. Grade A has light color while Grade B is the darkest. The darker syrups have a strong maple flavor. Maple syrup is rich in minerals and antioxidants. It is about two-third of table sugar and has its overconsumption associated with health issues like heart disease, type 2 diabetes, and obesity.

4.14 Miraculin

Miraculin is a protein obtained from the “Miracle Fruit” from West Africa. Berries coat the tongue upon chewing and change the taste perception for a period (Kurihara 1992). It has a zero glycemic index and hence is good for diabetics. The commercial potential of miraculin is not fully explored yet accepted for its use in the sweetening of sodas and ice lollies (Brouwer et al. 1968). Miraculin is helpful for patients suffering from poor taste of food due to certain treatments. It does not have GRAS approval in United State but in Japan and certain other countries. (Hirai et al. 2010)

4.15 Monatin

Monatin, commonly known as arruva, is obtained from the roots of a shrub that is native to South Africa. It is a natural sweetener found as four distinct molecules in the bark and root. Monatin is 3000 times sweeter than sugar. In taste, it is close to aspartame and superior over stevia and monk fruit. The industrial production through extraction or artificial synthesis is not possible for this molecule (O'Donnell and Kearsley 2012). It has zero glycemic index and classified as intense sweetener (Kulik and Waszkiewicz-Robak 2018).

4.16 Monellin

Monellin is also a natural sweeter with 1500 times more sweetness than sucrose. It is obtained from Serendipity Berry (native to Central and West Africa) (Morris et al. 1973). The Serendipity Berry is also featured in the 1972 Guinness Book of World Record. It became the first natural protein sweetener found in 1969. It contains four calories per gram but does not show any heat and pH stability (Kinghorn and Compadre 2016). Consequently, it is not appropriate for cooking or processing foods. So far, this sweetener has been approved only in Japan (Kim and Kinghorn 2002a).

4.17 Osladin

Osladin, a saponin, is isolated from the rhizome of *Polypodium vulgare*. It is 500 times sweeter than sucrose (Yamada and Nishizawa 1995).

4.18 Pentadin

Pentadin comes from the Oubli plant (native to West Africa). It is 500 times sweeter than sugar and contains four calories per gram (van der Wel et al. 1989). This sweetener was discovered in 1989 but remained unpopular and shadowed by brazzein. In terms of sweetness and flavor, it is not much appreciated. Furthermore, its pharmaceutical and food applications need to be examined.

4.19 Stevia

Stevia (*Stevia rebaudiana*) is a plant native to Paraguay in South America. Its leaves contain two compounds, stevioside and rebaudioside, which are 300 times sweeter than sugar. It has zero glycemic index and not harmful to teeth (Ashwell 2015). Stevia is now being cultivated in many countries of the world. It is heat stable and hence suitable for cooking and processing food. The product is sold in the market as powdered leaves or concentrated stevioside. Coca-Cola and Pepsi both are using stevia in their products called Truvia and PureVia, respectively. In Japan, it is being used since 1970s and approved there as a sweetener.

4.20 Thaumatin

Thaumatin is a protein that comes from katemfe fruit (*Thaumatococcus daniellii* Bennett) native to West Africa (Green 1999). It stands 2000 times sweeter than sugar. It has a zero glycemic index and is thus suitable for diabetics. It has GRAS in the United States and European Union as E957.

5 Natural High-Potency Sweeteners

Due to the increased demand for non-nutritive natural sweeteners, the search is being undertaken in all parts of the world. There are many natural non-carbohydrate sweet-tasting compounds known to man. Among the natural sweeteners, sweet proteins are unique in that they have no modified amino acids. These protein sweeteners have high potency compared to sugar and decompose into amino acids on hydrolysis. Such proteins also have an advantage that they can be used as probe molecules for basic science studies. Thaumatin and monellin are the most studied protein sweeteners. Recently, many other protein sweeteners have been discovered for which a brief comparative is compiled in Table 2 along with the information on artificial sweeteners in Table 3.

6 Sugar Alcohol

Polyols differ from other saccharides by reducing aldehyde or ketone functions. Some sugar alcohols are present in nature, especially in the vegetable kingdom, but since their extraction is hardly a viable proposition, they are produced industrially by the hydrogenation of the corresponding saccharides. The chemical structure of different plant-derived sweeteners is compiled in Fig. 3. Substitution in a sugar of

Table 2 Natural high potency sweeteners of plant origin

Class of sweeteners	Example	Plant source (plant part used)	Found in	Sweet principles	$P_w(10)$	References
Protein sweeteners	Thaumatin	*Thaumatococcus daniellii* Benth (Katemfe berry)	Tropical Western Africa	Thaumatin I and II	1600	Inglett (1976), Ayodeji et al. (2016)
	Monellin	*Dioscoreophyllum cumminsii*, (serendipity berry)	Western Africa	Sweet protein	3000	Morris and Cagan (1972), Morris et al. (1973), Wlodawer and Hodgson (1975)
	Sweet albumins	*Capparis masaikai* Levi (seeds)		Mabinlin I and mabinlin II	11,600 and 10,400	Liu et al. (1993), Nirasawa et al. (1993)
	Sweet protein	*Pentadiplandra brazzeana* (fruits)	Tropical Africa	Pentadin	12,000	van der Wel et al. (1989)
	Curculin	*Curculigo latifolia* (pulp of the fruit)	Western Malaysia	114 amino acid polypeptide	24,000	Yamashita et al. (1990), Barre et al. (1997)

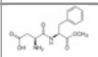
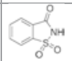
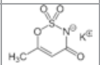
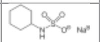
(continued)

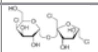
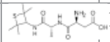
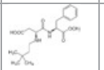
Table 2 (continued)

Class of sweeteners	Example	Plant source (plant part used)	Found in	Sweet principles	P_w(10)	References
Terpenoid sweeteners	Monoterpenoid	*Perilla frutescens*		Volatile oil	770	Liu et al. (2017), Dong et al. (2019)
	Sesquiterpenoid	*Lippia dulcis* Trev.		Hernandulcin	1800	Douglas Kinghorn and Kennelly (1995), Souto-Bachiller et al. (1996)
	Diterpenoid	Pine tree; *Stevia rebaudiana* Bertoni	Northeastern part of Paraguay	Rosin; diterpenoid glycosides	1600	Barton (1949), Yadav et al. (2011), Bouwmeester (2019)
	Triterpenoid	*Glycyrrhiza glabra* L. (roots)	Europe and Central Asia	Glycosides glycyrrhizin (Licorice "the crude extract of the plant")	33	Batiha et al. (2020)
		Periandra dulcis Mart.	Brazilian Licorice	Glycyrrhizin, oleanane-type triterpenoid glycosides		Negri and Tabach (2013)
		Polypodium vulgare L. (rhizomes)		Osladin	300	
		Polypodium glycyrrhiza	Pacific northwest region of the United States	Polypodoside A	600	Kim et al. (1988)
		Mamordica grosvenorii		Aglycone mogrosides IV and V	150	Kinghorn et al. (1986), Kinghorn (1987), Pawar et al. (2013)
		Bryonia dioica Jacq		Bryodulcosigenin A derivative of aglycone		Lavie and Glotter (1971)
		Hemsleya carnosiflora		Glycosides V and VI		Kinghorn et al. (1995)
		Abrus precatorius L. (leaves)		Abrusoside		Choi et al. (1989)

Class of sweeteners	Example	Plant source (plant part used)	Found in	Sweet principles	$P_w(10)$	References
Polyketide sweeteners	Dihydroisocoumarin	*Hydrangea macrophylla* (leaves)		Phyllodulcin, A 3,4-dihydroisocoumarin	400	Kinghorn et al. (1986)
	Dihydrochalcone.	*Smilax glyciphylla* (leaves)		Glycyphyllin		Soumyanath (2005)
		Symplocos microcalyx (leaves)		Trilobatin		Kinghorn et al. (1986)
		Lithocarpus litseifolius (leaves)	Yunnan, China	Phlorizin and trilobatin		Rui-Lin et al. (1982), Chen et al. (2009), Wei et al. (2020)
	Flavanone	Citrus fruits		Neohesperidin		Rouseff et al. (1987), Kroeze (2000)
		Engelhardtia chrysolepis (leaves)	Guangdong, Guangxi and Fujian, China	Dihydroflavonol rhamnoside		Kasai et al. (1991), Kim and Dubois (1991), Meng et al. (2020)
		Tessaria dodoneifolia (shoots)	Paraguay	Dihydroflavonol acetate	80-, 400	Kim and Kinghorn (2002b)

Table 3 Artificial sweeteners and their properties

Sweetener	Structure	Discovered/ developed in	Discovered/ developed by	Molecular formula	Molecular mass in g·mol^{-1}	Melting temperature in °C	Sweetness	Use in	Side effects
Aspartame		1965	James M. Schlatter	$C_{14}H_{18}N_2O_5$	294.307	246–247	200	Tabletop sweeteners, foods, and beverages, recipes that don't require too much heating and as a flavoring in medicines.	Aspartame is tried to be linked with many health problems such as cancer, heart diseases, stroke, dementia, headaches and migraines, etc.
Saccharin		1870s	Ira Remsen and Constantine Fahlberg	$C_7H_5NO_3S$	183.18	229–230	300	Food, beverages, and confectionery products	Headaches, breathing difficulties, diarrhea, and skin problems
Acesulfame K		1967	Clauss and Jansen	$C_4H_4KNO_4S$	201.24	225	200	Tabletop sweeteners, puddings, soft drinks, cough syrups, and toothpaste	Contains methylene chloride (a carcinogen). Its long-term exposure can cause headaches, depression, nausea, mental confusion, liver effects, kidney effects, visual disturbances, and cancer in humans
Cyclamate		1937	Michael Sveda	$C_6H_{12}NNaO_3S$	201.22	169–170	30–50	Baked goods, confections, desserts, soft drinks, preserves, and salad dressings.	Headaches, breathing difficulties, diarrhea, and skin problems

Sweetener	Structure	Discovered/ developed in	Discovered/ developed by	Molecular formula	Molecular mass in g·mol^{-1}	Melting temperature in °C	Sweetness	Use in	Side effects
Sucralose		1977	Tate and Lyle	$C_{12}H_{19}C_{13}O_8$	397.64	125	600	Food and beverage	Gastrointestinal problems, seizures, dizziness, and migraines, blurred vision, allergic reactions, blood sugar increases, and weight gain
Alitame		1980s	Pfizer	$C_{14}H_{25}N_3O_4S$	331.431	--	2000	Cooking and baking	No side effects
Neotame		1992	Claude Nofre and Jean-Marie Tinti	$C_{20}H_{30}N_2O_5$	378.469	80.9–83.4	8000	Flavor enhancer in foods (except in meat and poultry)	Low body weight gain

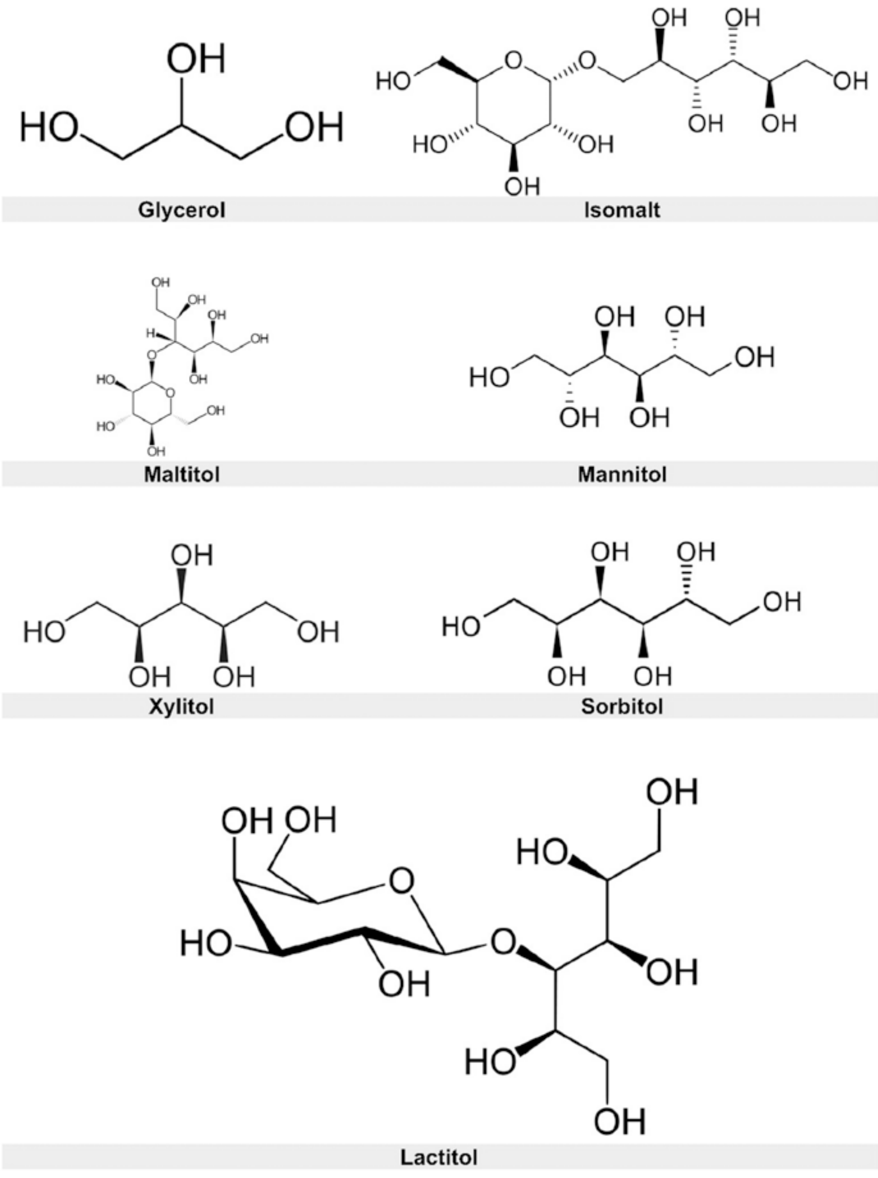


Fig. 3 Chemical structure of sugar alcohols

an alcohol function rather than an aldehyde or ketone group turns a cyclical form into a linear form and has the following implications:

- Greater chemical stability
- Higher affinity for the water
- Lower capacity to crystallize
- Lack of the Maillard response

6.1 Glycerol

Glycerol or glycerin usually obtained from soybean, coconut, or palm oils is called vegetable glycerin and made from animal and petroleum products. Glycerin is an odorless, low-calorie (4 calories per gram), and with a mild-sweetening taste sugar alcohol (polyol). It has a low glycemic index (Only 3—sugar is 65) which makes it good for diabetics, but it is not very popular as a sweetener. Vegetable glycerin has its main application in cosmetics. Glycerin has its applications in surgery, in laxative, and as part of many lotions and creams. Glycerin is harmless to teeth with no side effects except discomfort on taking it to excess.

6.2 Hydrogenated Starch Hydrolysates

Hydrogenated starch hydrolysates (HSH) is a sugar alcohol produced from starch. This sugar alcohol contains a high amount of sorbitol and maltitol. HSH is used in foods to provide bulk and texture. It also has a low glycemic index which makes it a suitable part of a diabetic diet. HSH is used to make sugar-free sweets and other low-calorie foods.

6.3 Isomalt

Isomalt is sugar alcohol with no effect on blood sugar levels. Its energy values account for half of sugar (Duffy and Anderson 1998). Like other sugar alcohol, it also carries a risk of stomach distress when consumed in large quantities. Its blend with high-intensity sweetener like sucralose is just as sweet as plain sugar. Isomalt is approved for use in many countries including the United States, Australia, Canada, Mexico, European Union, etc.

6.4 Maltitol

Maltitol is a sugar alcohol with less calories but a high glycemic index which makes it unsuitable for diabetics. It is described as natural sweetener due to its presence in chicory leaves (Rozzi 2007). Still, it is produced commercially from cereal crops. Maltitol is being used in processed foods such as sugar-free chocolate and coating of hard candies and chewing gums (Saraiva et al. 2020). Like other sugar alcohols, it also has a slightly laxative effect once consumed in large quantities (Saraiva et al. 2020). Maltitol has been approved for use in many countries.

6.5 Mannitol

Mannitol (a sugar alcohol) has low glycemic index which makes it appropriate for diabetics (Chen et al. 2020). However, its caloric count is not very low compared to sugar (1.6 calories/ gram). Because of its nonhygroscopic property, it is suitable for coating candy, pills, and tablets. Mannitol has numerous medical applications like in the treatment of head trauma, kidney failure cystic fibrosis, and as laxative for children (Chen et al. 2020). Mannitol is commercially manufactured from fructose or glucose syrup. Cargill is a world leader in the production of mannitol under brand names Mannidex and Roquette.

6.6 Xylitol

Xylitol is a sugar alcohol (polyol) with lower calories and very less glycemic index (Natah et al. 1997). Like the other animals, our body naturally produces it during metabolism (approximately 5 to 15 gm per day). Xylitol is found in small quantities in vegetables and fruits. Birchbark contains its highest natural concentration. Xylitol was found in 1890 and was widely used during World War 2 (Delgado Arcaño et al. 2020).

6.7 Sorbitol

Sorbitol also known as glucitol is sweet in flavor and widely used sugar alcohol. It is produced primarily from the potato starch and by the reduction of glucose. Sorbitol is also found in the wild in many fruit crops such as apples, peaches, prunes, etc (Forni et al. 1992; Lee 2015). Sorbitol is an isomer of mannitol that is another sugar alcohol. Sorbitol contains two-third calories of table sugar and its sweetness is 60%. It does not contribute to dental wear but not fully digested in the bowel. Sorbitol is used in the making of sugar-free chewing gum and liquid prescription. Overconsumption of sorbitol is sometimes linked to bloating and diarrhea (Jain et al. 1985; Badiga Jain et al. 1990). It is also viewed as less risky, non-stimulative laxative. Despite having so many adverse effects, sorbitol is approved by regulatory agencies in various countries.

6.8 Lactitol

Lactitol is a synthetic disaccharide primarily used for the treatment of constipation and liver encephalopathy (Morgan and Hawley 1987). It is like a lactulose-like glucose molecule that contains galactose as well as sorbitol. Lactitol is just 40%

sweeter than sugar and good for low-calorie diets. Due to its high stability, it is also used in making various bakery products (van Velthuijsen 1979; Zhang et al. 2020). Lactitol is used as prebiotic and in the treatment of constipation.

7 Effect of Sweeteners on Health

7.1 Effect on Dental Health

Over the past decade, the prevalence of dental caries among children, teenagers, and young adults has dropped substantially in most developed countries. This has resulted in a growing percentage of caries-free individuals and improved dental health. Dental caries is a complex sugar-dependent bacterial disease in which three main factors can be identified: host with susceptible teeth, substrate, and cariogenic microorganisms. The presence and interaction of all three factors are needed if dental caries are to develop.

The bacteria mainly *Streptococcus mutans* and *Lactobacilli* play a key role in fermenting dietary carbohydrates and converting them to acidic end products (lactic acid) followed by initiation of caries and demineralization of tooth surface (Hamada 2002). *Streptococcus mutans* can tolerate high sucrose concentrations. The effect of different plant-derived sweeteners and other sweeteners on dental health are already discussed above.

7.2 Effect on Metabolism

With the increased use of sweeteners, their health implications have become a major concern. The way these sweeteners affect metabolism and problems that are encountered by the patient with metabolic diseases such as diabetes and phenylketonuria require research focus (Finer 1991).

The basis of knowledge on metabolisms of different foodstuffs is the study of their single doses. However, actual digestion, absorption, and metabolisms of food depend on its physical condition which is addressed only very recently.

Absorption depends on its various factors, namely, rate of gastric emptying, digestion, and time of transit through the gut, etc. Bacteria in large bowel ferment undigested food (carbohydrates) into metabolites, including carbon dioxide, hydrogen, and methane which leads to abdominal pain and diarrhea.

7.3 Effect on Body Weight

Consumers are always concerned about their body weight, shape, figure, and fitness. Additionally, the doctors have raised the concern to avoid obesity and its related degenerative diseases. The role of sugars in obesity is only profound when sugar-rich diets or drinks are habits and susceptibility to weight gain (Devaux et al. 2011; Choo et al. 2015; Rippe and Angelopoulos 2016). People are mostly conscious about oily food on their diet but not about sugar. Hence, the role of low-calorie sweeteners becomes more profound in connection with this. Such alternative sweeteners provide a sweet taste and low or no calories. These low-calorie sweeteners (LCS) replacement in diet can benefit in weight management. LCS can be made part of more beverages and baking products. However, at the same time, the safety and health benefits of available sweeteners are a major concern. Many studies are underway to ensure the safety of LCS and are recognized by various international scientific expert committees such as the USFDA and JECFA managed jointly by the Food and Agriculture Organization of the United Nations (FAO) and WHO. In India, LCS is regulated by FSSAI (Kroger et al. 2006; Roberts 2016).

8 Conclusion

People are more aware of their weight management and controlling sugar element appears to be one of the effective ways. Completely removing sugar from the diet is not possible since it is one of the major ingredients of our households. Their concern ends up with the emergence of low-calorie sweeteners. Low-calorie sweeteners are used as food additives in place of sugar. There are many low-calorie or zero-calorie sweeteners available in the market. The source of these sweeteners is either natural or man-made (artificial). Sweeteners from natural sources have some limitations such as odd taste profile, unsuitable physical and chemical properties, stability, shelf-life, raw material scarcity, etc. At the same time, the cost of producing natural sweeteners is also less competitive. Hence, we see the market is now flooded with many artificial sweeteners. However, many researchers are conducting studies on the safety of both type of sweeteners. There has been an increased awareness of health problems caused by artificial sweeteners. Therefore, a clear tilt of consumers can be seen toward natural sweeteners. Thus, it is obligatory to conduct a more detailed study on the cost-effective production of natural sweeteners and its impact on human health. The recent advancements in the field of biotechnology can boon the large-scale production of natural protein-based sweeteners. Sweetener enhancers, bitterness blockers, and approved sweeteners are well into commercial development

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