International Food Research Journal 30(2): 303 - 323 (April 2023)
Journal homepage: *http://www.ifrj.upm.edu.my*

Review

Emerging natural and high-phenolic sweet substances: A review

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Article history

Received:
22 September 2021
Received in revised form:
18 June 2022
Accepted:
22 July 2022

Keywords

antioxidant activity,
dihydroflavonol,
functional sweetener,
wild honey,
phenolic compound

Abstract

Emerging high-phenolic sweeteners impart a sweet taste to foods and beverages, and are desirable sugar alternatives. Most refined sugars have a low antioxidant content due to polyphenol degradation occurring during sugar refining. Natural sweeteners such as honey, molasses, and dark brown sugar possess moderate to high phenolic content. Other phytochemicals found in natural sweeteners are carotenoids, organic acids, and terpenoids. Additionally, molasses and syrups synthesised from anthocyanin-rich fruits and roots contain anthocyanins apart from flavonoids. Non-nutritive sweeteners, such as sugar alcohols, are low in calories besides their sweet taste. Sweet proteins, dihydrochalcones, phenolics, and terpenoid derivatives are emerging sweeteners. These sweet substances are effective antioxidants that could help reduce oxidative stress in the human body although the amount ingested is usually low. The present review emphasised specific natural, high-phenolic, and other sweet compounds, and examined the antioxidative characteristics of these sweeteners. The risk of excessive ingestion of these sweet substances is yet to be proven.

DOI
https://doi.org/10.47836/ifrj.30.2.03

Introduction

Sweeteners are natural and artificial ingredients that impart a sweet taste to foods and beverages. Natural sweeteners are sweet materials produced or obtained from plants, whereas synthetic sweeteners are artificially synthesised. Among several sweeteners, carbohydrate-based sweeteners are the most prevalently used category of sweet ingredients (O’Donnell, 2005). Monosaccharides and disaccharides are the fundamental types of sweeteners, referred to as sugars. Honey, molasses, and other plant-based syrups are also carbohydrate-based sweeteners. Besides refined sugar and high-fructose corn syrup, most natural sweeteners possess phytochemicals (Edwards *et al.*, 2016; Singh *et al.*, 2019). Natural sweeteners such as honey, syrup, and molasses possess phenolic compounds as the principal phytochemicals. Phenolic acids and flavonoids are the recognised antioxidant phytochemicals in these natural sweeteners other than carbohydrates. Syrups and molasses manufactured by anthocyanin-rich parts of plants also contain anthocyanins as some major antioxidants (Kamiloglu *et al.*, 2013; Chen *et al.*, 2015). Additionally, protein-based sweeteners were observed, *e.g.*, like sweet protein isolates, peptides, and amino acids.

Isoprenoids are essential secondary plant metabolites. Unlike polyphenols, specific isoprenoids are naturally sweet substances extracted from plants (Kinghorn and Soejarto, 1989). These plant metabolites are potential sugar alternatives. Many terpenoids and steroidal saponins are isoprenoids that impart a sweet taste. The sweet taste of these isoprenoids is recognised through a process analogous to bitter chemicals, in which the molecules connect to G-protein-coupled receptors, thus leading to nerve stimulation. The investigation of sweet terpenoids isolated from fruits, leaves, and stems is currently a prominent research area. Some of these

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plant metabolites are a few hundred times sweeter than sucrose. They possess antioxidant properties although terpenoids do not have similar structures as polyphenols.

Based on the literature, plant terpenoids have less antioxidant activity than polyphenols (Park, 2020). Consequently, polyphenol outperforms terpenoid as an antioxidant (Turkiewicz *et al.*, 2019). Polyphenols, such as flavonoids and anthocyanin chalcones with a double-bond conjugated to the oxo (keto) group possess stronger antioxidant activities than the hydroxyl group (Khoo *et al.*, 2017; Yang *et al.*, 2019). The B-ring of flavonoids, which is catechol, demonstrates high antioxidant activity (Li *et al.*, 2022). Furthermore, most terpenoids, including carotenes, lack a hydroxyl group. They are natural antioxidative agents, and provide a sweet taste because unrefined carbohydrate-based sweeteners and sweet plant metabolites are isolated or obtained from different plant components.

Natural and artificial compounds make up non-nutritive sweeteners (NNSs). Plant metabolites and sugar alcohols are regarded as NNSs. Some of these natural sweeteners are chemically synthesised from naturally existing plant parts. The health implications of ingesting these NNSs are unknown. Chemical residues from extraction and refining may be present in these sweeteners. Therefore, honey, molasses, syrups, and minimally processed sugars are the best sweeteners because they are high in phytochemicals such as phenolic acids, flavonoids, anthocyanins, and terpenoids. Terpenoids, in addition to phenolic compounds, are some of the most important antioxidative components of plants (Graβmann, 2005).

Strategy for literature search

The present review was focussed on specific high-phenolic and emerging sweeteners. Three independent scientists researched electronic databases, including Google Scholar and PubMed, for relevant papers in English, from 1980 to 2022. Among the keywords used in the search were allulose, amino acids, peptides, antioxidant activity, artificial sweeteners, dihydrochalcone, emerging sweeteners, flavonoid, high-phenolic, honey, mogrosides, molasses, monosaccharides, natural sweeteners, NNSs, phenolic compounds, steviosides, sugars, sugar alcohols, sweet substances, syrups, and terpenoids. The literature search produced over a thousand data sources. The information linked to natural and artificial sweeteners were obtained from search engines such as Google and Bing. Selected references were obtained from a literature search. The present review also included information on other phenolic-containing sweeteners.

Types of sweeteners

Sweeteners are accessible in natural and synthetic forms. Natural sweeteners are primarily plant-based, whereas artificial sweeteners are either chemically manufactured or obtained from plants. Natural sweeteners are classified in the present review as carbohydrate-based, protein-based, and plant metabolites. Artificial sweeteners are calorie-free sugar alternatives. Some NNSs do exist in natural forms although most artificial sweeteners are non-nutritive. Table 1 shows the different forms of sweeteners.

Sugar is the most prevalent type of carbohydrate-based sweetener. Commercially accessible sweeteners include cane, beet, and palm sugars. Minimally treated sugar is unrefined or brown sugar. Sugar is composed of disaccharide units. Aside from sugars, simple carbohydrates, also known as monosaccharides, are the most common natural sweeteners. They are neutral monosaccharides, osamines, uronic acids, and sialic acids. Among the monosaccharides, neutral monosaccharides are simple sugars, such as glucose, fructose, and galactose, but refined sugar (white sugar) and unrefined sugars are disaccharides (unprocessed cane and non-cane sugars). Osamines, uronic acids, and sialic acids are not sugar alternatives although they are monosaccharides.

Glucose and fructose are two monosaccharides that are often utilised as sweeteners, with many other monosaccharides not widely being utilised as sweeteners. For example, allulose, another monosaccharide, is one of the zero-calorie sweeteners used as an alternative to sugar. These monosaccharides can be found in various plant parts including fruits, leaves, flowers, shoots, roots, and tubers. Monosaccharides and disaccharides are produced from plant components after a few processing and purification processes, and the final products are sugars in their natural state.

Sugar alcohols, purified sweet plant extracts, sweet plant metabolites, sweet amino acids, proteins and peptides, and artificial sweeteners are considered sugar substitutes. Sugar alcohol is a sweetener made from carbohydrate called polyol. Among the polyols,

Table 1. List of natural and non-nutritive sweeteners.

Category	**Sweetener**
	Carbohydrate-based
Honey	Monofloral honey: acacia, buckwheat, clover, heather, manuka, and others. Multifloral and wild honey: wildflower, Malaysian Tualang and Gelam. Others: Stingless bee honey, wasp honey, and non-floral honey with artificial feeding (syrup-feed honey).
Molasses	Fruit-based: Date, grape, mulberry, pomegranate, and others. Others: Carob, sugar beet, and sugarcane.
Monosaccharide	Allulose, arabinose, fructose, galactose, glucose, mannose, and xylose.
Sugar	Brown beet sugar, brown cane sugar, and refined cane sugar.
Sugar alcohol	Erythritol, fucitol, galactitol, glycerol, iditol, inositol, isomalt, lactitol, maltitol, mannitol, ribitol, sorbitol, threitol, volemitol, and xylitol.
Syrup	Agave, barley, brown rice, cassava, corn, date, fig, maple, spelt, sugarcane, wheat malt, and others.
	Protein-based
Amino acid, peptide, and protein isolate	Amino acids: L-alanine, L-glutamine, L-glycine, L-proline, L-serine, L-threonine, and L-valine. Dipeptide: Aspartame. Sweet proteins: Brazzein, curculin (neoculin), mabinlin, miraculin, monellin, pentadin, thaumatin, and lysozyme.
	Plant metabolites
Dihydrochalcone and their glycoside	Hesperidin dihydrochalcone, neohesperidin dihydrochalcone, naringin dihydrochalcone, glycyphyllin, and trilobatin.
Dihydroflavonol and phenolic derivative	Dihydroquercetin-3-acetate, dihydroisocoumarins (phyllodulcin and hydrangenol), cynarin (1,5-dicatteoyl quinic acid), and others.
Terpenoid, terpenoid glycoside, and steroidal saponin	Abrusosides, baiyunoside, carnosiflosides-V & VI, cycloartane glycoside, cyclocaryoside, ent-kaurene, glycyrrhizin, gaudichaudioside-A, hernandulcin, mogroside V, osladin, perillartine, periandrin V, polypodoside, pterocaryoside A & B, rebaudioside A, rubusoside, sauvioside A, stevioside, and strogin.
Other sweet substance	*Trans*-anethole and *trans*-cinnamaldehyde.

erythritol, mannitol, sorbitol, and xylitol are the most widely used sugar alcohols. Polyols are found in hydrogenated starches and hydrolysates (Das and Chakraborty, 2016). These polyols can be found in fruits and vegetables in their natural state. Only lactitol is the chemically generated sugar alcohol. Technically recognised sugar alcohols include polydextrose and polyol syrups. They are sugar alternatives due to their low glycaemic index (GI). Most sugar alcohols have a reduced sweetness when compared with sucrose, except for xylitol. A few decades ago, sugar alcohols were widely used in the food and beverage industry because they were nearly as sweet as sugars.

Syrups are sugars in liquid form. These sweet liquids are often made from fruits and leaves, and are the primary source of sweeteners in some cultures. Canadian maple syrup, Mexican agave syrup, and Middle Eastern date syrup are some examples of syrups. The Assyrians used fig syrup as a sweetener in ancient times. Syrups have also been prepared from grains and tubers such as barley, brown rice, cassava, spelt, and wheat malt. High-fructose corn syrup is another sugar used in the food processing industry. It is rich in calories, and has no phytochemicals, just like glucose solution. It is also a low-cost sweetener used in the food processing industry. As a result of the rising incidence of diabetes, several food manufacturers have begun employing sugar replacements with zero-calories, *e.g.*, artificial sweeteners, which are relatively cheaper.

Molasses are sweeteners with a smaller number of carbohydrates than refined sugars. They are remnants of the sugar refining process. There is a wide variety of molasses; they vary by plant sources, refining procedures, and phytochemical compositions (Valli *et al.*, 2012; Kamiloglu and Capanoglu, 2014; Molina-Cortés *et al.*, 2020). Molasses can be light, medium, or dark, as well as blackstrap molasses and treacle. Light molasses are by-products of the first refining stage of the sugar, whereas dark molasses are the remnant of the sugar boiling process. The remaining sugar is recovered as blackstrap molasses at the end of the final extraction process.

Honey is another carbohydrate-based sweetener aside from sugars, syrups, and molasses. It is a natural sweetener that contains phytochemicals. Honey can be identified by its floral and plant sources and geographical origins (Codex Alimentarius Commission, 2001). Monofloral, multifloral, and wild honey are types of floral honey. Acacia, clover, and manuka honey are some of the most well-known monofloral honey, and stingless bee honey is another type of floral-based honey (Chuttong *et al.*, 2016). Honey is produced by stingless bees (Meliponini). Honeydew honey is manufactured from the honeydew of leaves, stems, barks, and sap of trees and can be classified as multifloral honey. Non-floral honey, which is not to be confused with honeydew honey, is manufactured by artificially feeding honeybees. It is regarded as syrup-feed honey (Rashed and Soltan, 2004). Additionally, wasp honey is made by Mexican honey wasps. However, a scarcity of information on wasp honey was noted. The principal constituents of honey are monosaccharides, such as glucose and fructose. Honey is derived from a beehive, and requires less processing than sugar.

Sweet amino acids, peptides, and protein isolates are classified as protein-based sweeteners. Among them, monellin and thaumatin are the sweetest protein isolates described in the literature extracted from the fruits of *Dioscoreophyllum cumminsii* and *Thaumatococcus daniellii*, respectively (Masuda *et al.*, 2018). Aside from their sweet taste, these sweet proteins possess peptides and essential amino acids. Table 1 shows that the enumerated amino acids impart a sweet taste (Williams and Bernhard, 1981). Even though some protein extracts have a taste-modifying effect, they are not sweet. The protein extracts are miraculin and neoculin (Koizumi *et al.*, 2007). Miraculin is extracted from the red berries of *Synsepalum dulcificum*, and neoculin is from the edible fruit of *Curculigo latifolia* (Świąder *et al.*, 2019). They can transform sourness into sweetness.

Plant metabolites are the new examples of natural sweeteners (Table 1). These sweet chemicals are obtained principally from plants. They are in the form of dihydroflavonols, phenolic derivatives, steroidal saponins, terpenoids, and terpenoid glycosides. In addition, some dihydrochalcones and phenolic compounds are plant metabolites with a sweet taste. These dihydrochalcones are hesperidin, neohesperidin, and naringin dihydrochalcones. They have been isolated and refined from several types of plants.

Terpenoids and their glycosides isolated from stevia leaves (*Stevia rebaudiana*) and monkfruits (*Siraitia grosvenorii*) are commercially available as naturally occurring sweeteners. Other plant-based sweet compounds are steroidal saponins and glycosides. Cyclocaryoside, osladin, and polypodoside are the dammarane-type triterpenoid glycoside steroidal saponin. Cyclocaryoside and osladin are extracted from the rhizomes of *Polypodium vulgare* and *P. glycyrrhiza*, respectively, whereas polypodoside from the leaves of *Cyclocarya paliurus* (Priya *et al.*, 2011). Strogin is an oleanane-type triterpenoid saponin. According to Priya *et al.* (2011), strogin was discovered in the leaves of *Staurogyne merguensis*.

Some sweet plant metabolites are NNSs; however, not all are not artificial sweeteners. Most dihydrochalcones are artificial sweeteners, even though they exist naturally in plants. For instance, neohesperidin dihydrochalcone is manufactured from naringin (Mortensen, 2006). It is an approved sweetener used as a sweetening agent in the food industry. Similarly, sugar alcohols have been developed chemically from sugars and other saccharides. Consequently, they are more commonly referred to as non-nutritive sweetening agents. They are sweeteners that do not contain extra calories. However, most sugar alcohols provide energy to the human body.

Sugar alcohols are the most commonly used NNSs in the foods and beverage industry. They are extensively used in functional food products; however, some food processing industries prefer sweeteners from plants, such as stevioside from stevia leaves. Artificial sweeteners are a popular option for people with diabetes because they are inexpensive and readily available. Sweet plant metabolites may also impart undesirable flavours to foods and beverages because plant phenolics and terpenoids are aromatic compounds. Notwithstanding, these sweeteners are superior alternatives because they are phytochemical antioxidants, and do not increase the calorie content of foods and beverages; their GI value is 0.

Based on the literature, glucose and dextrose have a GI of 100 (Jenkins *et al.*, 1981), fructose has a GI of 25, maltose and maltodextrin have a GI of 105 and 110, respectively (Horowitz, 2013), sucrose has a GI of 65, and most caramel and syrups have GI values of 60 and lower. Maltitol has the highest GI (35) among the sugar alcohols (Horowitz, 2013; Grembecka, 2015), followed by xylitol (12 - 13), sorbitol (9), isomalt (9), lactitol (6), and mannitol (2). Erythritol, oligofructose, and inulin have similar GI (1). Notable differences in the GI values (1 - 60) of honey, syrup, and molasses were observed because the sugar concentrations of these natural sweeteners vary. Refined sugars and syrups demonstrate a higher monosaccharide concentration than the minimally treated sugars and molasses. Additionally, other non-monosaccharide-containing sweeteners have a GI of 0 (Horowitz, 2013).

Phenolic compounds in sweeteners

Plant-derived sweeteners naturally exist because they are extracted or isolated from plants. Crude plant extracts have a considerably high number of bioactive phytochemicals besides carbohydrates. Artificial sweeteners are chemically synthesised, unlike natural sweeteners. The loss of phytochemicals occurs during the processing and purification of a natural sweetener. Consequently, phenolic chemicals are lacking in plant-derived sweeteners, monosaccharides, and plant hydrolysates that have been severely processed.

Total phenolics, flavonoids, and anthocyanin concentrations of designated natural sweeteners are described in Table 2. Total phenolic content (TPC) has been stated in all enumerated natural sweeteners but not for total flavonoids and anthocyanins. Anthocyanins are identified only in natural sweeteners manufactured from anthocyanin-containing samples. Among the naturally occurring sweeteners described in the present review, phytochemical-rich molasses and syrups possess the highest TPC, followed by honey and minimally processed sugars such as brown sugars. The TPC is measured in gallic acid equivalent (GAE).

Table 2 shows that pomegranate molasses has the highest TPC (828.15 mg GAE/g sample), whereas sugar beet molasses have the lowest concentration of total phenolics (0.06 mg/g sample). Consequently, the phenolic content of the sugarcane molasses was approximately six times higher than that of sugar beet molasses (Valli *et al.*, 2012). Another investigation confirmed that sugarcane molasses had high TPC (Grabek-Lejko and Tomczyk-Ulanowska, 2013). The TPC of honey was as high as 0.27 mg GAE/g sample. In addition to the TPC of these honey samples, the TPC of 12 Mexican honey samples ranged from 15.29 to 32.18 mg GAE/100 g sample (Cortez, 2019). Moreover, fruit-based syrups had the greatest TPC, followed by grain, stem, leaf, and tuber-based syrups. Tadhani *et al.* (2007) also reported that sweet stevia leaves had a TPC of 25.18 mg/g leaves, of which stevioside was the principal component.

Table 2. Total phenolics, total flavonoids, and total anthocyanins of different sweeteners.

Type of sweetener	Total phenolics (gallic acid equivalent)	Total flavonoids (catechin equivalent)	Total anthocyanins (cyanidin-3-glucoside equivalent)	Citation
		Honey		
Buckwheat honey	0.27 ± 0.02*	N/A	N/A	1
Gelam honey	0.03 ± 0.006*	0.02 ± 0.002*	N/A	2
Manuka honey	0.05 ± 0.01*	0.03 ± 0.005*	N/A	2
Multifloral honey	0.10 ± 0.001*	N/A	N/A	1
Rape honey	0.05 ± 0.004*	N/A	N/A	1
Stingless bee honey	17.0 - 66.0**	N/A	N/A	3
Tualang honey	0.03 - 0.04*; 0.025 ± 0.008*	0.021 - 0.025*	N/A	2, 4
		Molasses		
Beet molasses	1.21 ± 0.17*	N/A	N/A	1
Black mulberry molasses	4.66 ± 0.19*	1.05 ± 0.05*	0.03 - 0.04*	5
Carob molasses	0.90 ± 0.05*	0.21 ± 0.02*	0.004*	5
Date molasses	176.1*	54.72*	N/A	6
Grape molasses	1.25 ± 0.05*	0.14 ± 0.02*	< 0.03*	4
Pomegranate molasses	118.28 - 828.15*; 90 - 179.5*	54.34 - 137.74*	87.5 - 118.0$^{##}$	6 - 8
Sugar beet molasses	17.28**; 0.06*	N/A	N/A	9, 10
Sugarcane molasses	11.38 ± 0.7*; 0.38*; 221**; 13.91 - 19.40$^{#}$	53.8*	N/A	1, 10 - 12
White mulberry molasses	2.86 ± 0.20*	0.75 ± 0.08*	< 0.03*	6

		Sugar		
Brown beet sugar	0.007 ± 0.004*	N/A	N/A	1
Brown cane sugar	0.08 - 1.73*	2.64 ± 0.38*	0.04 ± 0.01*	1, 13 - 14
Refined cane sugar	0.32 ± 0.03*	0.40 ± 0.01*	N/A	14
		Syrup		
Agave syrup	12.92 ± 0.22$^{\#\#}$; 0.22 - 3.00*	N/A	N/A	15 - 16
Barley syrup	2.38 ± 0.35*	N/A	N/A	1
Brown rice syrup	0.9 ± 0.003*; 12.76 ± 0.41$^{\#\#}$	N/A	N/A	1, 15
Cassava syrup	0.11 ± 0.08*	N/A	N/A	1
Corn syrup	0.73 ± 0.01*; 1.19 - 1.60*; 2.69 ± 0.14$^{\#\#}$	N/A	N/A	1, 15 - 16
Date syrup	3.92 ± 0.32*; 3.68 - 5.29*	0.39 - 1.945*	N/A	1, 17
Fig syrup	3.92*	0.95*	N/A	18
Maple syrup	14.94 ± 0.6$^{\#\#}$	N/A	N/A	15
Spelt syrup	3.043 ± 0.00*	N/A	N/A	1
Sugarcane syrup	1.80 - 1.85*	N/A	N/A	16
Wheat malt syrup	0.00 ± 0.00*	N/A	N/A	1
		Others		
Liquid fructose	0.01 ± 0.003*	N/A	N/A	1
Xylitol	0.00 ± 0.00*	N/A	N/A	1

All values are expressed per sample. *mg/g; **mg/g extract; #mg/g dry matter; ##mg/L; N/A: information not available. Citations: 1: Grabek-Lejko and Tomczyk-Ulanowska (2013); 2: Khalil *et al*. (2011); 3: da Silva *et al*. (2013); 4: Mohamed *et al*. (2010); 5: Kamiloglu and Capanoglu (2014); 6: Nasser *et al*. (2017); 7: Akpinar-Bayizit *et al*. (2016); 8: El Darra *et al*. (2017); 9: Chen *et al*. (2017); 10: Valli *et al*. (2012); 11: Ji *et al*. (2019); 12: Molina-Cortés *et al*. (2020); 13: Payet *et al*. (2005); 14: Azlan *et al*. (2020); 15: St-Pierre *et al*. (2014); 16: Velázquez Ríos *et al*. (2019); 17: Abbès *et al*. (2013); and 18: Jibril *et al*. (2019).

Phenolic acids in natural sweeteners are benzoic, caffeic, chlorogenic, cinnamic, ellagic, ferulic, gallic, *p*-coumaric, *p*-hydroxybenzoic, protocatechuic, syringic, and vanillic acids. Flavonoids in natural sweeteners include apigenin, chrysin, galangin, isorhamnetin, kaempferol, luteolin, myricetin, quercetin, rutin, tricetin, tricin, and vanillin. These phenolic compounds discovered in the sweeteners are obtained from plant sources (Tables 3 and 4). Phenylacetic and phenyllactic acids, in addition to phenolics, are organic acids with a phenyl functional group. They are non-phenolic phytochemicals. These organic acids are abundant in honey.

Polyphenols in honey are derived from floral pollen and nectar gathered by the honeybees. However, the origin of honey generated by honey wasps is unclear. Plant-based phenolic compounds have been discovered in molasses and syrups on top of honey samples. Table 3 shows that flavonoids such as vanillin, luteolin, and kaempferol are the principal antioxidants in sugar beet; in contrast, syringic and vanillic acids are the most prevalent phenolic acids in sugarcane molasses.

Honey, made from the nectar of flowers harvested by bees, is one of the best natural sweeteners. The most prominent type of honey is acacia honey, although more than a hundred varieties of honey exist. Honey has an extensive range of phytochemicals (Kesić *et al.*, 2009). Polyphenolic compounds in honey produced by honeybees depend on the flowers from which the nectar is collected. Wild honey has a low carbohydrate content and a better nutritional quality than orchard honey (Kesić *et al.*, 2009; Chua and Adnan, 2014). Additionally, Tualang and Gelam honey are two varieties of wild honey found in Malaysia (Khalil *et al.*, 2011).

Among the natural sweeteners reported in the literature, phenolic compounds have not been found in refined cane sugar, wheat malt syrup, and xylitol. However, anthocyanins have been identified only in the molasses and syrups manufactured from anthocyanin-rich fruits or carob beans. In addition, earlier investigations did not describe the total flavonoid concentration of several natural sweeteners besides TPC (Table 2). Surprisingly, findings from the literature have shown that liquid fructose has a TPC of 9.88 mg/kg sample (Grabek-Lejko and Tomczyk-Ulanowska, 2013). This could be because the fructose sample derived in the study was impure.

Antioxidative effect of phenolic-rich sweeteners

Phytochemicals from natural sweeteners are powerful antioxidants. Phenolic compounds are the principal phytochemical antioxidants present in these natural sweeteners. They are effective in scavenging free radicals and reducing oxidative stress (Grabek-Lejko and Tomczyk-Ulanowska, 2013). Plant-derived sweeteners such as mogrosides and steviosides possess antioxidative properties (Pawar *et al.*, 2013). Their potency could be a result of their isoprenoid structures. As explained earlier, terpenoids are sweet compounds extracted from plants. These compounds are also powerful antioxidants.

Polyphenols in sugar beet and sugarcane molasses decreased cellular oxidative stress in the HepG2 cells induced by 0.2 mM H_2O_2 as compared to the untreated cells (Grabek-Lejko and Tomczyk-Ulanowska, 2013). The antioxidative properties decreased TBARS value, increased GSH value, and improved cell viability (in percentage). Compounds derived from sugarcane molasses have also been described for their antioxidative properties (Molina-Cortés *et al.*, 2020). The major flavonoids in the molasses extract include apigenin, luteolin, and tricin. Consequently, polyphenol-rich sweeteners are essential for lowering oxidative stress because of their antioxidative properties.

The antioxidative properties of sweeteners are attributable to their bioactive phytochemicals. Phenolic compounds are the principal bioactive phytochemicals in several naturally occurring natural sweeteners. These phenolic compounds have high free radical scavenging activities. The ferric-reducing antioxidant power (FRAP), diphenylpicrylhydrazyl (DPPH), and 2, 2′-azino-di-(3-ethyl-benzthiazoline-6-sulphonic acid) (ABTS) radical scavenging effects of naturally occurring sweeteners are described in Table 5. Molasses exhibited the highest antioxidant activity among the natural sweeteners, followed by syrups, honey, and brown sugars. Pomegranate molasses demonstrated the highest antioxidant activity because of their high TPC. Additionally, most sweeteners demonstrated moderate to high antioxidant activities. Phenolic-rich sweeteners should have better antioxidant activity than non-phenolic-rich sweeteners because antioxidant activities are significantly associated with the total phenolics in plant extracts (Liu *et al.*, 2017).

Melanoidins are the major constituents of

Table 3. Bioactive phenolics in honey and sugar.

Sample	Analytical method/ Extraction solvent	Compound
		Honey
Acacia honey	HPLC (SPE; methanolic extract)	*Phenolic profile* (mg/kg): (Dimitrova *et al.*, 2007) Phenyllactic acid (9.71); phenylacetic acid (3.64); *m*-coumaric acid (1.41); 4-hydroxybenzoic acid (0.98); syringic acid (0.63); protocatechuic acid (0.61); vanillic acid (0.61); ferulic acid (0.53); caffeic acid (0.40); hydroxyphenyllactic acid (0.23); *p*-coumaric acid (0.22); *trans*-cinnamic acid (0.19); and *o*-coumaric acid (0.05).
Citrus honey	HPLC (ethyl acetate extract)	*Phenolic profile* (mg/100 g): (Hamdy *et al.*, 2009) Cinnamic acid (1.35); hesperetin (1.08); quercetin (0.6); and *p*-hydroxybenzoic acid (0.1).
Clover honey	HPLC (ethyl acetate extract)	*Phenolic profile* (mg/100 g): (Hamdy *et al.*, 2009) *p*-hydroxybenzoic acid (1.1); cinnamic acid (0.57); and quercetin (0.20).
	UPLC-TQD-MS (liquid-liquid extraction; ethyl acetate/methanolic extract)	*Phenolic profile* (µg GAE/100 mL): (St-Pierre *et al.*, 2014) *p*-coumaric acid (358.7); hydroxyphenyl acetic acid (163.0); salicylic acid (143.0); caffeic acid (126.2); hydroxybenzoic acid (105.9); chlorogenic acid (82.6); vanillic acid (82.4); syringic acid (77.4); ferulic acid (63.2); coumaroyl hexoside (23.3); syringic acid (18.3); dihydroxybenzoic acid (13.6); quercetin (365.9); kaempferol (150.5); kaempferol rutinoside (134.7); kaempferol hexoside (25.6); catechin (6.2); quercetin hexoside (5.8); myricetin (1.9); quercetin rhamnoside (1.3). Other: Scopoletin (4.0).
Cotton honey	HPLC (ethyl acetate extract)	*Phenolic profile* (mg/100 g): (Hamdy *et al.*, 2009) Cinnamic acid (0.65); quercetin (0.57); and *p*-hydroxybenzoic acid (0.07).
Buckwheat honey	LC-MS (methanolic extracts)	Pinobanksin; pinocembrin; and pinostrobin (Abbès *et al.*, 2013).
Chestnut honey	HPLC (SPE; methanolic extract)	*Phenolic profile* (mg/kg): (Jibril *et al.*, 2019) Benzoic acid (17.45); 3-hydroxybenzoic acid (8.51); 4-hydroxybenzoic acid (7.84); ferulic acid (6.00); hydroxyphenyllactic acid (6.00); protocatechuic acid (5.76); caffeic acid (5.44); vanillic acid (3.46); syringic acid (2.62); *p*-coumaric acid (2.03); *m*-coumaric acid (2.02); salicylic acid (1.81); *o*-coumaric acid (1.46); and *trans*-cinnamic acid (0.85). Organic acids (mg/kg): Phenylacetic acid (71.17); and phenyllactic acid (47.95).
Gelam honey	HPLC; LC-MS; GC-MS	*Phenolic profile* (mg/kg): (Khalil *et al.*, 2011; Jibril *et al.*, 2019) Benzoic acid (1.33); caffeic acid (< 0.01); *trans*-cinnamic acid (< 0.01); *p*-coumaric acid (< 0.01); gallic acid (< 0.01); syringic acid (< 0.01); vanillic acid (< 0.01); catechin (17.76); kaempferol (0.81); naringenin (0.61); luteolin (0.43); and apigenin (0.18). Others: dihydroxycinnamic acid; ellagic acid; ellagic glucoside; hesperetin; kaempferide; myricetin; quercetin; quercetin-3-*O*-glucoside; and rhamnosyl naringenin.

Heather honey	HPLC (SPE; methanolic extract)	*Phenolic profile* (mg/kg): (Dimitrova *et al.*, 2007) Benzoic acid (49.90); hydroxyphenyllactic acid (8.76); 4-salicylic acid (6.66); hydroxybenzoic acid (4.71); caffeic acid (2.97); protocatechuic acid (2.78); vanillic acid (2.30); syringic acid (2.08); *p*-coumaric acid (1.87); *trans*-cinnamic acid (1.84); ferulic acid (1.03); 4-hydroxybenzoic acid (0.98); *o*-coumaric acid (0.89); and gallic acid (0.63). Organic acids (mg/kg): Phenyllactic acid (820.38); and phenylacetic acid (176.61).
Lavender honey	HPLC (SPE; methanolic extract)	*Phenolic profile* (mg/kg): (Dimitrova *et al.*, 2007) Gallic acid (6.31); 4-hydroxybenzoic acid (1.71); hydroxyphenyllactic acid (1.12); caffeic acid (1.01); syringic acid (0.64); salicylic acid (4.61); *p*-coumaric acid (0.29); ferulic acid (0.25); *trans*-cinnamic acid (0.13); *o*-coumaric acid (0.09). Organic acids (mg/kg): Phenyllactic acid (40.52); and phenylacetic acid (6.50).
Lime honey	HPLC (SPE; methanolic extract)	*Phenolic profile* (mg/kg): (Dimitrova *et al.*, 2007) 3-Hydroxybenzoic acid (4.71); protocatechuic acid (2.18); caffeic acid (1.57); *p*-coumaric acid (1.41); vanillic acid (1.19); 4-hydroxybenzoic acid (0.98); ferulic acid (0.94); *trans*-cinnamic acid (0.46); and syringic acid (0.29). Organic acids (mg/kg): Phenylacetic acid (29.77); and phenyllactic acid (26.41).
Manuka honey	HPLC	*Phenolic profile* (mg/kg): (Khalil *et al.*, 2011; Abbès *et al.*, 2013) *p*-coumaric acid (1.03); caffeic acid (0.05); benzoic acid (< 0.01); *trans*-cinnamic acid (< 0.01); gallic acid (< 0.01); syringic acid (< 0.01); vanillic acid (< 0.01); ellagic acid; catechin (36.77); apigenin (< 0.01); hesperetin (< 0.01); kaempferol (< 0.01); luteolin (< 0.01); naringenin (< 0.01); and naringin (< 0.01). Others: Chrysin; and isorhamnectin.
Rapeseed honey	HPLC (SPE; methanolic extract)	*Phenolic profile* (mg/kg): (Dimitrova *et al.*, 2007) Phenylacetic acid (4.16); benzoic acid (3.66); ferulic acid (0.68); syringic acid (0.54); 4-hydroxybenzoic acid (0.52); *p*-coumaric acid (0.47); *o*-coumaric acid (0.42); vanillic acid (0.36); caffeic acid (0.33); protocatechuic acid (0.16); and *trans*-cinnamic acid (0.14).
Stingless bee honey	HPLC; GC-MS (SPE; methanolic extracts)	*Phenolic profile* (mg/100 g): (da Silva *et al.*, 2013; Jibril *et al.*, 2019) 4-Hydroxybenzoic acid (0 - 0.42); syringic acid (0 - 1.51); salicylic acid (0 - 0.17); coumaric acid (0 - 0.15); cinnamic acid (0 - 0.11); gallic acid (0.02 - 0.09); protocatechuic acid (0 - 0.03); chlorogenic acid; vanillic acid; taxifolin (3.80 - 67.00); catechol (0 - 8.76); luteolin (0 - 2.26); naringenin (0 - 1.30). Others: Bergamottin; catechol; coumarin; fraxin; isorhamnetin; luteolin-7-*O*-glucoside; quercetin; and scopoletin.
Tualang honey	HPLC	*Phenolic profile* (mg/kg): (Khalil *et al.*, 2011) Benzoic acid (0.20 - 0.96); *trans*-cinnamic acid (0.01 - 0.50); gallic acid (0 - 0.43); syringic acid (0 - 0.07); *p*-coumaric acid (0 - 0.04); caffeic acid (< 0.01); vanillic acid (< 0.01); catechin (12.90 - 35.58); naringenin (0 - 0.57); kaempferol (0 - 0.15); apigenin (< 0.01); hesperetin (< 0.01); and luteolin (< 0.01). Others: Rhamnosyl naringenin.
	Sugar	
Brown cane sugar	LC-MS (dichloromethane extract)	*Phenolic profile* (μg/kg): (Valli *et al.*, 2012) Syringic acid (71.3 - 1610.1); vanillic acid (29.4 - 750.4); benzoic acid (62.4 - 221.2); *p*-coumaric acid (7.8 - 332.0); ferulic acid (8.6 - 160.6); *p*-hydroxybenzoic acid (1.9 - 240.9); homovanillic acid (0 - 141.1); vanillin (194.5 - 529.8); acetosyringone (0 - 83.9); and coniferyl alcohol (0 - 23.5).

Phenylacetic and phenyllactic acids are organic acids with a phenyl functional group.

Table 4. Bioactive phenolics in molasses and syrups.

Sample	Analytical method/ Extraction solvent	Compound
		Molasses
Sugar beet molasses	HPLC-DAD-ESI-MS (Dissolved in water; 1:10; w/v)	*Phenolic profile* (µg/g): (da Silva *et al.*, 2013) Vanillin (17.41); luteolin/kaempferol (17.24); ferulic acid (14.83); feruloyl-arabinose-arabinose (4.51); hydroxybenzaldehyde (2.93); syringic acid (2.26); caffeoyltartaric acid (1.95); and hydroxybenzoic acid (1.12).
	HPLC-DAD-MS/MS (Acidified ethanolic extract)	*Phenolic profile* (mg/mL extract): (Chen *et al.*, 2017) Ferulic acid (1.56); vanillin (1.26); gallic acid (0.45); catechin (0.16); syringic acid (0.12); hydroxybenzoic acid (0.06); cyanidin-3-*O*-rutinoside (0.05); delphinidin-3-*O*-rutinoside (0.03); cyanidin-3-*O*-glucoside (0.02); and delphinidin-3-*O*-glucuronide (0.02).
Sugarcane molasses	HPLC-DAD-ESI-MS (Dissolved in water; 1:10; w/v)	*Phenolic profile* (µg/g): (da Silva *et al.*, 2013) Syringic acid (85.53); vanillic acid (30.07); caffeoylquinic acid (10.45); ferulic acid (6.25); 4-hydroxyphenylacetic acid (5.83); feruoylquinic acid (5.32); diferuoylquinic acid (5.23); caffeoyl-*O*-malonyl-*O*-coumaroylquinic acid (4.19); 6,8-dihydroxykaempferol (22.35); catechin (16.42); 5,7-dihydroxyflavanone (9.71); apigenin-hexoside-pentoside (53.66); feruloyl-arabinose-arabinose (35.99); quercetin-3-*O*-glucosyl-xyloxide (25.27); 7-methylapigenin-6-*C*-glucoside (22.28); tricin-7-*O*-glucoside (16.45); tricin-7-*O*-β-(6-p-methoxycinnamate)-glucoside (15.52); and dicaffeoylquinic acid glucoside (2.08)
Sugarcane molasses (commercial product)	UPLC-TQD-MS (liquid-liquid extraction; ethyl acetate/methanolic extract)	*Phenolic profile* (µg GAE/100 mL): (St-Pierre *et al.*, 2014) *p*-coumaric acid (1736.0); chlorogenic acid (1538.0); syringic acid (1165.2); vanillic acid (671.1); dihydroxybenzoic acid (517.5); caffeic acid (441.51); salicylic acid (419.2); hydroxybenzoic acid (324.5); hydroxyphenyl acetic acid (323.1); coumaroyl hexoside (274.9); ferulic acid (222.9); caffeoyl hexoside (105.5); synaptic acid (79.8); syringaldehyde (10.9); kaempferol hexoside (1009.0); myricetin hexoside (110.0); kaempferol glucoronide (90.1); kaempferol rutinoside (40.2); quercetin rhamnoside (8.2); myricetin arabinoside (6.9); and quercetin (2.6). Others: Lariciresinol (83.3); phlorizin (9.1); and secoisolariciresinol (5.83).
		Syrup
Agave syrup	UPLC-TQD-MS (liquid-liquid extraction; ethyl acetate/methanolic extract)	*Phenolic profile* (µg GAE/100 mL): (St-Pierre *et al.*, 2014) Caffeoyl hexoside (1175.1); vanillic acid (18.8); syringic acid (18.3); dihydroxybenzoic acid (9.1); hydroxyphenyl acetic acid (7.5); hydroxybenzoic acid (4.9); chlorogenic acid (3.4); caffeic acid (2.8); salicylic acid (2.6); quercetin hexoside (24.6); quercetin arabinoside (15.9); quercetin rhamnoside (5.6); myricetin hexoside (1.6); and quercetin (0.6). Other: Phlorizin (11.2).

Brown rice syrup	UPLC-TQD-MS (liquid-liquid extraction; ethyl acetate/methanolic extract)	*Phenolic profile* (µg GAE/100 mL): (St-Pierre *et al.*, 2014) *p*-coumaric acid (567.6); ferulic acid (426.9); salicylic acid (75.1); synaptic acid (41.7); hydroxybenzoic acid (38.0); hydroxyphenyl acetic acid (18.8); syringic acid (12.3); syringaldehyde (9.3); vanillic acid (8.6); dihydroxybenzoic acid (5.1); caffeic acid (1.7); kaempferol hexoside (51.4); quercetin hexoside (11.2); kaempferol rutinoside (6.1); and quercetin arabinoside (2.6).
Corn syrup	UPLC-TQD-MS (liquid-liquid extraction; ethyl acetate/methanolic extract)	*Phenolic profile* (µg GAE/100 mL): (St-Pierre *et al.*, 2014) Syringic acid (42.2); vanillic acid (28.9); chlorogenic acid (13.0); *p*-coumaric acid (12.1); dihydroxybenzoic acid (12.1); salicylic acid (7.6); hydroxyphenyl acetic acid (7.2); ferulic acid (2.8); hydroxybenzoic acid (2.7); quercetin arabinoside (59.4); quercetin hexoside (53.3); quercetin rhamnoside (15.6); quercetin (4.9); and rutin (4.6). Other: Phlorizin (11.2).
Date syrup	HPLC (hot water extract - 100°C for 15 min)	*Phenolic profile* (µg/100 g): (Abbès *et al.*, 2013) Coumaric acid (794.26); vanillic acid (300.18); *trans*-cinnamic (190.43); ferulic acid (124.23); sinapic acid (108.94); syringic acid (31.90); catechin (25.09); and caffeic acid (22.63).
Fig syrup	HPLC-DAD-MS (methanol containing 1% butylated hydroxytoluene)	*Phenolic profile* (mg/g): (Puoci *et al.*, 2011) Chlorogenic acid (0.10); gallic acid (0.021); syringic acid (0.008); rutin (1.9); catechin (0.34); and epicatechin (0.007).
Maple syrup	UPLC-TQD-MS (liquid-liquid extraction; ethyl acetate/methanolic extract)	*Phenolic profile* (µg GAE/100 mL): (St-Pierre *et al.*, 2014) Hydroxyphenyl acetic acid (81.0); vanillic acid (49.0); syringaldehyde (10.2); *p*-coumaric acid (9.7); dihydroxybenzoic acid (6.6); syringic acid (1.7); feruloyl hexoside (1.6); quercetin arabinoside (1.3); quercetin hexoside (5.3); quercetin rhamnoside (0.7); quercetin (4.4); and rutin (1.6). Others: Lariciresinol (920.9); scopoletin (284.8); and secoisolariciresinol (116.1).
Maple syrup	HPLC-ESI-MS; ^{1}H/^{13}C NMR (liquid-liquid extraction; ethyl acetate/butanol extract)	*Phenolic profile*: (Li and Seeram, 2010) *Polyphenols*: gallic acid; syringic acid; catechol; fraxetin; lyoniresinol; secoisolariciresinol; scopoletin; syringenin; and vanillin. *Polyphenolic alcohols*: (*E*)-coniferol; dehydroconiferyl alcohol; 5'-methoxydehydroconiferyl alcohol; guaiacylglycerol-β-O-4'-coniferyl alcohol; guaiacylglycerol-β-O-4'-dihydroconiferyl alcohol; and C-veratroylglycol. *Polyphenolic derivatives*: (*E*)-3,3'-dimethoxy-4,4'-dihydroxystilbene; 2-hydroxy-3',4'-dihydroxyacetophenone; 2,4,5-trihydroxyacetophenone; 1-(2,3,4-trihydroxy-5-methylphenyl)ethanone; catechaldehyde; and trimethyl gallic acid methyl ester.

Table 5. DPPH, FRAP, and ABTS values of different sweeteners.

Type of sweetener	DPPH (%)	FRAP (mM Fe(II)/kg)	ABTS (Trolox equivalent, mM/kg)	Citation
		Honey		
Buckwheat honey	N/A	5.74 ± 0.09	2.13 ± 0.11	1
Gelam honey	14.36 ± 0.83$^{\#}$	0.644 ± 0.01	N/A	2
Manuka honey	4.71 ± 0.36$^{\#}$	1.295 ± 0.01	N/A	2
Multifloral honey	N/A	1.70 ± 0.02	0.65 ± 0.06	1
Rape honey	N/A	1.32 ± 0.04	0.38 ± 0.03	1
Stingless bee honey	N/A	N/A	0.2 - 0.3$^{\#}$	3
Tualang honey	5.24 - 8.60$^{\#}$; 41.3 ± 0.78	0.652 - 0.892; 322.1 ± 9.7***	N/A	2, 4
		Molasses		
Beet molasses	N/A	42.19 ± 1.81	5.98 ± 0.28	1
Black mulberry molasses	411 ± 14*	408 ± 16*	970 ± 43*	5
Carob molasses	284 ± 12*	178 ± 1*	440 ± 33*	5
Date molasses	84	N/A	N/A	6
Grape molasses	52 ± 4*	78 ± 6*	166 ± 7*	5
Pomegranate molasses	6.8 - 17; 66.1 - 90.6; 560.23 - 1885.23**	N/A	N/A	6 - 8
Sugarcane molasses	N/A	260.80 ± 6.43	20.85 ± 0.47	1
White mulberry molasses	295 ± 10*	313 ± 20*	584 ± 11*	5
		Sugar		
Brown beet sugar	N/A	0.95 ± 0.04	0.27 ± 0.01	1
Brown cane sugar	14.5 - 88.11	2.94 ± 0.06; 0.003	0.90 ± 0.00; 25.6 - 48.4$^{\#\#}$	1, 9 - 10
Refined cane sugar	89.70 ± 0.69	0.08 ± 0.01; 0.001	0.20 ± 0.00	1, 9

		Syrup		
Agave syrup	10.46 - 40.57; 199 - 7340$^{\#}$	N/A	N/A	11
Barley syrup	N/A	37.87 ± 3.09	6.41 ± 0.26	1
Brown rice syrup	N/A	5.19 ± 0.28	1.20 ± 0.03	1
Cassava syrup	N/A	3.04 ± 0.52	0.43 ± 0.01	1
Corn syrup	8.71 - 9.15; 30820 - 35800$^{\#}$	14.23 ± 1.17	2.01 ± 0.01	1, 11
Date syrup	25; 27.97 - 76.40; 10.22 - 42.62$^{\#}$	26.36 ± 0.24; 23.7 - 42.9	16.07 ± 1.31	1, 12
	N/A	N/A	16.07 ± 1.31	1
Fig syrup	1.06$^{\#}$	N/A	N/A	13
Maple syrup	0.06$^{\#}$; > 1.0$^{\#}$	N/A	N/A	14 - 15
Spelt syrup	N/A	15.28 ± 1.21	4.18 ± 0.09	16
Sugarcane syrup	15.15 - 36.33; 251 - 404$^{\#}$	N/A	N/A	11
Wheat malt syrup	N/A	27.13 ± 0.60	0.16 ± 0.05	1
		Others		
Liquid fructose	N/A	1.06 ± 0.00	0.21 ± 0.02	1
Xylitol	N/A	0.02 ± 0.01	0.14 ± 0.02	1

*Trolox equivalent (mg/100 g dry weight); **Trolox equivalent (μmol/g sample); ***FRAP (μM); $^{\#}$IC$_{50}$/EC$_{50}$(mg/mL); $^{\#\#}$% of inhibition/ scavenging activity; N/A: information not available. Citations: 1: Grabek-Lejko and Tomczyk-Ulanowska (2013); 2: Khalil *et al.* (2011); 3: da Silva *et al.* (2013); 4: Mohamed *et al.* (2010); 5: Kamiloglu and Capanoglu (2014); 6: Nasser *et al.* (2017); 7: Akpinar-Bayizit *et al.* (2016); 8: El Darra *et al.* (2017); 9: Payet *et al.* (2005); 10: Azlan *et al.* (2020); 11: Velázquez Ríos *et al.* (2019); 12: Abbès *et al.* (2013); 13: Puoci *et al.* (2011); 14: Li and Seeram (2010); 15: Liu *et al.* (2017); and 16: Rashed and Soltan (2004).

molasses and various other naturally occurring sweeteners, and produced during the Maillard reaction. They are described as condensation products of sugars and amino acids during the browning reaction (Chandra *et al.*, 2008), and these chemicals produced are high molecular weight polymers generated during the process. The antioxidant properties of melanoidins have been described by Kim (2020). The findings revealed that free melanoidins had reduced antioxidant effects when compared with bound melanoidins. The increased antioxidant properties of bound melanoidins may be due to the linkage between phenolic compounds and melanoidins. Similar to honey, phenolic compounds of the molasses are not directly linked to bioactivity.

The antioxidative and protective activities against oxidative stress in the human body could be due to the ingestion of these sweeteners. Other phytochemicals in sweeteners such as organic acids and terpenoids, are powerful antioxidants. They have something to do with free radical scavenging effects and inhibition of oxidative stress (Graβmann, 2005; Yang *et al.*, 2015). However, an earlier investigation asserted that glucose demonstrated an antioxidative effect *via* the scavenging of hydroxyl radicals (Hajihashemi and Geuns, 2013). The scavenging effect of the monosaccharide was analogous to that of ascorbic acid. Therefore, it could be a result of glucose being a reducing agent (Bollenbach *et al.*, 2016). The hydroxyl radical quenching ability is attributable to the hydrogen atom donating capacity of the hydroxyl groups (Li *et al.*, 2022). Therefore, glucose plays a crucial role in redox homeostasis, and mediates epigenetic modification (Cherkas *et al.*, 2020).

Emerging sources of healthier sweeteners

Plant-based NNSs are a new type of sweetener used worldwide. They are superior sugar alternative because the compounds give a sweet taste to foods and beverages without increasing the calorie content. NNSs are extensively consumed in the USA because they constitute a staple of the western diet (Sylvetsky *et al.*, 2017). The sweet compounds are primarily present in beverages such as soda and sweetened packet drinks. NNSs are also commonly found in other foods such as condiments, yogurts, cereals, snacks, and desserts. The US Food and Drug Administration certified several sugar alternatives like acesulfame-potassium, aspartame, neotame, saccharin, sucralose, stevia, and monkfruit extract as Generally Recognized as Safe (GRAS). These chemicals have been found in various processed foods.

Among the NNSs, allulose, mogrosides, and steviosides are the emerging sugar alternatives for domestic and industrial applications. Allulose, also known as D-psicose, is a low-calorie and non-nutritive monosaccharide. It exists naturally in jackfruit peel (Muangthai and Katinted, 2014), dried fruits, and processed foods (Oshima *et al.*, 2006). Commercially available allulose is manufactured from D-fructose because it is an epimer of D-fructose (Jia *et al.*, 2021). It is synthesised from D-fructose *via* an enzymatic process (Wang *et al.*, 2022). A recent investigation suggested that D-psicose content in processed foods was as high as 130.6 mg/100 g of fresh weight. In addition, allulose has been established as a reducing agent like other monosaccharides. It has previously been used as a sugar substitute for beverages. It should be regarded as an effective antioxidant, even though no evidence shows that it is an antioxidant.

Mogroside is considered a triterpene glycoside, also an antioxidant; however, it is not a member of the phenolic group. Mogroside V has been used extensively as a natural sweetener since a few years ago. Based on the literature, the mogroside-rich extract of monkfruit possessed TPC levels ranging between 33.6 and 34.5 mg/g of dried powder (Liu *et al.*, 2011). The TPC level of the fruit extract is comparable to that reported in various molasses, which may be because the crude extract is being produced without mogroside purification. The compound also has a chemical formula of $C_{60}H_{102}O_{29}$. Mogroside V has a relatively strong antioxidant activity, particularly the scavenging of hydroxyl radicals. The EC_{50} value (hydroxyl radical scavenging) of mogroside V (48.44 µg/mL) was thrice lower than 11-oxo-mogroside V (Chen *et al.*, 2007). Consequently, the 11-oxo-mogroside V had an EC_{50} value for the inhibitory activity on hydroxyl radical-induced DNA damage as low as 3.09 µg/mL.

Stevioside is a glycosidic-based sweet phytochemical isolated from the stevia plant. Rebaudioside A, rubusoside, and sauviosides A and B are steviol glycosides. Steviol is a tetracyclic diterpene with the molecular formula of $C_{20}H_{30}O_3$. Steviol glycosides have also been found in the leaves of *Rubus suavissimus* (Koh *et al.*, 2009). Stevia leaf isolate and stevioside are powerful free radical scavengers (Geuns and Hajihashemi, 2015). The antioxidant activity of stevioside could be attributable to the hydroxyl group at the carbon ring (Casas-Grajales *et al.*, 2019). These compounds are emerging as potential natural replacements for sugar due to their intense sweetness. The antioxidant activity of quercetin is more powerful than steviol glycosides although steviols are antioxidants (Hajihashemi and Geuns, 2013).

In the present review, specific emerging sweeteners are addressed. They include sweet protein isolates and phenolic derivatives (Table 1) which are powerful sources of sugar alternatives. Among these chemicals, sweet amino acids are L-alanine, L-glutamine, L-glycine, L-proline, L-serine, L-threonine, and L-valine (Delompré *et al.*, 2019). They are sugar replacements made from unpopular sweet ingredients. The most widely used sugar replacement is aspartame. It is a dipeptide derivative used extensively since a few decades ago and the most talked about artificial sweetener. Future studies should establish the physicochemical and antioxidative activities of these sweet proteins and peptides, where the data derived will be helpful for health promotion, manufacturing, and commercialisation of these sweeteners. *In vivo* bioactivities of these sweet amino acids, peptides, and proteins should also be established.

Dihydroflavonols, phenolic derivatives, and dihydrochalcones are the alternative sources of sweeteners. Cynarin, a hydroxycinnamic acid derivative, is a sweet polyphenol. It is one of the phenolic components observed in artichoke (Jun *et al.*, 2007). Dihydrochalcones isolated from the fruits are also a few hundred times sweeter than sugar. Some phenolic acids are taste-modifying compounds, whereas caffeoylquinic acid and chlorogenic acid are less potent inhibitors of carbohydrate-digestive enzymes (Nyambe-Silavwe and Williamson, 2018).

Estimated and acceptable daily intakes of the selected sweeteners

Natural sweeteners are non-toxic, and can be found in foods and beverages. They are safe for consumption. However, overconsumption of these substances, particularly sweet plant metabolites, may be detrimental to humans. Several international organisations have proposed safe intake standards for NNSs and other extremely sweet compounds. The acceptable daily intake (ADI) values of the commercially available artificial sweeteners have been defined by the US Food and Drug Administration. The ADI values of acesulfame-potassium, advantame, aspartame, neotame, saccharin, and sucralose are 15, 32.8, 50, 0.3, 15, and 5 mg/kg body weight (BW)/day, respectively (USFDA, 2018).

D-allulose is a sweetener approved as GRAS for application in food systems as a food additive. D-allulose consumption of up to 2,500 mg/kg BW/day from the diet is GRAS (GRAS Associates, 2017). The suggested use content of mogroside V is 1,000 mg/kg extract (EFSA Panel on Food Additives and Flavourings *et al.*, 2019). No ADI value has been described for mogroside V. These substances are emerging sugar alternatives. Consequently, many adults diagnosed with diabetes mellitus are unaware of allulose and mogroside V, which are sweet substances that can be used as sugar alternatives.

Neohesperidin dihydrochalcone is another new sweetener. It has been chemically produced from naringin or neohesperidin although it originates from plants. The ADI of neohesperidin dihydrochalcone is 1 mg greater than the steviol glycosides (4 mg/kg BW/day) which may be because the phenolic compounds are less toxic than terpenoids. However, the negative impact of heightened intake of terpenoids could be the build-up of prenyl side chains in the cells (Sivy *et al.*, 2011).

Conclusion

Phenolic compounds are powerful antioxidants identified in natural sweeteners. Phenolic-rich sweeteners including unrefined sugars, honey, syrups, and molasses contain phenolic acids, flavonoids, and anthocyanins as the principal bioactives. These sweeteners have moderate to high antioxidant activities, which can mainly be attributed to the high-phenolic substances in the sweeteners. Plant-based sweeteners are healthier substitutes for artificial sweeteners in replacing refined sugar because they contain antioxidants. Allulose, mogrosides, and steviosides are the emerging sweeteners discussed in the present review. Plant metabolites with a sweet taste are also sweeteners originating from plants. Therefore, informing the population to select healthier and safer sugar substitutes having higher antioxidants is essential. Future studies should also emphasise the bioavailability and bioactivities of these sweet plant isolates and metabolites.

Acknowledgement

The authors would like to acknowledge the Guangxi Key Laboratory of Electrochemical and Magneto-chemical Functional Materials of Guilin University of Technology (grant no.: Guilin 541006 − EMFM20211104) and the Natural Science Foundation of Guangxi Province (grant no.: 2021GXNSFAA220072) for the financial support received.

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