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REVIEW ARTICLE



A comprehensive review on natural sweeteners: impact on sensory properties, food structure, and new frontiers for their application

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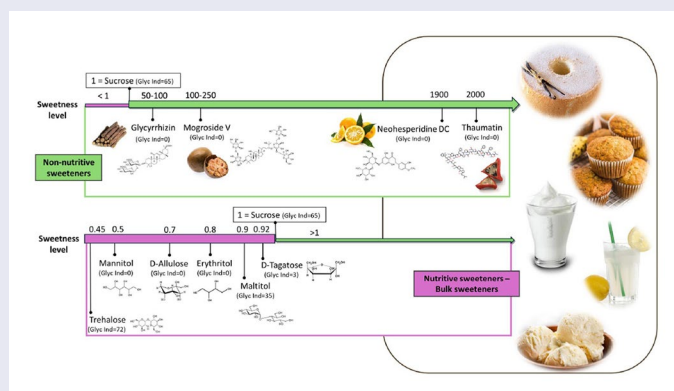
ABSTRACT

In recent years, the worldwide increase in lifestyle diseases and metabolic disorders has been ascribed to the excessive consumption of sucrose and added sugars. For this reason, many approaches have been developed in order to replace sucrose in food and beverage formulations with alternative sweetening compounds. The raising awareness concerning the synthetic sweeteners due to their negative impact on health, triggered the need to search for alternative substances. Natural sweeteners may be classified in: (i) non-nutritive (e.g., neohesperidine dihydrochalcone, thaumatin, glycyrrhizin mogroside and stevia) and (ii) bulk sweeteners, including both polyols (e.g., maltitol, mannitol, erythritol) and rare sugars (e.g., tagatose and allulose). In this review we discuss the most popular natural sweeteners and their application in the main food sectors (e.g., bakery, dairy, confectionary and beverage), providing a full understanding of their impact on the textural and sensory properties in comparison to sucrose. Furthermore, we analyze the use of natural sweeteners in blends, which in addition to enabling an effective replacement of sugar, in order to complement the merits and limits of individual compounds. Finally, microencapsulation technology is presented as an alternative strategy to solving some issues such as aftertaste, bitterness, unpleasant flavors, but also to enhance their stability and ease of use.

KEYWORDS

Non-nutritive and bulk sweeteners; food application; sweeteners blends; microencapsulation

GRAPHICAL ABSTRACT



Introduction

Natural sweeteners are substitutes for refined sugar (containing 99% sucrose), commonly obtained from sugar cane (70%) and sugar beets (30%) (Arshad et al. 2022), as well as for artificial sweeteners. These natural food additives provide or mimic a sweet taste like sucrose but with less caloric energy; therefore, their impact on the diet is significantly reduced (Carocho, Morales, and Ferreira 2017).

In the last decade, the global demand for sugar has declined due to the growing concerns about its potential health effects and its excessive intake. However, FAO data suggest that sucrose consumption will remain high in

developing countries, increasing by 32 Mt (2028), in comparison to the approximate amount of 203 Mt (2008) (Castro-Muñoz et al. 2022). Overall, artificial sweeteners are characterized by low-calorie content and intense sweetness, making them appealing to consumers and food industries (Saraiva et al. 2020a). Notably, these compounds are metabolized differently from the other sweeteners due to their different properties. However, the consumption of artificial sweeteners may be associated to lifestyle diseases (e.g., obesity, type II diabetes, etc.) due to their effect in body weight regulation, glucose homeostasis and gut microbiota (Martyn et al. 2018, Castro-Muñoz et al. 2022). The growing health awareness

among consumers is driving the market for natural sweeteners, which may be used as sucrose and artificial sweetener substitutes. Current market trends foresee that natural foods are more appealing to consumers, who identify them as healthier options. Therefore, the use of natural sweeteners may represent a substantial new business opportunity for many companies (Van Laar, Grootaert, and Van Camp 2021). An increasing number of studies, likewise, report that natural sweeteners have positive influences, such as enhancing metabolic health, preventing weight gain and reducing blood sugar level. Additionally, they have low glycemic potency, which is useful for low glycemic index diets (Arshad et al. 2022). The increasing application of natural sweeteners in the food sector [desserts, confectionery, bakeries (Sahin et al. 2019), beverages (Chen et al. 2022), dairy products (McCain, Kaliappan, and Drake 2018), etc.] is fueling the growth of the natural sweeteners global market, which is estimated to expand at a CAGR of 8.2% from 2021 to 2031 (Transparency Market Research 2021). In this context, the emerging consumer trend is addressed toward a “clean label,” namely an ingredient list easy to understand for food products free of chemical additives or preservatives, which have undergone natural or limited processing (Schiatti-Sisó, Quintana, and García-Zapateiro 2023).

In spite of their high market value as natural ingredients, challenges associated with the lengthy and expensive extraction and purification processes have slowed down their application in the food industry until now. Regarding the recovery of natural sweeteners, in addition to the conventional extraction by aqueous or alcoholic solvents, the extraction assisted by a source of auxiliary energy (e.g., ultrasounds, microwaves, liquid pressurization) has been extensively applied (Sun et al. 2024), as well as the membrane-based technologies (e.g., microfiltration, ultrafiltration, nanofiltration, diafiltration, and their combinations,

Díaz-Montes, García-Depraect, and Castro-Muñoz 2021). Recently, advanced techniques such as supercritical CO₂, subcritical or superheated water extraction have been developed for the recovery of glycyrrhizin from the licorice root (Sun et al. 2024).

For the purposes of this review, natural sweeteners that provide energy will be indicated as “nutritive sweeteners” (NS), whereas those that supply unimportant level of energy will be designated as “non-nutritive sweeteners” (NNS). NS will be further categorized into sugars (e.g., sweet-tasting mono- and disaccharides) and bulk sweeteners (e.g., polyols) (Table 1).

In this context, it is worth pointing out that scientific research follows the market interest in natural sweeteners. The year of publication, the type of paper, the most cited fields of study along with the geographical areas of greatest interest, have been examined in the bibliometric analysis. The Scopus database (www.scopus.com) has been retrieved in November/December 2023 using the search terms “natural sweetener.” The above research method cites 1964 articles. After 2006, the number of articles increased almost steadily every year, starting with 16 published papers, and exceeding 200 in 2022 (Figure 1). The distribution of works by article type from 1970 to 2023 is shown in Figure 1. It clearly emerges that research papers (73%), reviews (13%), and book chapters (7%) are the most used for publishing this topic. In addition, the analysis of papers by country revealed that the top 15 countries accounted for 82% ($n=1615$) of all articles (Figure 1). The United States comes in first with 16.6% of all the produced papers, followed by China (12.2%), India (11.4%), Brazil (5.2%), Spain (4.3%) and Germany, Italy, South Korea, and Japan (about 3.5% each one). As regards the areas of greatest interest, the first five are: Agricultural and Biological Sciences (50.5%), Biochemistry, Genetics and Molecular Biology (26.3%),

Table 1. Characteristics of the sweeteners described in this review.

Sweetener	Chemical classification	Chemical formula	E index	Relative sweetness ¹	Caloric value (kcal/g)	Glycemic index	Aftertaste	Reference
Nutritive sweeteners								
Sucrose	Disaccharides	C ₁₂ H ₂₂ O ₁₁	–	1	4	65	none	Grembecka 2015
Non-nutritive sweeteners								
Neohesperidine DC	Flavonoid glycoside	C ₂₈ H ₃₆ O ₁₅	E959	1900	0	0	lingering menthol/licorice-like	Wal, Pal, and Wal 2019
Thaumatococin	Sweet-tasting protein	207 amino acids	E957	2000	4	0	artificial licorice-like	Wal, Pal, and Wal 2019
Glycyrrhizin	Triterpenoid saponin	C ₃₀ H ₄₆ O ₄	E958	50–100	low	0	lingering licorice-like	Wal, Pal, and Wal 2019
Mogroside V	Triterpenoid saponin	C ₆₀ H ₁₀₂ O ₂₉	–	100–250	0	0	slightly licorice-like	Harshita 2023
Rebaudioside A	Steviol glycosides	C ₄₄ H ₇₀ O ₂₃	E960	250–300	0	0	licorice-like	Wang et al. 2023
Bulk sweeteners								
D-Tagatose	Monosaccharide	C ₆ H ₁₂ O ₆	E963	0.92	1.5	3	sweet	Edwards et al. 2016
D-Allulose	Monosaccharide	C ₆ H ₁₂ O ₆	–	0.70	0.4	0	sweet	Yuma et al. 2023
Trehalose	Disaccharide	C ₁₂ H ₂₂ O ₁₁	–	0.45	4.0	72	not perceived	Mizote et al. 2016
Maltitol	Sugar alcohol	C ₁₂ H ₂₄ O ₁₁	E965	0.90	2.4	35	not perceived	Grembecka 2015
Erythritol	Sugar alcohol	C ₄ H ₁₀ O ₄	E968	0.6–0.8	0.2	0	not perceived	Grembecka 2015
Mannitol	Sugar alcohol	C ₆ H ₁₄ O ₆	E421	0.5–0.7	1.5	0	astringent mouthfeel	Grembecka 2015

¹Sweetness is expressed as relative to sucrose, whose sweetness index is set at 1.

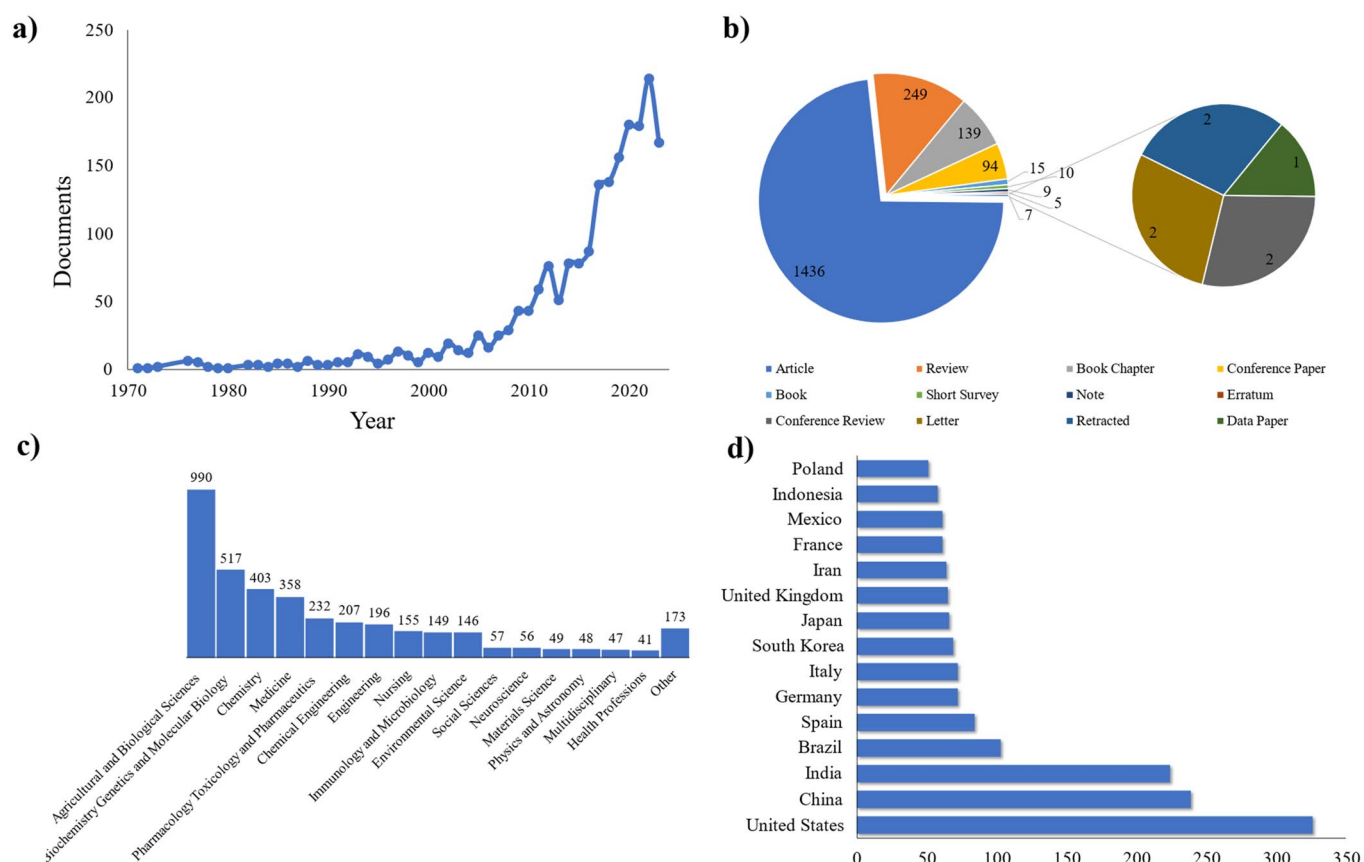


Figure 1. Bibliographic overview, related to natural sweeteners based on the scopus database, on: (a) annual scientific production of papers, (b) article types, (c) main research topics, and (d) number of publications per country.

Chemistry (20.5%), Medicine (18.2%), Pharmacology, Toxicology and Pharmaceutics (11.8%) (Figure 1).

In this review, the state of the art about natural sweeteners has been examined providing a very detailed overview of the most currently used and their applications in the food industry. Starting from the characteristics of each sweetener, the reader will move on to applications in the major food sectors, taking into account its use alone or combined in a blend.

Non-nutritive sweeteners

Sweeteners that provide either no energy or a negligible amount when used as sugar substitute are described as Non-Nutritive Sweeteners (NNS, Table 1). In light of today's major public health challenges, it is understandable that NNS, which supply a high amount of sweetness with fewer calories, are of great interest to consumers (Edwards et al. 2016). Thaumatin, glycyrrhizin, Monk fruit extract, stevia and neohesperidine dihydrochalcone (DC) are currently the subject of many studies and applications.

Thaumatococcus

Thaumatococcus (E957) is a natural plant protein material, extracted from the *Thaumatococcus daniellii* Bennett plant, and contains two principal proteins (thaumatocin I and thaumatocin II, with molecular mass of 22,209 and 22,293 Da,

respectively). Thaumatocin II is composed of a single-chain of 207 amino acid residues (Table 1), and provides a sweet taste also at a very low concentration (about 50 nM) (Carocho, Morales, and Ferreira 2017). Thaumatocin global market is expected to grow at a CAGR of 6.1% over the period of 2023–2030 (Business Research Insights 2023). According to Commission Regulation No 231/2012, thaumatocin is obtained by acidic aqueous extraction of the arils followed by ultrafiltration. However, considering the high cost of its recovery from natural source, different authors suggested the bioproduction through genetically engineered microorganisms and transgenic plants (Joseph et al. 2019). Considering its high sweetness intensity and flavor enhancement, several data were found in the literature on the use of thaumatocin in food applications. De Souza et al. (2013) determined the equivalent amount of different sweeteners, necessary to achieve the same ideal degree of sweetness in mixed fruit jam (marolo, sweet passion fruit and soursop) and to characterize the time–intensity profile and consumer acceptance. Regarding sensory acceptability, no significant difference was observed between low-sugar jam containing sucralose/thaumatocin (1:0.6) and the traditional one (containing sucrose). The technological and sensory quality of biscuits have been preserved by the addition of formulations containing less sucrose in combination with thaumatocin (Silva et al. 2022). The 25% and 35% sucrose reduction tests resulted in minimal changes of the rheological characteristics and provided better biscuit dough's physical quality in terms

of firmness, consistency, and hardness. These attributes positively affected the sensory quality of the resulting baked biscuits, increasing crunchiness and mouthfeel.

The addition of thaumatin (0.11%) in skyr yogurt, with mango pulp, was studied by Pereira et al. (2021), who observed that thaumatin did not affect the consistency and syneresis of natural skyr yogurt compared to the sucrose yogurt sample. Furthermore, formulations containing thaumatin as a sweetening agent were characterized by an increased cohesion in comparison to skyr natural yogurt. Concerning the sensory impact, the combination of a sweet protein (thaumatin) with an acidic matrix (yogurt) contributed to a longer time of sweetness perception. Furthermore, thaumatin added in guava jam (0.0125 to 0.025%, relative to the amount of pulp added), affected the texture profile of the final product, mainly increasing the cohesiveness, suggesting the occurrence of chemical interactions between the sweetener and the gel network (Pereira et al. 2017). De Souza et al. (2011) verified both the equivalent sweetness and the magnitude of sweetness of cheese produced by adding different sweeteners or combinations of them. A lower concentration of sucrose (-17%) in strawberry petit Suisse cheese was required by using a blend of thaumatin/sucralose (ratio 2:1) at 0.018%, reaching the same sweetness sensation as evaluated sucrose. Thaumatin may be likewise applied as flavor enhancer under acidic conditions in salted, pickled (stored for 6 months), and in processed tomatoes (Firsov et al. 2021). Its sweet properties were not affected during salting, acidification (pH = 3.1) and storage. However, salted and pickled tomato samples were characterized by a common aftertaste.

Finally, concerning the use of thaumatin in beverages, it is still limited due to its interaction with synthetic colorants which can lead to the loss of sweetness (Chen et al. 2022). Previous papers suggested the interaction between thaumatin positive ionic charge with negatively charged synthetic colorants. This may cause the precipitation of resulting complexes or, even if precipitation doesn't occur, there may be a loss of color (Dahal and Xu 2014).

Glycyrrhizin

Glycyrrhizin (E958) is a triterpene saponin from licorice with a characteristic sweet taste, about 50 times higher than that of sucrose (Table 1). It is recognized for several pharmacological and biological activities, such as anti-tumor, anti-inflammatory, hepatoprotective, antioxidant and antiviral (Carocho, Morales, and Ferreira 2017). Glycyrrhizin global market is growing with a CAGR of 6.8% over the period of 2023–2030 (Allied Market Research 2023). The conventional methods for glycyrrhizin separation from the licorice root include the use of hot water at ambient pressure and alkaline pH (ammonia solution), as well as aqueous methanol and ethanol. Other new approaches, such as ultrasound, supercritical CO₂, subcritical or superheated water extraction, have also been proposed (Shabkhiz et al. 2016; Sun et al. 2024).

Comprehensive research was conducted by El-Lahot et al. (2017) in order to use glycyrrhizin as a substitute for sucrose

to sweeten toffee and cake preparation (Figure 2a). The sensory attributes of the products (toffee and cakes) along with glycyrrhizin *in vivo* biological effects (e.g., hematological and biochemical parameters, body and relative organ weight, enzyme activities) were investigated. Toffee prepared by replacing glucose sirup with glycyrrhizin at 50% achieved the highest sensory and overall acceptability scores. In the case of cakes sweetened with the same percentage, glycyrrhizin had little influence on the organoleptic attributes, even if it noticeably diminished the caloric value (El-Lahot et al. 2017). Regarding the *in vivo* study, carried out on young male rats, a significant reduction in triglycerides, with a decrease alanine transaminase, aspartate transaminase, and acid phosphatase values were observed in the glycyrrhizin-treated group compared to the control.

Recently it has been proved that glycyrrhizin may be converted in glycyrrhetic acid 3-O-mono- β -D-glucuronide (GAMG), which is about 5 to 1000 times sweeter than glycyrrhizin and sucrose, respectively, and tastes better (less aftertaste) than its precursor (Gao et al. 2021). The enzymatic bioconversion of glycyrrhizin by β -glucuronidases (β -GUS) represents a viable alternative for GAMG production under mild reaction conditions, and high production efficiency (Guo et al. 2018). Different immobilization procedures, aimed at confining enzymes within or on the surface of insoluble solid supports (usually microsphere of inert material) by physical or covalent binding, have been applied for improving the biocatalytic efficiency and reusability. Purified β -GUS from *Aspergillus terreus* was immobilized *via* entrapment in alginate gel (Amin et al. 2011). More recently, purified recombinant β -GUS from *Aspergillus oryzae* Li-3 was immobilized *via* adsorption on zinc oxide nanoparticles (Kaleem et al. 2017). The immobilization of β -GUS from *Patella vulgata* was also carried out following different strategies such as: entrapment in biomimetic silica nanoparticles, covalent binding and ionic adsorption on magnetic nanoparticles (Correa et al. 2020). Authors demonstrated that the nature of carrier material (specifically a mixed matrix composed by biomimetic silica and magnetic nanoparticles) used for enzyme immobilization could remarkably affect the activity and stability of β -GUS from *Patella vulgata*.

Monk fruit

Monk fruit extract is a non-nutritive sweetener, generally recognized as safe (GRAS) in the USA since 2010; indeed, it is rich of mogrosides, especially mogroside V, characterized by non-nutritive and sweet properties (Harshita 2023). This compound is 100–250 times sweeter than sucrose (Table 1) and it is also characterized by other attractive health properties (e.g., antitussive, anti-asthmatic, liver-protective, glucose-lowering, immunoregulating activity, Ban, Cheng, et al. 2020). Monk fruit sweetener has gained popularity in recent years given that, unlike some other NNS, it does not have a bitter aftertaste (Harshita 2023). Concerning the market trend, it is anticipated to garner a 4.8% CAGR from 2023 to 2031 (Transparency Market Research 2023). Only few studies are available about the recovery of mogrosides from the fruit; the monk fruit extract is usually produced through a process

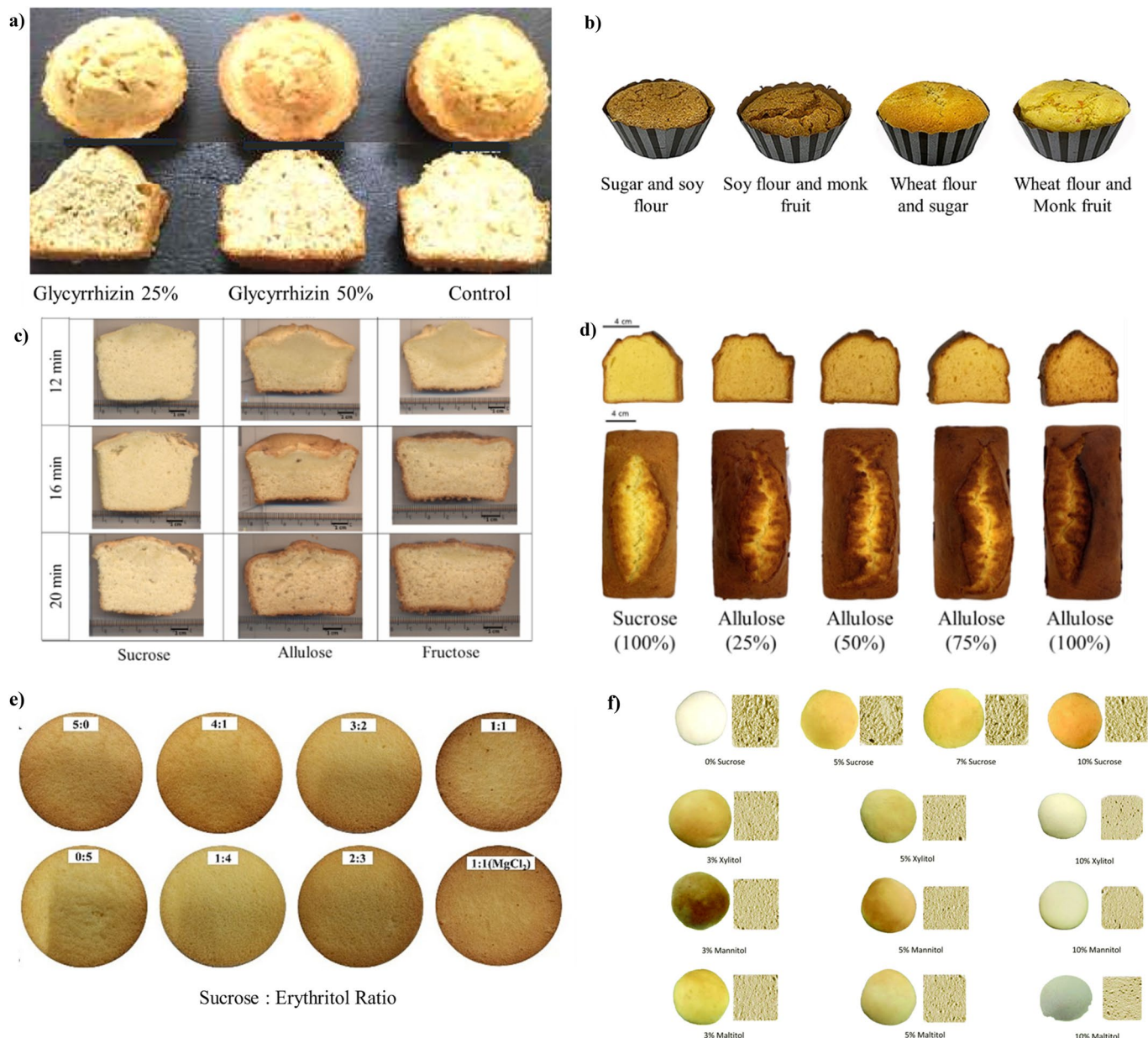


Figure 2. Effect of natural sweeteners on visual appearance of different food matrices: (a) cakes prepared with glycyrrhizin (adapted from El-Lahot et al. 2017), (b) cupcakes with monk fruit extract (modified from Bahraminejad et al. 2023), (c) cupcakes containing D-allulose and D-fructose (amended from Bolger et al. 2021), (d) pound cakes with tagatose (overhauled from Lee et al. 2020), (e) angel cakes containing erythritol (customized from Yan et al. 2023), (f) burger buns with xylitol, mannitol and maltitol (Sahin et al. 2018).

involving water extraction, filtration and selective concentration of the sweetening compounds (EFSA, 2019).

In the interesting study conducted by Bahraminejad et al. (2023), sucrose- and gluten-free cupcakes were prepared using monk fruit sweetener and soy flour as substitutes for sucrose and wheat flour, respectively (Figure 2b). The use of this NNS diminished the viscosity of the batter, which is desirable in soy cupcake due to its high compactness and viscosity. Moreover, the addition of two natural gums, based on *Cydonia oblonga* (*Cydonia Vulgaris*) and *Plantago ovata* (*Plantago genus*), had positive effects on the specific volume, porosity index, and weight loss of samples.

Bickelhaupt (2022) optimized the production process of cranberry-infused breakfast cereals. After determining the best formulation using rice flour (45%), cranberry pomace

(15%) and soy flour (40%), the author proceeded to detect the best zero calorie sweetener formulation (0–5% monk fruit extract) to improve its sensory profile. No relevant differences were perceived comparing samples, as further proved by the sensory evaluation, although assessors expressed preference for the cranberry-infused breakfast cereals containing 5% monk fruit extract.

Monk fruit and stevia have been also tested in green tea agar jellies (Akesowan and Choonhahirun 2021) at various sugar substitute concentrations (25%, 50%, 75%, and 100% based on the sweetness of the sucrose equivalent). Total soluble solids, hardness, color and syneresis of the sample were assessed, and the like test was conducted to evaluate sensory characteristics such as color, taste, flavor, texture, and overall liking. The highest substitution level diminished the total

soluble solids but raised the firmness and lightness of the samples. Low-sugar jellies (containing monk fruit and stevia) exhibited a lower syneresis than those with sucrose, probably due to the small pores in the gel structure. The substitution level remarkably affected the taste and aroma of the agar jellies: samples with 100% sugar replacement exhibited an undesirable bitter or metallic aftertaste, whereas the jellies with 50% and 75% sugar substitute were preferred by panelists for their balanced sweetness.

The research proved that monk fruit extract is a suitable sweetener for yogurt production. The use of monk fruit sweetener (0, 0.42, 1.27 and 2.54 g/L) resulted in changed physicochemical and microbiological properties of camel milk yogurt (Buchilina and Aryana 2021). The physicochemical properties (pH, titratable acidity and viscosity) along with the microbiological counts were investigated during storage for 42 days. The addition of the sweetener at 1.27 and 2.54 g/L significantly lowered the pH and increased the viscosity. The growth of probiotic cultures (*S. thermophilus*, *L. bulgaricus* and *L. acidophilus*), meanwhile, was not influenced by the addition of monk fruit sweetener. Ban, Liu, et al. (2020) demonstrated that monk fruit extract may be used in the formulation of low glycemic index yogurt suitable for diabetic consumers. The addition of 0.1% or less of the sweetener was sufficient to substitute sucrose, improving the nutraceutical property, and maintaining similar microstructural characteristics in comparison to the sucrose containing sample.

Recently, He et al. (2022) studied the effect of several sweeteners (e.g., white sugar, mogrosides, and stevia glycoside) on the quality, fatty acid and volatile flavor compounds of braised pork. The results demonstrated that the addition of mogroside prevented protein and lipid oxidation and also reduced cooking loss during stewing.

Stevia

Steviol glycosides (E960), from the leaves of *Stevia rebaudiana* Bertoni, are mixtures of different compounds (e.g., stevioside 5–10%, rebaudioside A 2–5%, rebaudioside C 1%, rebaudioside D, E and F 0.2%, dulcoside A 0.5%) and among them, the sweetest compound is rebaudioside A (Carocho, Morales, and Ferreira 2017). The combination of these molecules has a sweetening power 300 times greater than sucrose (Table 1). Furthermore, the caloric contribution of steviol glycosides is negligible, and therefore safe for diabetic patients. In addition, anti-inflammatory, cardiogenic and anti-cancer properties make them widespread and promising NNS (Castro-Muñoz et al. 2022). Stevia market size is estimated at USD 0.84 billion in 2024, and is expected to reach USD 1.36 billion by 2029, growing at a CAGR of 10.12% during the forecast period (2024–2029) (Mordor Intelligence 2024). Due to its attractive properties, stevia has been deeply investigated in order to: (i) maximize the extraction yield from leaves by different techniques (e.g., microfiltration, ultrafiltration, nanofiltration, diafiltration, and their combinations, Díaz-Montes et al. 2020, Castro-Muñoz et al. 2021); (ii) study its effect as a sucrose substitute in food. Its

applications include a wide variety of products: ice cream, yogurt, cakes, sauces, beverages, bread, pastries, flavored milk, spices and as a table-top sweetener.

In different bakery products, stevia has been successfully applied, improving the sensorial and nutritional properties (Schiatti-Sisó, Quintana, and García-Zapateiro 2023). Rana et al. (2020) proved that the replacement of sucrose by stevia up to 50% in biscuits did not affect physicochemical (e.g., diameter, thickness, spread ratio, mass, volume, density and compression force) and sensory (e.g., color, flavor, texture and overall acceptability) properties. Oatmeal cookies, prepared by replacing 25 and 50% of sucrose with stevia extract (Figure 3d) were characterized by a good aroma, an ideal consistency, sweetness and crunchiness. However, at higher levels (75 and 100%), stevia addition negatively affected the sensory properties such as appearance, taste, odor and texture (Góngora Salazar et al. 2018).

Reyes and Ludeña (2015) formulated a low-calorie yogurt using sucralose and stevia, proving that the physicochemical properties and the growth of probiotic microorganisms were not remarkably altered. Steviol glycosides have been also used as sweetening agent, alone or blended with low sucrose amounts, in low-calorie chocolate ice cream with functional properties (Peres et al. 2018). Samples containing rebaudioside 97% were similar to the control in terms of appearance, aroma, flavor, texture, and overall acceptability (Peres et al. 2018). In lactose-free chocolate ice cream, otherwise, stevia addition resulted in a decreased consumer acceptance, due to the increased bitter taste perception (de Medeiros, Filho, and Bolini 2019).

Jelly or jam prepared with steviol glycoside might be an optional food product for health-conscious consumers or patients with non-communicable diseases, such as diabetes mellitus. The research investigated the sensory impact of added stevia in jam and jelly (e.g., pumpkin, strawberry, blackberries jams and coconut jelly), suggesting that the partial substitution of sucrose does not impair the texture and the overall consumers' acceptability (Schiatti-Sisó, Quintana, and García-Zapateiro 2023).

In recent years, many beverages have been formulated with steviol glycosides, including more than 300 types of teas placed on the market from 2010 to 2017. In low-calorie iced tea, stevia is used as frequently as sucralose and several carbonated beverage manufacturers (including Coca-Cola) have introduced steviol glycosides-containing soft drinks in their product portfolio (Chen et al. 2022).

Semi-synthetic sweetener

A separate section is devoted to a semi-synthetic glycoside chalcone, neohesperidin dihydrochalcone (DC), produced by the catalytic hydrogenation under alkaline conditions of neohesperidine from bitter orange (*Citrus aurantium*) or of naringin obtained from grapefruit (*Citrus paradisi*, Kwon et al. 2022).

Neohesperidine DC

Neohesperidine DC (E-959), a semi-natural molecule from bitter orange, is an intense flavonoid glycoside sweetener

(Table 1) and its market will grow at a CAGR of 4.6% in the period of 2023–2030 (Growth Market Reports 2022). Its beneficial properties (e.g., suppression of the level of triacylglycerol accumulation, lipogenesis, adipogenesis, proinflammatory cytokines, and inhibition of subcutaneous fat and lipid accumulation) have been recently proved (Kwon et al. 2022). Several conventional and non-conventional extraction methods have been applied for the recovery of neohesperidine, including hydrodistillation, solvent and Soxhlet extraction, microwave-, supercritical fluid- and ultrasound-assisted extraction (Maksoud et al. 2021).

In the prospective of applying high intensity sweeteners (such as neohesperidine DC) in the food industry, it is important to determine whether the products have an adequate shelf-life and if there is no effective loss of sweetness under intended use and storage conditions. Montijano, Tomás-Barberán, and Borrego (1995) pointed out that neohesperidine DC may be added to dairy products such as yogurt still remaining stable during pasteurization and the lactic fermentation process. In detail, no remarkable impairment was detected during and after milk pasteurization, fermentation and 6 wk storage at refrigerated conditions (3°C). Additionally, the maximum authorized concentration of neohesperidine DC (50 mg/kg) did not affect the acidification rate by lactic acid bacteria during the fermentation. Tomás-Barberán et al. (1995) demonstrated the thermal (102–106°C during 35–40 min) and storage (18 months at room temperature) stability of this semi-natural compound (0.001 w/w) providing useful information for its potential use in blackcurrant jam preparations. Further research confirmed the thermal stability of neohesperidine DC (10 mg/L) during the pasteurization of citrus juice-based soft drinks (orange, lemon, apple and pineapple, Montijano, Coll, and Borrego 1996). Only at the lowest pH tested (2.0 in a lemon beverage) a significant loss of this compound (-8%) was detected. The stability of neohesperidine DC (0.1% w/w) added in a carbonated lemonade was additionally proved during the storage of 1 year at room temperature in the light and in the dark, or after a 3-month period at 40°C.

Bulk sweeteners

Energy-providing sweeteners may be referred to as nutritive sweeteners (NS), which are further sub-categorized into sugars (i.e., sweet-tasting mono- and disaccharides) and bulk sweeteners which include some rare sugars and sugar alcohols (Edwards et al. 2016). Polyols, or sugar alcohols, are saccharide derivatives occurring in fruit, vegetables and some fermented foods, and may be chemically synthesized by hydrogenation of mono- or di-saccharides (Edwards et al. 2016). Compared to sugars, these compounds are poorly absorbed and therefore provide fewer calories and lower glycemic responses (Gwak et al. 2012), increasing their popularity for use in low-calorie food and beverages (Edwards et al. 2016). Despite the many positive effects of sugar alcohols, their consumption is frequently associated with irritable bowel syndrome and abnormal flatulence (Mäkinen

2016). Among bulk sweeteners the most popular ones are discussed below.

D-Tagatose

As reported by Roy et al. (2018), D-tagatose (E963) is classified in the group of rare sugars due to its limited occurrence in nature. Among emerging natural sweeteners, this compound occupies a relevant niche due to its low caloric value (Table 1), antidiabetic properties and growth-promoting effects on beneficial intestinal bacteria (Roy et al. 2018). With a goal for novel food ingredients, tagatose market is expected to grow at a CAGR of nearly 5.2% during the forecast period of 2023–2033 (Persistence Market Research 2023). Due to its scarcity in nature, the production of D-tagatose has been suggested either by chemical or biological processes (Roy et al. 2018).

Rojo-Poveda et al. (2020) investigated the production of cocoa bean shell-based biscuits in which sucrose was totally replaced with tagatose (100 g/500 g_{dough}) and compared to a biscuit recipe containing sucrose as control (Figure 3a). Tagatose affected some physical parameters of the baked biscuits such as diameter, thickness and hardness, probably due to its lower solubility in comparison to sucrose. More specifically, despite no significant differences were found among samples regarding weight loss, biscuit diameter showed slight differences (6.51 and 6.12 cm, respectively) as well as thickness (0.86 vs 0.92 cm, respectively). Solubility appeared to be a key factor, also affecting hardness given that sucrose biscuits were significantly crispier than those containing tagatose. It has been hypothesized that the greater solubility of sucrose than tagatose produced a weaker gluten network, less sugar crystallization after the cooling following cooking, and, therefore, crispier biscuits. Furthermore, considering consumer acceptance in terms of appearance, aroma, flavor and texture, sucrose biscuits were more preferred than those containing tagatose, although the authors reported that tagatose did not differ much from sucrose in terms of taste. These preliminary results suggest the need to improve tagatose-based recipes, also blending with other sweetener compounds, for the formulation of foods recommended for diabetic consumers. Taylor, Fasina, and Bell (2008) investigated the suitability of tagatose (at various levels, 25–100%) as a substitute for sucrose in cookies (Figure 3b). The rheological properties of the dough prepared with tagatose were quite similar to the control (recipe containing only sucrose), suggesting it has no effect on the processability of cookie dough containing tagatose. Following cooking, cookies made by blending sucrose and tagatose were characterized by a hardness similar to the control and a lower spread and darker color, which are not necessarily negative aspects. It is interesting to point out that cookies with tagatose required a shorter cooking time, which would equate to cost savings resulting from a lower energy consumption. Overall, the sensory characterization suggested that novel cookies may be prepared using a blend of sucrose and tagatose rather than only tagatose (Taylor, Fasina, and Bell 2008).

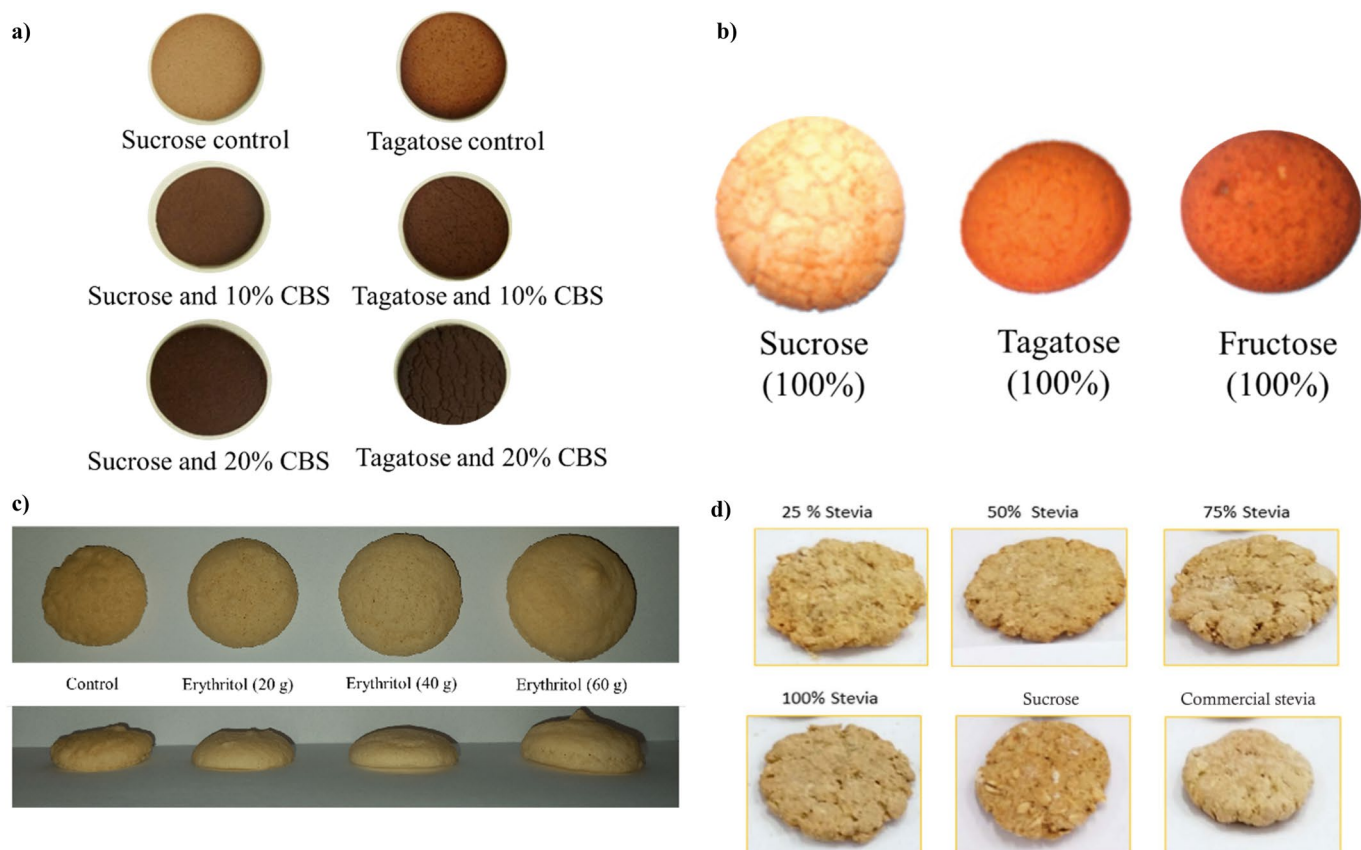


Figure 3. Effect of natural sweeteners on visual appearance of different food matrices: (a) biscuits containing tagatose (revised from Rojo-Poveda et al. 2020), (b) cookies with tagatose (revised from Taylor, Fasina, and Bell 2008), (c) macarons produced adding whey protein isolate and erythritol (adapted from Nastaj et al. 2023), (d) oatmeal cookies elaborated by aqueous extract of *S. rebaudiana* (Góngora Salazar et al. 2018).

Another interesting study was proposed by Moss et al. (2022) for the formulation of vanilla-flavored muffins with tagatose or sucrose as a control. The results of this application, in which a one-to-one substitution of sucrose with tagatose was made, showed that the physical characteristics of the finished muffins were not significantly different within the treatment group regarding the parameters of volume, firmness, cohesion, adhesion and springiness. Muffins with tagatose differed from those containing sucrose in terms of water activity and crust color. In addition, a consumer panel assessed the acceptability of sucrose-replaced formulations, demonstrating a comparable intention of purchase for foods containing substitutes and those that are sucrose-based. Many other examples are available in the literature concerning the use of tagatose for the total or partial replacement of sucrose in bakery products. In the research carried out by Armstrong, Luecke, and Bell (2009) cinnamon muffins, lemon cookies, and chocolate cakes were prepared with 1 or 2% of tagatose, while an equal amount of sucrose was added to the control products. Applying triangle tests, untrained consumer panels were unable to distinguish between the flavor of products with and without tagatose. Hwang, Kim, and Lee (2015) evaluated the effect of different tagatose amounts [T0 (no tagatose added), T25 (tagatose: sugar = 25:75 (w/w) and T50 (tagatose: sugar = 50:50 w/w)] on the muffin characteristics. It is noteworthy mentioning that as the tagatose content increased, the Maillard reaction occurred more and therefore the color of the muffin crust became darker. The

moisture content is an important parameter for the storage of bakery products. Although the moisture content of T25 and T50 was significantly higher in comparison to T0, no differences were detected between samples after 3 days of storage. The increase of tagatose content improved other relevant rheological parameters such as hardness, chewiness, and how much it crumbles. No remarkable effect, meanwhile, was revealed in terms of elasticity, cohesion and overall quality when tagatose was partially added to the muffins up to 50% as a sugar substitute.

The replacement of sucrose with this rare sugar has also been successfully applied in dairy production. In Torrico et al. (2019), six yogurt samples containing a decreasing amount of sucrose (from 8.50 to 1.70 g/100 g) and an increasing level of tagatose (from 0.00 to 9.24 g/100 g) were tested, as well as the quality and shelf-life of products. Sucrose lowering by the addition of up to 80% tagatose had a limited effect on the main physico-chemical properties ($^{\circ}\text{Brix}$, pH, total acidity, water holding capacity, viscosity, and color) and triggered the intention of purchase of the strawberry yogurts. Also, it is important to highlight that the addition of tagatose (100%) remarkably preserved the color attributes (higher L^* and b^* values) of strawberry-flavored yogurt stored for 28 days at refrigerated conditions (4°C) compared to those containing sucrose (100%). This may be ascribed to the low solubility of tagatose.

Recently, this rare sugar has also been used as a natural sweetener to replace sucrose in chocolate production (Son

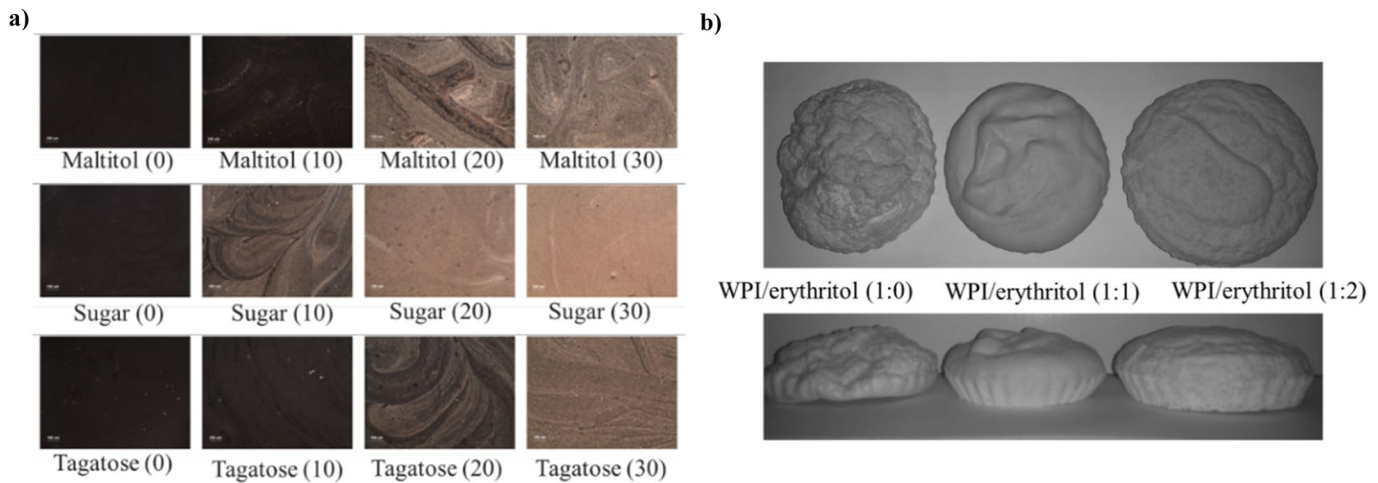


Figure 4. Effect of natural sweeteners on visual appearance of different food matrices: (a) chocolate prepared using maltitol and tagatose (modified from Son et al. 2018), (b) meringues obtained from whey protein isolate and erythritol (modified from Nastaj et al. 2020).

et al. 2018). From an industrial point of view, it is worth noticing that chocolate products added with tagatose (47 g/100 g) have shown greater storage stability thanks to its anti-blooming effects (Figure 4a). It is equally appealing to emphasize that such products may have improved health properties, such as non-carcinogenic effects and better regulation of type 2 diabetes symptoms).

Tagast et al. (2018) examined two low-calorie sweeteners, tagatose (0.3 g/100 g) and stevia (3.2 g/100 g), in dark chocolate in comparison with sucrose (46.9 g/100 g). The tagatose chocolate was judged as more similar to the control than stevia regarding the overall acceptability, texture, bitterness, duration and intensity of aftertaste.

D-Allulose

D-allulose is a rare low-calorie monosaccharide (ketohexose) that may be used as a sweetener in food thanks to its good sweetening power (approximately 70% of sucrose), and its caloric content of only 0.4 kcal/g (Table 1). Furthermore, a large number of studies have shown that allulose may regulate a variety of physiological functions, such as suppression of blood glucose increase, improvement in serum lipid metabolism, reduction in body fat accumulation, and increased scavenging activity of reactive oxygen molecules, Zhang et al. 2023). Although allulose is not yet allowed in the EU, in the USA it is a GRAS compound and is even exempt from “sugars” or “added sugars” labeling (Bolger et al. 2021). Its global market is expected to grow at a CAGR of 11.7% over the period of 2022–2032 (Allied Market Research 2022). This rare sugar is commonly synthesized through chemical or enzymatic techniques from the raw materials including whey, starches and hemicellulose wastes (Mahmood et al. 2023).

Allulose is mainly used in baked goods because of its Millard reaction activity; when sucrose was replaced with this rare sugar in pound cakes, the crust browning index increased as the amount of added allulose increased (Figure 2d). Regarding the sensory evaluation, the cakes containing this ketohexose (25%) were characterized by higher overall acceptability, similar to the control sample (Lee et al. 2020).

Bolger et al. (2021) investigated the allulose properties as the main sugar component in cupcakes (Figure 2c), in terms of its effect on the thermal setting mechanism of batter and physical parameters, in comparison to those of control samples. D-allulose showed a greater water-holding ability than that of sucrose, minimizing the water evaporation during early cupcake baking. However, due to its intrinsic properties (e.g., its water-holding ability, its not retarding starch gelatinization, its increased protein denaturation time) the use of D-allulose in a cupcake recipe resulted in dense and compact samples, characterized by a greater firmness and lower cohesiveness and springiness than sucrose cupcakes.

O'Charoen et al. (2014) proved that baked meringue containing-ketohexose (0%, 10%, 20%, 30%, 40%, and 50% w/w) had smaller sized air bubbles compared to the control sample (100% sucrose). The different microstructures of baked meringues resulted in a different texture and samples having smaller air bubbles which had more crunchiness. Interestingly, allulose also enhanced the antioxidant activity and, thus, it may be helpful for modifying functional properties of baked meringue (O'Charoen et al. 2014).

In addition, the research demonstrated that D-allulose may improve food gelling behavior. Ilhan et al. (2020) added this rare sugar (0–30%) to starch-based confectionery gels and the new formulations were characterized by a lower retrogradation and slightly improved shelf-life. Ogawa et al. (2017) studied the effect of D-allulose instead of sucrose, as a sweetener, and gel modifier on the gelation of heat-induced surimi. The gel strength and water holding capacity of this compound were significantly higher than those of sucrose and sorbitol. This may be because the interaction of myofibrillar proteins with D-allulose can promote the formation of disulfide and non-disulfide crosslinks.

Gelatin-based soft candies, formulated with various amount of allulose (10, 20, 30, and 40% w/w) in combination with sucrose, were characterized by a higher moisture content, leading to a softer structure, which was preserved over 28-days storage (Pocan, Ilhan, and Oztop 2019).

Over the past few years, health-beneficial plant-based yogurt or drinks with low fat, low calorie, and low sugar

content have been growing in popularity. This market trend represents a good opportunity to develop allulose-containing soy yogurt with lower calories. In soy yogurt fermentation, when sucrose was substituted with 50% of allulose, the resulting product was characterized by a greater overall preference, a higher lactic acid bacteria content, in addition to a pH range similar to those typical of yogurt (Kim and Han 2019).

Trehalose

Trehalose naturally occurs in plants, fungi, insects, and yeasts and it is made of two glucose units linked with α -1,1-glycosidic bond (Valencia 2022). Among the numerous biological activities, various studies have recently shown that trehalose is able to stabilize blood sugar levels through a slower release of glucose, thanks to a milder insulin response compared to other monosaccharides and disaccharides (Chen and Gibney 2023). For this reason, its use as a natural additive has been widely consolidated and its global market is projected to grow at a CAGR of 5.34% during the forecast period of 2020–2025 (Mordor Intelligence 2020).

Because the extraction and purification steps of trehalose from natural sources are laborious and time-consuming, the currently available approaches for its production are based on enzymatic transformations rather than the recovery from biomass or *in vitro* chemical synthesis (Chen and Gibney 2023).

The popularity of trehalose, which is half as sweet as sucrose, is mainly associated to its ability in eliciting a very low insulin response (Table 1). In addition, it is recognized as a stabilizing agent, able to preserve the structure and stability of proteins such as enzymes, lipids and carbohydrates (Richards et al. 2002).

The use as a sweetener has been successfully reported for confectionery products and frozen food at a concentration of 5% which also demonstrated a good cryoprotective action (Sokołowska et al. 2022; Ohtake and Wang 2011). The study of Moriano and Alamprese (2017) proved that it may be successfully exploited in ice cream recipes. Indeed, the total replacement of sucrose with trehalose led to a melting rate significantly lower than the ice cream recipe containing sucrose, a very high firmness, and a higher extrusion temperature.

Erythritol

Erythritol (E968) is a natural sweetener found in fruits [e.g., grapes (0–42 mg/kg), melons (22–47 mg/kg), pears (0–40 mg/kg)], mushrooms, seaweeds, beverages [e.g., wines (130–300 mg/L), beer, soy sauce (910 mg/L), sake (1550 mg/L)] and miso bean paste (1310 mg/L) (Rzechonek et al. 2018). This compound is a non-caloric and non-glycemic sweetener (Table 1); therefore it is suitable for diabetic patients because it has no influence on blood insulin levels, due to its chemical structure, and is secreted through urine (Mironczuk et al. 2015). Erythritol global market is growing with a CAGR of 6.5% over the period of 2023–2030 (Zion Market Research 2023).

The industrial production of erythritol is mainly based on the fermentation processes carried out by osmophilic yeasts, such as *Moniliella spp.* or *Trichosporonoides megachiliensis*, as well as by some lactic acid bacteria, such as, *Oenococcus oeni*, *L. mesenteroides* and *L. sanfranciscensis* (Martău, Coman, and Vodnar 2020).

Reviewing the papers in literature, it is well known that this sweetener is among the most used in baked goods as a total or partial surrogate for sucrose to enhance the textural properties (Sahin et al. 2019). Lin, Hwang, and Yeh (2003) studied novel formulations for the production of chiffon cake with erythritol as sucrose substitute, highlighting its effects on the physical and sensory characteristics of the final product. The main results of the research proved that chiffon cakes prepared with erythritol at 25%, 50%, 75%, and 100% were lighter brown in the crust and less sweet than those with only sucrose. The specific gravity of cake batter, volume, and moisture content were similar in the recipe based on sucrose and erythritol. Sensory analysis also proved no remarkable differences in cake color, moistness, and tenderness among samples. Yan et al. (2023) investigated the effects of sugar substitutes on the angel cake in terms of protein foaming, baking performance and digestion properties (Figure 2e). For this purpose, erythritol was used in substitution of sucrose at different percentages (0, 20, 40, 50, 60, 80 and 100%). Surprisingly, in the case of 50% erythritol replacement, the sugar-egg white complex structure unfolded and had the best foaming capacity. At erythritol substitution levels lower than 50%, the sensory quality of cakes was not greatly affected, and samples had good color, dense structure, and texture. However, when the substitution was lower than 50%, the specific gravity of the batter and the specific volume of the cakes were slightly reduced. Another interesting result was that protein and glucose gastric-intestinal digestion, modeled through kinetic analysis, was positively affected by the use of erythritol as resulted by the reduction of blood glucose level *in vivo* (Yan et al. 2023).

The interactions of sucrose substitutes on the foaming and thermal properties of egg proteins in the production of baked goods represent a key aspect that needs to be extensively investigated. Hao et al. (2016) evaluated the use of maltitol, xylitol, and erythritol to substitute sucrose in sponge cake recipes. The substitution of sucrose by erythritol increased the apparent viscosity of liquid whole egg and diminished the foaming stability. Furthermore, the specific volume of sponge cakes significantly decreased and the hardness after cooking increased (+96.8%), resulting in a more compact and dense product. In Miller et al. (2017) this polyol was used to completely replace sucrose in the white layer cake formulation. Samples containing erythritol had similar volume indices in comparison to sucrose control, although during mixing the sugar alcohol did not completely dissolve, resulting in a gritty and sand-like batter. This was not surprising due to the poor solubility of erythritol in water. Overall, cakes containing the polyol were less acceptable due to the odd, bitter aftertaste and slight burning of the throat after swallowing.

Regarding the formulation of other baked products such as muffins, conflicting results have been reported in the

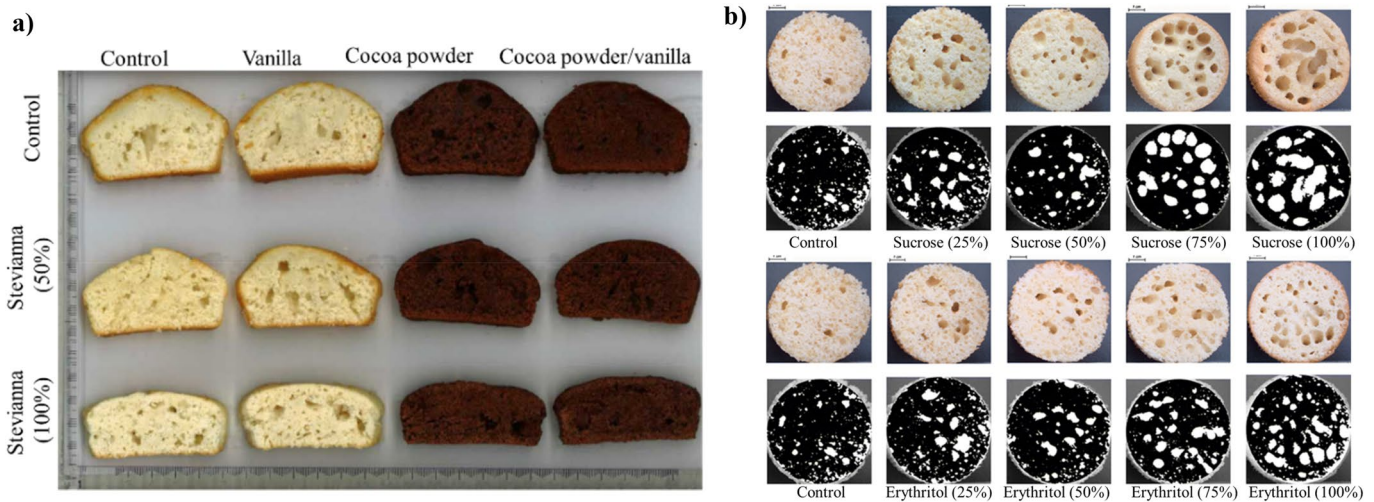


Figure 5. Effect of natural sweeteners on visual appearance of different food matrices: (a) muffins with “Stevianna” (adapted from Gao et al. 2017), (b) Spanish muffins containing erythritol (adapted from Martínez-Cervera et al. 2012).

literature. Martínez-Cervera, Salvador, and Sanz (2014) compared the suitability of different polyols (e.g., sorbitol, maltitol, isomalt and erythritol) as total substitutes for sucrose. Texture and consumer acceptability data revealed that erythritol was the less suitable polyol to replace sucrose in muffins. This may be related to the fact that this compound showed the highest differences in terms of starch gelatinization and in the batter rheological properties before and during heating. Better results were obtained in the research carried out by Martínez-Cervera et al. (2012), in which the suitability of erythritol used to replace sucrose in Spanish muffins was investigated (Figure 5b). Erythritol has allowed an increase in the air content of the batter, and consequently in the number of bubbles, resulting in a greater muffin height in comparison to the corresponding sucrose sample. The positive effect of erythritol on muffin properties may be linked to the fact that this sugar alcohol, similarly to sucrose, limits the decrease in elasticity during heating and raises the thermosetting temperature. Furthermore, to improve the volume and consistency of the muffins, other compounds including xanthan gum have been added to the basic recipe containing erythritol. In this way, it was possible to obtain products with more similar properties of the sucrose-based recipe.

Concerning cookies and biscuits, Lin et al. (2010) studied the effect of added erythritol on the characteristics of Danish cookies, formulated using this polyol (0, 25, 50, 75 and 100%) in combination to sucrose. It is interesting to note how erythritol was stable during baking and, further, no difference was revealed among samples in terms of moisture, protein, fat, ash and hardness. Moreover, the cookies surface color became lighter, and their sweetness diminished as the level of erythritol increased and at the same time the sucrose decreased. In hedonic test, the degree of hardness, flavor and overall liking of cookies prepared with 0, 25 and 50% of erythritol revealed no difference with respect to sucrose control. Even in this case it is possible to find conflicting results in literature; several papers pointed out the adverse impact of this polyol on the sensory properties of cookies and biscuits (Laguna, Primo-Martín, et al. 2013; Laguna, Vallons, et al. 2013).

The effect of sucrose replacement by erythritol at two levels (25% and 50% of total sucrose content) was also investigated in short-dough cookies (Laguna, Primo-Martín, et al. 2013) and in biscuits (Laguna, Vallons, et al. 2013). Although the use of erythritol allowed the production of a suitable dough from a processing point of view, the sugar alcohol led to the manufacture of too hard cookies (Laguna, Primo-Martín, et al. 2013), and worsening texture quality (e.g., fracture behavior) (Laguna, Vallons, et al. 2013). Despite this, the biscuits with low erythritol-content were compact, elastic, and resistant to the breaking force compared to the control.

Macarons are a particularly delicate baked good, in which sucrose is an essential ingredient to provide their shells contributing both to the flavor and sweetness, but above all it provides their unique structure and lightness. Nastaj et al. (2023) applied different levels of erythritol to obtain sucrose-free macarons (Figure 3c). The typical macaron structure was unexpectedly obtained even at the lowest erythritol addition (20 g); the stability and rheological parameters of the doughs were enhanced using the medium erythritol amount (40 g); whereas the greatest increase in the final macaron volume was achieved at its highest dosage (60 g) along with the better mechanical properties and extended shelf-life.

Recently, an interesting study involved the erythritol addition in order to produce sucrose-free meringues using whey protein isolate (WPI) (Nastaj et al. 2020) at different ratios erythritol:WPI (Figure 4b). The results highlighted that the 1:2 ratio was detrimental for both the overrun and the rheological properties of liquid foams before baking; however, it resulted in improved foam stability and final volume of the meringues. Higher concentration of erythritol (2:1) produced a smoothing effect and the meringue surface was less rough. Concerning the textural parameters, such as hardness and crumbly quality, both of them increased as the WPI and erythritol concentration were higher. The 1:1 erythritol:WPI ratio was the most effective in maintaining a uniformly aerated structure and gas bubbles. The samples without erythritol, meanwhile, were characterized by the greatest spreading kinetic.

The replacement of sucrose with erythritol has also been successfully applied in frozen dairy products. Fuangpaiboon and Kijroongrojana (2013) evaluated the formulation of a low glycemic index (GI) coconut milk ice cream by replacing 12% sucrose with xylitol (12.83%), erythritol (19.51%) or inulin (24%) with the goal of reaching the same sweetness. Sensory evaluation proved that the ice cream with erythritol obtained the highest overall liking scores (5 times-higher than the control). Also considering the main parameters to describe the properties of an ice cream, such as overrun, viscoelasticity of serum phase, thermal properties and hardness, it may be emphasized that erythritol seemed to be the most promising sweetener for the low GI coconut ice cream production. Moriano and Alamprese (2017) studied the effect of alternative sweeteners (e.g., honey, trehalose, and erythritol) to partially (50%) or totally replace sucrose in artisanal ice cream, using a sample added with table sugar as a control. The ice cream was prepared using only erythritol and had the consistency required for the extrusion at a higher temperature and with a longer freezing process than sucrose, also increasing the consistency. Furthermore, the total substitution of sucrose with the polyol caused a remarkable decrease in melting rate, likely caused by the slower melting of the amorphous solid formed by the sugar during freezing and the lower solubility of this sweetener. Finally, it is important to underline that ice cream containing erythritol resulted in a calorie reduction of about 45% and 23% with respect to the reference sample (Moriano and Alamprese 2017). Khuenpet et al. (2015) investigated the effect of sucrose replacement with alternative sweeteners on the quality of vanilla-flavored ice cream. The addition of erythritol increased the viscosity, lowered the meltdown percentage and improved the nuance of vanilla-flavored ice cream, with respect to the reference sample.

Mannitol and maltitol

Mannitol (E421) is the only non-hygroscopic compound among the functional sugar alcohols and since its glycemic and insulinemic indices are zero (Table 1), it is highly suitable for dieters and diabetics (Chen et al. 2020). It is widely distributed in pumpkins, celery, carrot, pineapple and seaweed, although in small quantities (Chen et al. 2020). Maltitol (E965) is a low-calorie sweetener, occurring naturally in different fruits and vegetables, such as chicory leaves, corn, wheat and potatoes, widely used in food preparation due to its desirable physical and chemical properties (Saraiva et al. 2020b). Additionally, it has 90% of the sweetness of sucrose (Table 1) and, furthermore, it is indicated as a texture developing compound (Zormand, Eshaghi, and Nateghi 2022). Mannitol and Maltitol global market is expected to grow at a CAGR of 7.1% and 6.2%, respectively, over the period of 2023–2033 (Future Market Insights 2023; Verified Market Research 2023).

With the only exception of erythritol, to date, all the polyols are obtained by catalytic hydrogenation of suitable reducing sugars, enzymatic conversion or microbial fermentation (Dobrev et al. 2013).

Sugar-free and low-fat biscuits have been recently prepared using maltitol, lactitol and sorbitol (Zoulias,

Oreopoulou, and Kounalaki 2002). Maltitol-based biscuits were characterized by the highest flavor and general acceptance scores, due to an improved flavor along with a greater diameter in comparison with sucrose-based sample. On the other hand, biscuits prepared with maltitol showed greater hardness and fragility than the control. These results were also confirmed in previous work (Zoulias, Piknis, and Oreopoulou 2000). Psimouli and Oreopoulou (2012) investigated whether certain polyols, such as mannitol, maltitol, sorbitol, lactitol, may replace sucrose by an equal amount of each substitute in cake recipes. The best results were obtained by using lactitol or maltitol as sugar substitutes, whereas mannitol led to cakes of poor-quality characteristics, as was demonstrated by rheological parameters and sensory evaluation. Ronda et al. (2005) studied the addition of maltitol and mannitol to completely replace the table sugar in sponge cakes. The effect of this replacement on cake quality was investigated by instrumental and sensory analysis, measuring texture, color and volume after baking. The sponge cakes prepared with maltitol were the most similar to the control sample manufactured with sucrose. In contrast, mannitol appeared to be a worse substitute for sucrose, since mannitol cakes received the lowest acceptability scores by panelists.

Zormand, Eshaghi, and Nateghi (2022) investigated the physicochemical and organoleptic characteristics of low-calorie jellies prepared with mannitol and maltitol. Sugar alcohols at an amount of 25, 50, 75, and 100 g were incorporated to the jelly recipe, and sucrose was used both in the reduced sugar jellies and in the control sample (only sucrose). Substitution of sucrose with sugar alcohols did not affect pH, acidity, brix, and moisture. Comparing samples, those containing mannitol and maltitol were characterized by a higher syneresis value, whereas no notable differences were appreciated in terms of consistency and sensory parameters. Therefore, a substitution of up to 50% w/w of table sugar with maltitol and/or mannitol may be useful in the production of sugar-reduced jellies.

Sahin et al. (2018) analyzed the effect of xylitol, mannitol and maltitol, as partial or total sugar replacers, on burger buns and their dough properties (Figure 2f). Sweeteners were individually incorporated in a burger bun system, by replacing sucrose (30%, 50% and 100%). Compared to sugar-rich doughs, polyols lowered the fermentation yield, resulting in lower dough development (-37 to -81%) and poorer gaseous release (-62 to -87%). Furthermore, a delay in gluten network development (+50 to +161%) and a decrease in extensibility (-14 to -18%) with increasing concentrations were detected. It is interesting to note that maltitol had no effect on the pasting properties, meanwhile mannitol needed a higher temperature (+15°C). Moreover, these compounds did not affect the viscoelastic characteristics of the batter despite the fact that their addition resulted in a remarkable decrease in specific volume (-30 to -48%), a harder crumb texture (+135 to +678%), along with a very pale crust color at increasing amounts. Overall, the possibility to halve the amount of sucrose by adding polyols has been demonstrated, and mannitol appeared to be the most suitable sweetener among those tested.

Sweeteners impact on food texture properties

As highlighted by the above critical literature analysis, a dedicated paragraph focused on the effect of both NNS and NS on food textural properties appears to be of great relevance.

Mainly during cooking, these compounds interact with other ingredients, in particular water, starch, proteins, yeast and lipids. The partial replacement of sucrose with bulk sweeteners, mainly sugar alcohols, has become of great interest owing to their similarity with sucrose in terms of starch gelatinization and viscosity effect in baked goods (Sahin et al. 2018).

Maltitol has been recognized as a suitable and sole sweetener both in cakes (Ronda et al. 2005) and muffins (Martínez-Cervera, Salvador, and Sanz 2014), given the delay in the temperature of the inflexion point induced, like sucrose. This property, crucial for appropriate air and vapor expansion during baking, provided a good stability of the dough, a high specific volume, and a low browning tendency.

Also in biscuits and cookies recipes (Zoulias, Piknis, and Oreopoulou 2000), maltitol provided textural properties similar to sucrose, such as low hardness and adhesiveness of the dough and less browning during cooking. The effects of erythritol on cake and muffin properties have been widely debated with controversial results. Some authors (Lin, Hwang, and Yeh 2003; Hao et al. 2016; Miller et al. 2017; Yan et al. 2023) found the erythritol responsible for a decrease in the peak temperature during starch gelatinization, associated by an increase in the hardness (5 times compared to the control) and chewiness. As regards to its use in biscuits (Lin et al. 2010), otherwise, erythritol enhanced hardness and decreased the browning attitude (Laguna, Primo-Martín, et al. 2013; Laguna, Vallons, et al. 2013).

Erythritol may also be successfully applied to dairy products. Preparing ice cream with erythritol, as a total or partial substitute for sucrose, the product showed a consistency suitable for extrusion even at a higher temperature and with a longer freezing process than sucrose (Moriani and Alamprese 2017). Another important aspect to consider is that the total replacement of sucrose with this sugar alcohol induced a notable decrease in the fusion velocity. This phenomenon may be ascribed to a slow melting of the amorphous solid formed by the sugar during freezing and to the lower solubility of this sweetener. Instead, the use of maltitol for similar preparations produced the opposite effects probably due to its high viscosity, with a drastic reduction in overrun and therefore a worsening of ice cream textural characteristics (Khuenpet et al. 2015).

Concerning the use of rare sugars, it clearly emerged from the previous discussion that both allulose and tagatose have physical and textural characteristics analogous to sucrose. Furthermore, it was confirmed they could be successfully used in the baking industry, especially when combined with extended cooking durations or other products, which require less volume increase and have a lower moisture content. Allulose may improve the texture in some food systems, even the particularly delicate meringues, but also in

biscuits and cakes (O'Charoen et al. 2014). It has been supposed the d-ketohexose binding capacity to proteins through hydrogen bonding, leads to a change in the surface hydrophobicity of proteins, thus resulting in textural properties increase (O'Charoen et al. 2014).

Sweetener blends

In light of the research that has been reviewed in this paper, it seems clear how an ideal natural sweetener that may completely replace all the physicochemical functions of sucrose is not yet available. A feasible strategy to address this limitation is to blend multiple NNS and bulk sweeteners (Jang et al. 2021). Indeed, it is well known that different types of sweeteners show different onset, duration, decay and extinction times (Schiffman, Sattely-Miller, and Bishay 2007). For example, monosaccharide rare sugars (e.g., allulose and tagatose) have an early onset of maximum sweetness intensity and a short time to extinction, while protein sweeteners (e.g., thaumatin) are characterized by a significant delay in the time of maximum sweetness intensity and they take much longer to extinguish (Jang et al. 2021). A potential method for altering sweet temporal quality is to blend two or more sweeteners together, thereby creating a mixture with temporal properties more resembling those of sucrose (Waldrop and Ross 2014). Sweetener blends may mask undesirable aftertaste (e.g., glycyrrhizin) and offer a chance for improving the temporal profile, as well as the storage stability of a product (Kushwaha et al. 2018). Furthermore, a synergistic effect could also occur, meaning that the sweetness obtained from the mixture of sweeteners is greater than what would be expected from the addition of individual compounds (Mooradian, Smith, and Tokuda 2017).

Several papers, available in literature, proved the usefulness of sweetener blends. Benavente-García et al. (2001) demonstrated a significant technological advantage in terms of sweetness synergy and cost-saving when neohesperidine DC was used in a blend with other intense or bulk sweeteners, such as sodium saccharin or sodium cyclamate. An improved solubility (207- and 52-times greater) was revealed combining neohesperidine DC with sodium cyclamate and sodium saccharin (10:90), respectively.

Jang et al. (2021) investigated the synergism and the sensory characteristics of 24 ternary and 47 quaternary low-calorie sweetener blends, formulated using bulk sweeteners (allulose, tagatose, and erythritol) and potent sweeteners (sucralose and three rebaudiosides) in model solution. The authors proved that increasing the number of sweetener types with different physicochemical characteristics gave rise to blends with a less bitter taste or astringent mouthfeel, complementing the merits and limits of individual compounds.

Blends of allulose or maltitol with glycosyl Rebaudioside (Reb) A in a ratio of 1:1 contributed to lowering its off-flavor (Jung et al. 2021). Mixtures containing maltitol were less bitter and astringent than Reb A, suggesting an enhanced sensory profile, although a synergistic effect on sweetness was not perceived. Mora et al. (2023) showed that blends of allulose, erythritol, Reb D, and Reb M enhanced taste

perception, whereas the combined use of Reb A, monk fruit, and thaumatin did not mitigate their off-flavor.

Concerning the use of blends in real food (Table 2), binary sweetener mixtures made of a bulk sweetener (xylose, tagatose or erythritol) combined with a highly intense sweetener (sucralose or stevia) were investigated in milk and instant coffee (Choi and Chung 2015). The synergistic effect was mainly revealed in milk rather than in coffee and it was affected by the concentration and the nature of sweetener compounds (Table 2). Acevedo et al. (2018) selected an optimal mixture of natural sweeteners (sucrose/stevia/tagatose) for carbonated soft drinks. A reduction of about 60% of sucrose may be achieved adding both stevia and tagatose, lowering the stevia's bitter, metallic, licorice-like aftertaste (Table 2). Ternary mixtures with a higher proportion of tagatose allowed them to achieve a 79% reduction of total calories in comparison to the regular soft drink containing sucrose. Recently, tagatose has been applied with other sweeteners such as isomaltulose and oligofructose in the preparation of various jams (orange and mandarin) and jellies (citrus and watermelon). Also, in these real foods the most suitable solution was the use of tagatose in binary or ternary systems, due to the fact that its high concentration (>50%) masked the undesired bitter taste (Souza et al. 2022) (Table 2).

A blend composed of erythritol (98–99%) and rebaudioside A (1–2%) already available on the market, produced in New Zealand and called “Stevianna,” has been applied in the preparation of muffins. The 50% replacement level appeared to be appropriate in terms of texture and sensory properties (Figure 5a). A total substitution, meanwhile, led to poor physicochemical characteristics along with a bitter aftertaste, an unpleasant appearance, an increased crumb hardness and a dry mouthfeel (Gao et al. 2017; Sahin et al. 2019) (Table 2).

Woodyer, Cohen, and Bridges (2018) patented a blend containing allulose and mogroside from monk fruit extract to be used in food and beverage, pharmaceutical and cosmetic products, and which was able to provide a reduction in off-taste and a desirable temporal profile.

Chocolate milk could be partially sweetened with a mixture of monk fruit (46 mg/L) and stevia (30 mg/L), diminishing sucrose and preserving a sweet taste and a similar temporal sweetness profile (Li, Lopetcharat, and Drake 2015). Finally, Mahato et al. (2021) investigated the simultaneous addition of stevia and monk fruit extract in chocolate-flavored milk. The authors concluded that the combination of stevia (56.27 ppm) and monk fruit extract (81.90 ppm) showed optimum sensory properties for the overall acceptability, visual, taste and flavor perception. Accordingly, sugar-free chocolates have been prepared adding monk fruit and fiber extract blends, resulting in chocolate suitable for people with diabetes (Pandey and Chauhan 2019).

Microencapsulation of sweeteners

Some properties of natural sweeteners such as a high intense sweet taste, aftertaste, thermo-sensitivity, hygroscopicity and

Table 2. Sweetener blends applied in food sector.

Food	Blend	Reference
Milk 	Xylose (4.5%) + Stevia (0.03%) Tagatose (3.3%) + Stevia (0.03%) Erythritol (5%) + Stevia (0.03%) Xylose (4.5%) + Sucralose (0.003%) Tagatose (3.3%) + Sucralose (0.003%) Erythritol (5%) + Sucralose (0.003%)	Choi and Chung 2015
Instant coffee 	Xylose (5.2%) + Stevia (0.057%) Tagatose (4%) + Stevia (0.057%) Erythritol (5.4%) + Stevia (0.057%) Xylose (5.2%) + Sucralose (0.003%) Tagatose (4%) + Sucralose (0.003%) Erythritol (5.4%) + Sucralose (0.003%)	Choi and Chung 2015
Carbonated soft drink 	Sucrose (23–39 g/L) + Stevia (0.19–0.34 g/L) + Tagatose (34–42 g/L)	Acevedo et al. 2018
Mandarin/orange Jam Lemon Jam 	Tagatose (25%) + Isomaltulose (75%) Tagatose (60%) + Isomaltulose (40%) Tagatose (50%) + Isomaltulose (50%) Tagatose (30%) + Isomaltulose (70%)	Souza et al. 2022
Citrus Jelly Watermelon Jelly 	Tagatose (50%) + Isomaltulose (50%) Tagatose (50%) + Isomaltulose (50%)	Souza et al. 2022
Muffin 	Erythritol (98–99%) + Rebaudioside A (1–2%)	Gao et al. 2017

reactivity, may limit their use and potential marketability, especially in food products (Favaro-Trindade, Rocha-Selmi, and dos Santos 2015). In this context, microencapsulation may be a very promising technology since it allows

incorporating more easily non-nutritive sweeteners, making their industrial application possible. This approach is useful for: (i) improving the sweetener resistance against high temperature and moisture; (ii) lowering aftertaste and hygroscopicity; (iii) diminishing bitterness and other unpleasant flavors; (iv) developing desirable texture; (v) preserving the structural integrity and the stability (in particular for thaumatin). In addition, this technique enhances fluidity, turning liquid sweeteners into easily handled powders enabling their use and dosage (Favaro-Trindade, Rocha-Selmi, and dos Santos 2015).

In recent years, different encapsulation techniques have been developed depending on the nature of the compound and the objective to be achieved. Favaro-Trindade, Rocha-Selmi, and dos Santos (2015) reported the most common methods of encapsulation: spray drying, spray chilling/cooling/congealing, spray coating, molecular inclusion, emulsification, encapsulation in nanostructured lipid matrices, liposomes and micelle, simple and complex coacervation, processing with microfluidic devices, extrusion, encapsulation by supercritical fluids, and solvent evaporation.

Neohesperidine DC has a persistent aftertaste, which restricts its application in food industry. The encapsulation of this compound (100 ppm) in β -cyclodextrin (β -CD, at 0.01%, 0.03%, 0.1%, 0.17%) provided a significant reduction of its aftertaste, although a concurrent lowered sweetness was revealed (Chung 1996). This finding leads to speculating the possibility that β -CD may form an inclusion complex with neohesperidine, such that the hydrophobic portion was encapsulated in the cavity of β -CD and the carbohydrate portion was oriented toward the outside of the cavity.

More recently, D'hoore, Ríos, and Montero (2022) patented a novel sweetener made of neohesperidine DC and γ -cyclodextrin which provided an outstanding synergistic effect, thus achieving the desired sweetness level using less amount of neohesperidine. Moreover, both the lingering aftertaste and the onset time were remarkably reduced, thus providing a better overall taste profile, more similar to sucrose. The application fields of this new encapsulated sweetener include: (i) beverage (carbonated and non-carbonated, alcoholic and non-alcoholic), (ii) baked goods (e. g. bread, cakes, biscuits, and muffins), (iii) dairy (e.g., yogurt, drinkable yogurt, frozen yogurt, milk-based beverages, condensed milk, cream, cheese and ice cream), and (iv) confectionary (e.g., chocolate, caramels, candies, marzipan, and chewing gums) products.

Microencapsulation has been also applied to protect thaumatin structure against thermal denaturation which causes the loss of the sweetness property, and to provide its controlled release. Cherukuri, Faust, and Orlandi (1993) encapsulated thaumatin using a fluidized bed to facilitate its addition in chewing gums, confections, and pharmaceutical preparations. Furthermore, the patent by Thorengaard (2010) described thaumatin microencapsulation in polyvinyl acetate and natural resin for application in confectionery products.

Also, in the case of glycyrrhizin, the bitter aftertaste along with the slight distinctive licorice flavor and the yellowish-brown color, limits its direct utilization in the production of food and beverage. Sarabi-Aghdam et al. (2021) studied the

use of chickpea protein isolate and persian gum for glycyrrhizin encapsulation proving that more than 90% of glycyrrhizin was successfully encapsulated using complex coacervation. These complexes significantly masked color and bitter aftertaste attributed to glycyrrhizin in model beverage.

Concerning bulk sweeteners, especially polyols, their microencapsulation is not commonly applied as with the other compounds because the sweetness provided by bulk substances is less or equal than that of sucrose, so the microencapsulation process could lower their sweetness (Favaro-Trindade, Rocha-Selmi, and dos Santos 2015).

Conclusion and outlook

Despite the extensive research efforts, the use of natural sweeteners to fully replace sucrose is still a challenge in the food industry. Many studies suggest that natural sweeteners may be applied in combination with low amounts of sucrose in different food products such as baked goods, dairy, confectionaries and beverages, in order to diminish the consumption of table sugar. However, the nature and composition of food matrix, along with the process conditions to which it is subjected, remarkably affect their impact on structure and sensory properties. The new frontiers for the application of natural sweeteners turned out to be the use of binary and ternary blends including non-nutritive and bulk sweeteners, as well as the encapsulated formulations able to mitigate any unpleasant flavor, to enhance stability, and to simplify the use and dosage.

Although the current application of natural sweeteners in the food industry opens up wide perspectives and their benefits to human health is still open to discussion, the bioactivity of many of them highlight their potential use as food supplements and in the pharmaceutical sector.

Authors' contributions

Data curation, writing-original draft preparation, and investigation: Claudio Lombardelli, Ilaria Benucci. Conceptualization, methodology, supervision, validation, writing-reviewing, and editing: Ilaria Benucci, Marco Esti. All authors have read and agreed to the published version of the manuscript.

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