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Review

Industrial manufacture of sugar-free chocolates – Applicability of alternative sweeteners and carbohydrate polymers as raw materials in product development

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Chocolate is dense suspension of solid particles comprising 60–70% sugar and non-fat cocoa solids. Until recently, it was rarely produced as a sugar-free product due to the multi-functional properties of sweetness, bulkiness and textural characteristics that sugar offers to products. Today's consumers are concerned about the high sugar levels, calories and cariogenicity effects in confectionery products, hence increasing popularity of 'light' and 'sugar-free' products. Development of sugar-free chocolates is most challenging since all sugar needs to be replaced. In-depth understanding of the applicability of alternative sweeteners and carbohydrate polymers as ingredients in sugar-free chocolate manufacture would therefore have significant industrial applications.

Introduction

Chocolate is one of the fastest growing products within the confectionery industry, with worldwide sales showing a growth rate of 7% from 2006 to 2007 (about $ 2.2 billion) (Nielsen, 2008; Palazzo, Carvalho, Efraim, & Bolini, 2011). Its unique texture, flavor and eating pleasure are the main reasons for its expanding consumption throughout the world (Afoakwa, 2010). Increasingly, consumers are becoming concerned about the sugar and calorie content as well as the cariogenicity of confectionery products, with 'light' and 'sugar-free' products growing in popularity. A food product can assume a "light" or "sugar-free" claim if it provides less than 40 calories per serving or provides less than 0.5 g of sugars per serving, respectively (http://www.myfooddiary.com/Resources/label_claims.asp). The growing popularity of these products have led to an increased quest for the use of alternative sweeteners in the dairy, confectionery and beverage industries within the past decade.

While the use of sucrose prevails in traditional chocolate industry, numerous nutritive and non-nutritive sweeteners offer new opportunities for the manufacturer. Consequently, edible carbohydrates with lower energy contents have been developed which are suitable for inclusion as bulking agents in chocolate manufacture (Afoakwa, Paterson, & Fowler, 2007a; Rudolf & Stergios, 1995). Nutritive sweeteners are ingredients that substitute for both the physical bulk and sweetness of sugar. Products of this type, sometimes called "sugar replacers" or "bulk sweeteners", include the sugar alcohols (also called "polyols") sorbitol, mannitol, xylitol, isomalt, erythritol, lactitol, and maltitol. Trehalose, tagatose and isomaltulose are bulk sweeteners similar in function to the polyols but are actually sugars

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rather than sugar alcohols (Beckett, 2009; Kroger, Meister, & Kava, 2006; Salminen & Hallikainen, 2002). Non-nutritive sweeteners are substances with intense sweet taste used in small amounts to replace the sweetness of a much larger amount of sugar or sucrose. These include acesulfame-K, aspartame, neotame, saccharin, sucralose, alitame, cyclamate, stevia/steviol glycosides (Kroger *et al.*, 2006) and thaumatin.

Today, sugar-free chocolates on the market are more diverse and offer various levels of quality in terms of appearance, texture, taste and flavor dissimilar to that of their sugar counterparts. This review characterizes the major types of alternative sweeteners and carbohydrate polymers used in the food industry and their suitability and applicability to the manufacture of sugar-free chocolates of acceptable quality.

Functionality of sucrose in chocolate manufacture

Sucrose is the most commonly used sugar in the food industry and it is a popular ingredient to obtain sweetness in human food preparation (Jamieson, 2008). It is extracted from sugar cane or sugar beet and used as an industrial sweetener in baking, drinks, confectionary, jams, jellies and preserves. Sucrose is a disaccharide composed of the chemically linked monosaccharides glucose and fructose (Beckett, 2009). It has a clean sweet taste, with a quick onset and a minimum persistence. Sucrose is also useful as a bulking agent, texture modifier, mouthfeel modifier, flavor enhancer and preservative (Afoakwa *et al.*, 2007a; Salminen & Hallikainen, 2002). It is mainly valued for its sweetness and serves as an important source of energy, providing 394 kcal/100 g of refined sugar.

Chocolate is dense suspension consisting of sugar particles, cocoa solids, and milk powder (depending on type) dispersed in cocoa butter as a continuous phase (Afoakwa *et al.*, 2007a; Beckett, 2009; Sokmen & Gunes, 2006). The composition of sucrose in chocolate is about 40–50% (depending on type) and this confers multiple functional properties on chocolate including sweetness, particle size distribution (PSD) and mouthfeel (texture). Its impact on rheological properties is also important for the end product quality (Afoakwa, Paterson, & Fowler, 2007b; Jeffery, 1999). During processing, the components are mixed, refined and conched to attain desired rheological properties. Finally, tempering, cooling and storage are important for the final product texture and melting characteristics. Guinard and Mazzucchelli (1999) noted that sucrose is added to promote sweetness in chocolate but also affects other flavors. Barringer and Prawira (2009) investigated the effect of sucrose composition on consumer preference for milk chocolate. Chocolates with 40% sucrose were significantly higher in chocolate flavor than those with 30% sucrose despite containing less cocoa liquor. The bitterness attribute was also significantly affected by sucrose levels with panelists rating chocolate with 30% sucrose significantly more bitter than chocolate with 44.3 and 50% sucrose. Similar results were obtained by Guinard and Mazzucchelli (1999) where milk chocolates with less sucrose were also rated by a trained panel more bitter than samples with higher sucrose content.

Alternative sweetening solutions in chocolate manufacture

Sucrose is the conventional sweetening agent prevailing in the traditional chocolate processing industry. The high sugar content of chocolate have led to the search for low calorie, low glycemic index, healthier alternatives. While sucrose alternatives do not provide a comparable amount of calories, they are generally poor in mimicking the physical attributes of sucrose, i.e. body, mouthfeel and texture (Clayton & Conn, 2005). Alternative sweeteners are successful if they match closely the taste quality of sucrose. Given that all the sucrose need to be replaced, sugar-free products, depending upon the application, are usually the most challenging to develop. The different categories of ingredients that may be used are discussed below.

High potency sweeteners

High potency sweeteners (HPSs) are often called high-intensity sweeteners. They deliver a sweetness punch from hundreds to thousands of times than that of sucrose and, therefore, are used at levels of “parts per million” (ppm). Many types exist but a handful is approved for use in Europe and the United States. These include saccharin, sucralose, acesulfame-K, aspartame and neotame (Jamieson, 2008). The technical characteristics of these sweeteners and their regulatory status are summarized in Table 1.

In addition, stevia or steviol glycosides, herb extracts of intense sweetness from *Stevia rebaudiana* Bertoni, have received much attention in recent times (Palazzo *et al.*, 2011). Steviol glycoside products consist primarily of stevioside (>80%) or rebaudioside A (>90%). Rebaudioside A has the most desirable flavor profile and is the most stable of the steviol glycosides (DuBois, 2000). JECFA (Joint Expect Commission on Food Additives) recommended a final Acceptable Daily Intake (ADI) of 0–4 steviol equivalents (safety factor 100X) in 2008. In December 2008, the United States Food and Drugs Administration (USFDA) accepted the GRAS (Generally Recognized as Safe) status of rebaudioside A (USFDA, 2008) and, in 2009, for the mixture of steviol glycosides. In September 2009, the French authorities authorized rebA (>97% purity) as a food additive, excluding its use as a table top sweetener. However, in January 2010 rebaudioside A was also authorized as a table top sweetener (Rieck, Lankes, Wawrzun, & Wüst, 2010). The market segment currently utilizing this sweetener seems to be the beverage industry, where being considered “natural” has significant potential (Jamieson, 2008). Some studies have been conducted on its applicability in chocolates (Melo, Bolini, & Efraim, 2007; Palazzo *et al.*, 2011; Shah, Jones, & Vasiljevic, 2010).

Table 1. High potency sweeteners.

	Aspartame	Acesulfame-K	Rebaudioside A	Saccharin	Sucralose	Neotame
Sweetness potency (times that of sucrose)	180–200	130–250	200–300	300–500	500–700	8000–13,000
Taste/Profile	Slow onset, lingering sweetness	Quick onset with no significant lingering sweetness	Moderate to quick onset with little to no lingering sweetness	Quick onset with no significant lingering sweetness	Clean sweetness with slow onset and lingering sweetness	Slow onset, lingering sweetness
	Clean sweetness with little to no aftertaste	Can have a bitter aftertaste	Potential for bitter or black licorice aftertaste	Potential for metallic, bitter aftertaste		Clean sweetness with little to no aftertaste
Stability	Limited stability at elevated temperature and low pH	Good stability at elevated temperatures and low pH	Good stability at elevated temperatures and low pH	Good stability at elevated temperatures and low pH	Good stability at elevated temperatures and low pH	Limited stability at elevated temperature and low pH
Blending options	Good synergy with acesulfame-K and saccharin	Good synergy with aspartame and sucralose	N/A	Good synergy with aspartame and sucralose	Good synergy with acesulfame-K and saccharin	Good synergy with acesulfame-K and saccharin
Advantages	Widely used, sweetness profile and cost-effectiveness	Stability and synergies with other HPSs	"Natural" status and stability	Cost-effectiveness and stability	Sweetness profile, branding and stability	Sweetness profile and cost-effectiveness
Regulatory[a] status	Food additive ADI 50 mg/kg of body weight/d	Food additive ADI 15 mg/kg of body weight/d	–	Permitted for use under an interim regulation	Food additive ADI 5 mg/kg/d	Food additive ADI 18 mg/p/d

[a] ADI values listed here are those established by the US Food and Drug Administration (expressed in milligrams per kilogram of body weight per day). Neotame is however expressed in terms of milligrams per person per day (mg/p/d).
Sources: Jamieson (2008); [a] Kroger *et al.* (2006).

Thaumatin, an intensely sweet-tasting protein isolated from the arils of *Thaumatococcus daniellii* Benth, a plant native to tropical West Africa has gained GRAS status in the US, where it is used as a flavor enhancer, and is approved as a sweetening agent in Australia, Switzerland, and the United Kingdom (Kinghorn et al., 1998). Thaumatin consists of at least five sweet forms; with two major components (Thaumatin I and Thaumatin II) and three minor components (Thaumatin a, b, and c). All five forms elicit a sweet taste at approximately 50 nM, and are 100,000-fold sweeter than sucrose on a molar basis. Thaumatin I is the most abundant component of the plant. The sweetness profile has been described as presenting a relatively slow onset of sweetness and a slight liquorice aftertaste. Thus, thaumatin will most probably be used in combination with other sweeteners (Calvino & Griddo, 2000). Heat stability above 100 °C has been demonstrated even at pH values below 5.5, with no loss in sweetness.

Replacement of sugar with HPSs poses a serious challenge in chocolate confections, because sucrose fulfills both a structural and sweetening function in these products. Combination of HPSs with bulk sweeteners is therefore needed to provide an integral solution for sugar replacement.

Bulk sweeteners

Bulk sweeteners are ingredients that can substitute for both the physical bulk and sweetness of sucrose. Often referred to as "sugar replacers", bulk sweeteners are constantly being explored industrially for their importance in food applications. Several health promoting effects have been attributed to these ingredients and thus have potential advantages over sugar as food ingredients.

Polyols (sugar alcohols)

Polyols (also known as sugar alcohols) originate from traditional corn syrups modified by reducing the reactive sites (aldehyde or ketone) through catalytic hydrogenation, enzymatic conversion or fermentation. Only the reactive groups are changed so the polyol retains much of the sugar's structure, bulk and function, making them ideal for 1:1 bulk sugar replacement (Jamieson, 2008). Polyols vary in sweetness from half as sweet to about as sweet as sucrose, at the same time providing almost zero to about one-half the calories of sugar on a per weight basis. They include sorbitol, isomalt, erythritol, maltitol, lactitol, mannitol and xylitol. Their chemical properties are summarized in Table 2.

Jamieson (2008) noted that polyols can exhibit a wide range of physical characteristics beyond that of the typical

Table 2. Characteristics of polyols (sugar alcohols).

Polyol	Properties
Sorbitol	Derived from glucose; 60% as sweet as sucrose. Good solubility – 70% at 20 °C. Melting point – 97.2 °C. Very hygroscopic and has a cooling effect in crystal form only.
Xylitol	Derived from xylose. Equal in sweetness to sucrose. It has a solubility of 63% with low melting point of 94 °C. Less laxative and less hygroscopic.
Isomalt	Derived from sucrose; about 40% as sweet as sucrose. Has solubility of 25% at 20 °C which increases with temperature. Melting point between 145 and 150 °C. Not hygroscopic, forms agglomerates with high residual moisture. Less viscous thereby decreasing the viscosity of other polyols.
Mannitol	Derived from mannose; about 70% as sweet as sucrose. It crystallizes out because of the poor solubility – 18% at 20 °C. Melting point between 165 and 169 °C. Not hygroscopic but has the highest laxative effect.
Maltitol	Derived from glucose syrup; 95% as sweet as sucrose. Has a solubility of 62% at 20 °C with a melting point lying between 130 and 135 °C. Very hygroscopic.
Lactitol	Derived from lactose; about 40% sweet as sucrose and exists in two forms – monohydrate and anhydrous with melting points of 75 °C and 120 °C respectively. Less hygroscopic than sorbitol or xylitol.
Erythritol	Derived from fermentation of glucose and sucrose by *Trichosporonoides megachiliensis*; about 60–80% sweet as sucrose. Has humectant and bulking properties and produces laxative effect upon high consumption.

solubility, molecular weight and sweetness. They have other unique properties such as cooling effects which occur when crystalline polyols, exhibiting a very negative heat of solution, are dissolved in water (often reducing the temperature of their surroundings). This may be a welcomed property in applications such as mints or breath-refreshing chewing gum but not necessarily so in chocolates.

Most polyols are incompletely digested and poorly absorbed. This is the primary reason why their caloric values are lower than that of sugar. Incomplete absorption, however, may also have disadvantages. Undigested carbohydrate has an osmotic effect, pulling water into the intestine (Kroger *et al*., 2006). The label statement "excess consumption may have a laxative effect" is therefore required by the USFDA for some products containing sorbitol or mannitol if consumption of the product is likely to result in ingestion of 50 g or more per day of sorbitol or 20 g or more per day of mannitol. Children, because of their small body size, may be particularly sensitive to gastrointestinal effects resulting from consumption of relatively small quantities of polyols (Payne, Craig, & William, 1997).

Tagatose

Tagatose, an isomer of D-galactose and stereoisomer of D-fructose, is a naturally occurring simple sugar that has been established as GRAS by the FAO/WHO since 2001 for use in food and beverages. The FDA approved its use as a food additive in 2003. Tagatose occurs naturally in *Sterculia setigera* gum and small quantities have been found in sterilized and powdered cow's milk, a variety of cheeses, and other dairy products (Mendoza, Olano, & Villamiel, 2005). Classified as a monosaccharide, the structure of tagatose differs from fructose only in the position of the hydroxyl group on the fourth carbon. Its molecular formula is $C_6H_{12}O_6$ with a molecular weight of 180 g/mol. Tagatose, like the polyols, has a low caloric value and tooth-friendly properties. It is poorly absorbed by the upper gastrointestinal tract (Bertelsen, Jensen, & Buemann, 1999; Laerke, Jensen, & Hojsgaard, 2000) providing less than 1.5 kcal/g. EU directive 2008/100/EC assigns a caloric value of 2.4 kcal/g to tagatose (Directive 2008/100/EC, 2008). Lee and Storey (1999) compared gastrointestinal tolerance of sucrose, lactitol and tagatose in chocolate. The authors reported that a 20 g dose of tagatose given in 40 g of plain chocolate does not provoke significantly higher reporting of bloating, colic and flatulence compared to an identical dose of lactitol.

The sweetening power of tagatose is only slightly less than that of sucrose with a relative sweetness of 92% when compared in 10% solutions. It has a sucrose-like taste with no cooling effect or aftertaste. With a sweetness and bulk similar to sucrose, tagatose could be used as a sugar replacer in the formulation of reduced-calorie foods as well as foods low in metabolizable sugars (for example, diabetic foods) (Taylor, Fasina, & Bell, 2008). To deliver its prebiotic effect, tagatose should experience only minimal degradation during processing and storage. The melting temperature of tagatose is 134 °C, and it is stable at pH 2–7. It has high solubility [58% (w/w) at 21 °C], which makes it ideal as a flavor enhancer or fiber in soft drinks and yogurts. It is less hygroscopic than fructose and lower in viscosity [180 cP at 70% (w/w) and 20 °C] than sucrose at the same concentration. As a reducing sugar, tagatose is involved in browning reactions during heat treatment and decomposes more readily than sucrose at high temperatures (Kim, 2004; Levin, 2002). JECFA found tagatose to be safe and did not specify any maximum acceptable daily intake (WHO, 2005). Developing a knowledge base of tagatose functionality in chocolate products would be beneficial to the sugar-free chocolate industry.

Trehalose

Trehalose, also known as mycose, is a natural α-linked disaccharide formed by an α,α-1,1-glucoside linkage of two α-glucose units. Its molecular formula and weight are $C_{12}H_{22}O_{11}$ and 342.31 g/mol, respectively. Trehalose was first discovered in the early 19th century as a component of the ergot of rye (Wiggers, 1963). It is naturally found in insects, plants, fungi, and bacteria. Although the α,α isomer is commonly referred to as trehalose, α,β and β,β isomers exist in nature and display physical properties that are quite different from α,α-trehalose (Elbein, 1974). Purified commercial trehalose is usually in the dihydrate form. Trehalose technical qualities, mechanisms of action and natural functions make its applications in the food, cosmetic and medical industries possible. Trehalose was mainly applied in medicine and cosmetics as its use in the food industry was limited by cost (Sugimoto, 1995). With the advent of new manufacturing processes, the cost of production of trehalose has been dramatically reduced allowing its use in a wide variety of foods.

The popularity of trehalose may be due to its lower sweetness and longer persistence (in sweetness) in comparison with sucrose. It is almost half as sweet as sucrose and thus can be used in combination with other bulk sweeteners (Portmann & Birch, 1995). A 22.2% solution of trehalose was judged to be about 45% as sweet as sucrose by a Japanese taste panel. 85% of the panel preferred the taste of trehalose compared to sucrose (Richards *et al.*, 2002). Portmann and Birch (1995) reported a faster increase in the perceived sweetness of trehalose compared to sucrose (by a factor of 2.5) as the concentration of the solutions increased from 2.3 to 9.2%. A three-fold increase was also noted in the perceived persistence of the sweetness of trehalose (Portmann & Birch, 1995).

Trehalose is one of the most chemically stable sugars. Due to the 1,1 glycosidic linkages, trehalose is non-reducing, highly resistant to hydrolysis, and chemically inert in its interactions with proteins. It is stable in a wider pH range, compared to other sugars and less soluble in water (34 g/100 g H_2O at 5 °C and 40.6–69 g/100 g H_2O at 20 °C) than sucrose. The melting temperature can considerably vary due to its polymorphic nature, which can exist as anhydrous or dihydrate (α, β or γ) (Kubota, 2008). Trehalose was approved in 1991 in the UK as a novel food for use as a cryoprotectant for freeze-dried foods at concentrations of up to 5%. It was approved as a food ingredient in Korea and Taiwan in 1998 with no usage limits. In 2000 it obtained the GRAS status by the USFDA. JECFA reviewed and approved trehalose in June 2000 but no ADI (Acceptable Daily Intake) was specified. Regulatory approval as a novel food or food ingredient in Europe was granted in September 2001. Human consumption of trehalose in doses up to 50 g has been demonstrated to be safe (Ushijima, Fugisawa, & Kretchmer, 1995). No barriers therefore exist for the inclusion of trehalose in future food products.

Isomaltulose

In the last two decades there has been increasing interest in the use of isomaltulose. Also known as Palatinose® or Lylose®, isomaltulose is naturally found in honey and sugar cane extract, and considered a promising substitute for sucrose. It is a reducing disaccharide (6-O-α-D-glucopyranosyl-D-fructofuranose) (CAS. No. 13718-94-0) consisting of a glucose and a fructose joined by an α-1,6 glycosidic bond. It is industrially produced from sucrose by enzymatic rearrangement of the glycosidic linkage from a (1,2)-fructoside to a (1,6)-fructoside, followed by crystallization (Schiweck, Munir, Rapp, Schneider, & Vogel, 1990).

Isomaltulose has a mild sweet taste, with about 50% of the sweetness of sucrose. Its sweetness profile is similar to sucrose, leaving no aftertaste and when used as a sugar replacer in confectionery and chocolate, no difference in sweetness was noted (Huang, Hsu, & Su, 1998). Its naturally sweet taste and physical and organoleptic similarities to sucrose in food and beverage applications make this disaccharide a popular choice as a low-calorie sweetener. Without changes to traditional manufacturing processes, isomaltulose has been applied as a sugar replacer in bakery products, candies, canned fruits, chewing gum, chocolate-based products, confectionery, sports drinks and toothpaste (Irwin & Sträter, 1991, chap. 16). It melts at a lower temperature (123–124 °C) compared to sucrose (160–185 °C) and is more stable under acidic conditions. Solutions of 20% isomaltulose boiled at pH 2.0 for 1 h, did not undergo hydrolysis (Irwin & Sträter, 1991, chap. 16). At room temperature, the solubility of isomaltulose is half that of sucrose and viscosities of aqueous solutions of both sugars are similar.

Being an isomer of sucrose, isomaltulose is completely metabolized in the intestine, although much more slowly than sucrose and other sugars (Lina, Jonker, & Kozianowski, 2002). This causes a very low glycemic and insulinemic response, a property that is favorable for both diabetics and non-diabetics. Unlike sucrose, isomaltulose is barely fermented by oral microbes and inhibits the formation of insoluble glucans, making it non-cariogenic. Several studies have shown similarities in gastrointestinal tolerance of isomaltulose and sucrose even at high dose levels. In humans, no intestinal discomfort occurred at levels up to 50 g/day (Kashimura, Nakajima, Benno, & Mitsuoka, 1990; Spengler & Sommerauer, 1989). Isomaltulose was designated GRAS in 2006 by the USFDA and has been granted a non-cariogenic health claim. The overall physicochemical properties of isomaltulose thus permit its use as a sucrose substitute in most sweet foods.

Low-digestible carbohydrate polymers

Fiber or fiber-like ingredients known as low-digestible carbohydrate (LDC) polymers have been utilized within the past two decades as bulking agents in the manufacture of sugar-free chocolates. They are composed of sugars such as glucose, mannose and fructose, linked together in such a way that their digestibility, as well as caloric contribution, is significantly reduced. They come from many diverse and unique sources lending them to have many variations in their functional characteristics. These carbohydrate polymers tend to have a high molecular weight, often providing viscosity and body to most food applications. They can be used to help obtain a sugar-free claim as well as fiber claim (Jamieson, 2008). LDC polymers not only provide the bulk needed to replace sucrose, but are typically more slowly digested through various metabolic pathways, yielding lower calories, reduced glucose response, increased satiety and a reduction in dental caries (cavities).

Even though LDC polymers have been used for decades by diabetics, the landscape of ingredients available today, as well as their understanding has changed greatly. This has opened the door for product developers to create sugar-free products of higher quality that look, taste and eat like traditional confections. The end results are products proving to be useful tools for consumers to enjoy while trying to live a healthier lifestyle. Polydextrose, inulin, oligofructose and maltodextrin fall in this category and will be extensively discussed.

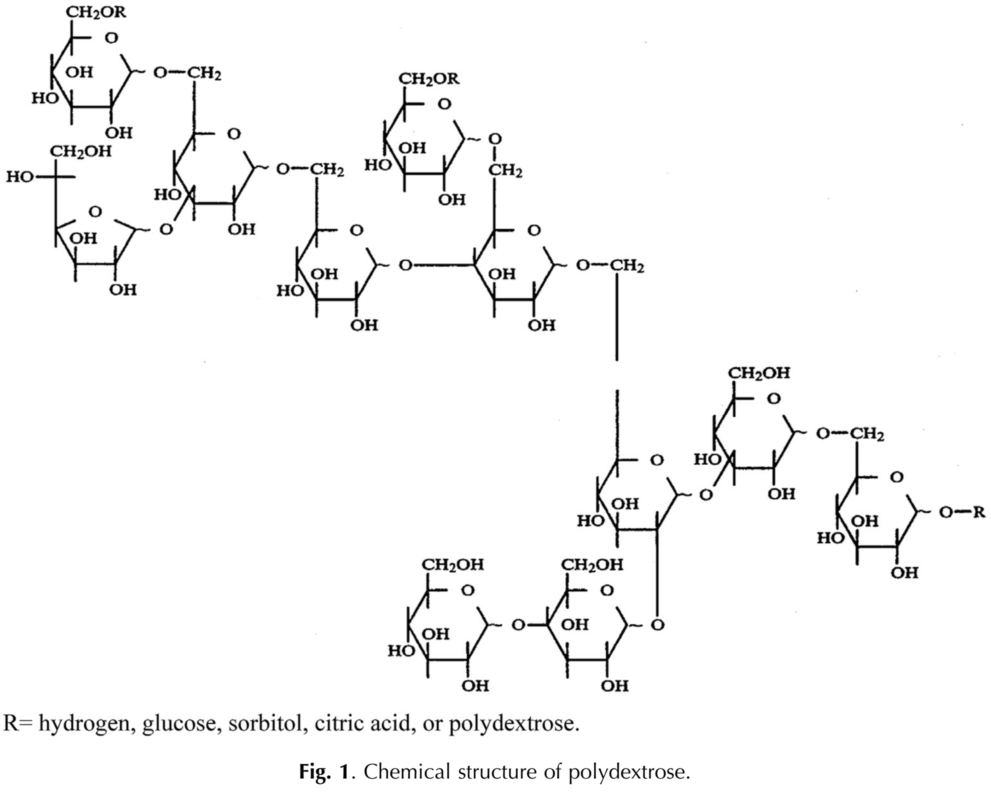
Polydextrose

Polydextrose is a randomly linked polymer of glucose with similar technological properties as sucrose except for sweet taste (Afoakwa *et al.*, 2007b; Beckett, 2009; Burdock & Flamm, 1999). It is regarded as either a resistant polysaccharide (RP) or a resistant oligosaccharide (RO) with an average degree of polymerization (DP) of ~12 (weight average molecular weight of ~2000). Polydextrose, as a commercial available preparation, is produced by the condensation of a melt which consists of approximately 89% D-glucose, 10% sorbitol and 1% citric acid on a weight basis (Colliopoulos, John, & Tsau, 1986). The chemical structure is shown in Fig. 1. Typically offered as an amorphous powder, polydextrose is hygroscopic and can easily pick up moisture. This is a great property for controlling water activity and shelf life in certain applications but could be counterproductive in others like hard candy by increasing stickiness and limiting shelf life.

Polydextrose has been successfully incorporated into a wide range of foods including baked goods, beverages, confectionery and frozen desserts. It provides the bulk and appropriate textural and mouthfeel qualities usually associated with sugar and fat while lacking the sweet taste and caloric value connected with those conventional food ingredients (Lauridsen, 2004). When used as a sugar replacement, polydextrose is generally combined with intense sweeteners in order to provide the desired sweet taste in the product in question.

Polydextrose is approved as a direct food additive by the US Food and Drugs Administration for use as a nutrient supplement, texturizer, stabilizer or thickener, formulation aid and humectants. The FDA estimated the per capita individual consumption of polydextrose for currently approved uses to be 14.3 g/day or 0.24 g/kg body weight/day, based on MRCA 5-year menu census (1982–87) (DiNovi, 1992). LDC polymers are effective tools for sugar replacement but are – as their name implies – low digestible. Subsequently, as they pass mostly untouched into the lower gastrointestinal tract, they can lead to osmotic imbalances and/or fermentation by bacteria. As a result, if overconsumed, individuals may experience loose stools and gas.

Polydextrose is well tolerated, and JECFA and the European Commission Scientific Committee for Food (EC/SCF) concluded a mean laxative threshold of polydextrose of 90 g/day (1.3 g/kg bw) or 50 g as a single dose. It is



R= hydrogen, glucose, sorbitol, citric acid, or polydextrose.

Fig. 1. Chemical structure of polydextrose.

approved in over 50 countries around the world and can be labeled as a fiber in Argentina, Egypt, Indonesia, Japan, Korea, Poland, and Taiwan. Specification monographs are published in the Food Chemicals Codex (FCC) (NAS, 1996) and the FAO Compendium of Food Additive Specifications (JFECFA, 1995).

Inulin and oligofructose

Inulin and oligofructose belong to a class of carbohydrates known as fructans. Fructans are linear or branched fructose polymers, which are either β 2→1 linked inulins or β 2→6 linked levans. The main sources of inulin and oligofructose used in the food industry are chicory and Jerusalem artichoke. Inulin and oligofructose are considered as functional food ingredients, resulting in better health and reduction in the risk of many diseases (Abbasi & Farzanmehr, 2009; Kaur & Gupta, 2002). The average daily consumption of inulin and oligofructose has been estimated to be 1–4 g in the United States and 3–11 g in Europe. Their energy content is only 40–50% of that of digestible carbohydrates, giving them a caloric value of 1.0–2.0 kcal/g (Kaur & Gupta, 2002).

Inulin is comprised fructose molecules linked together, ending with a glucose molecule, to form polymers of various lengths. The chemical structure is shown in Fig. 2. Native or medium chain length inulin, as present in chicory, has a degree of polymerization (DP) ranging from 3 to 60 monosaccharide units, with an average of about 10. Inulin is processed by the food industry to produce either short chain fructans, namely oligofructose (DP, 2–10; average 5) as a result of partial enzymatic (endoinulinase EC 3.2.1.7) hydrolysis, or long chain fructans by applying industrial physical separation techniques (De Leenheer, 1996). Typically, the smaller the polymers, the more soluble and sweet they become. Also, depending upon the source, inulin can be either highly branched or linear. The more branched the polymers, the more soluble they will become (up to 230 g in 100 g of water), offering slightly less viscosity than the linear ones. The extensive use of inulin in the food industry is based on its nutritional and technological properties. For the former not only the dietary fiber properties of inulin are important, such as the positive effect on bowel habit (Tungland & Meyer, 2002), but also the prebiotic properties. The technological use of inulin is based on its properties as a sugar replacer (especially in combination with high-intensity sweeteners), as a fat replacer and texture modifier. When inulin is added to food in low concentrations the rheological properties and the sensory quality of the product will not be affected strongly due to its neutral or slightly sweet taste and its limited effect on viscosity (Kalyani Nair, Kharb, & Thompkinson, 2010). EU directive 2008/100/EC assigns a caloric value of 2 kcal/g (Directive 2008/100/EC, 2008).

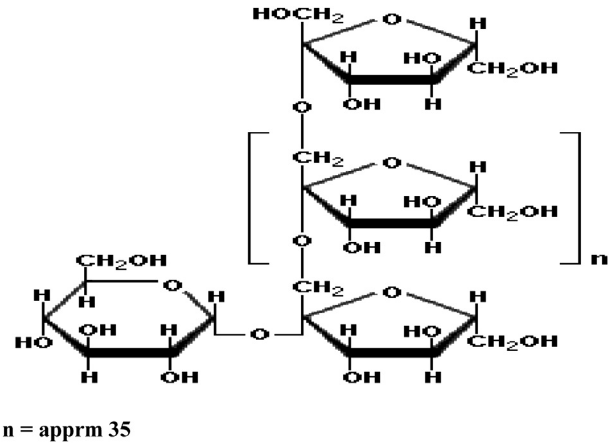


Fig. 2. Chemical structure of inulin.

Oligofructose is composed of shorter chain oligomers and possesses functional qualities similar to sugar or glucose syrups. It is more soluble than sucrose and provides about 30–50% of the sweetness of table sugar. Oligofructose contributes body to dairy products and humectancy to soft baked goods. It acts as a binder in nutritional or granola bars in much the same way as sugar, but with the added benefits of less calories, fiber enrichment and other nutritional properties. Oligofructose is often used in combination with high-intensity sweeteners to replace sugars, providing a well balanced sweetener profile and masking the aftertaste of aspartame or acesulfame-K (Weidmann & Jager, 1997, pp. 51–56).

The differences in chain length between inulin and oligofructose account for their distinctly different functional attributes. Due to its longer chain length, inulin is less soluble than oligofructose. Unlike other fibers, inulin and oligofructose have no “off flavors” and may be used to add fiber without contributing viscosity. These properties allow the formulation of high fiber foods that look and taste like standard food formulations (Niness, 1999). Unfortunately inulin and oligofructose have a propensity to cause bloating and flatulence when consumed in moderate to large quantities (Brown, Grewenig, & Matheson, 2008).

Maltodextrin

Maltodextrin is another low-digestible carbohydrate polymer that has great potential in the development of functional confectionery. Maltodextrins are considered as a glucose polymer joined by a (1→4) linkages, with dextrose equivalent (DE) lower than 20 (Baucal, Dokic, & Jakovljevic, 2004). The chemical structure is shown in Fig. 3. Maltodextrin is made by combining corn starch, heat and acid to create unique bonds between glucose molecules, effectively limiting its digestion. The molecules of maltodextrin are typically large in size and highly branched allowing them to be very soluble.

Maltodextrin is sold as powder only and, like polydextrose, can be hydrogenated. The hydrogenated form results in decreased reactivity as well as increased solubility and heat stability, lending itself to a wide range of

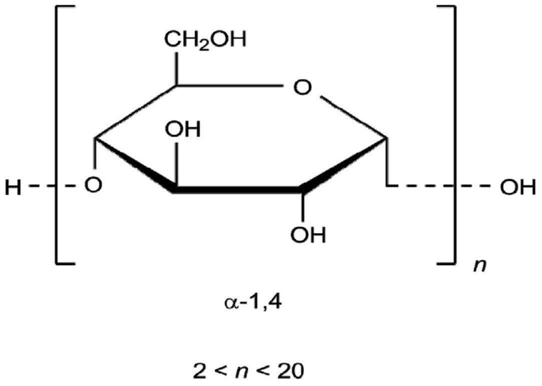


Fig. 3. Chemical structure of maltodextrin.

confectionery applications such as caramels, toffee, soft chews and potentially hard candy. Maltodextrin is very soluble, up to 240 g in 100 g of water, but not as hygroscopic as polydextrose in powder form. It is considered GRAS by the USFDA providing 1.0–1.5 kcal/g. EU directive 2008/100/EC however assigns a caloric value of 2 kcal/g (Directive 2008/100/EC, 2008). Individuals can consume at least 60 g a day over an extended period of time without any significant issues, indicating that maltodextrin can be well tolerated.

Applicability and suitability of different sweeteners and polymers in chocolate processing

Over the past decade, various researchers have investigated the use and applicability of several sweeteners and polysaccharides as bulking agents in the production of sugar-free chocolates (Bolini-Cardello, Da Silva, & Damasio, 1999; Farzanmehr & Abbasi, 2009; Golob, Micovic, Bertoncelj, & Jamnik, 2004; Melo *et al*., 2007; Pallazo *et al*., 2011; Shah *et al*., 2010; Wada, Sugatani, Terada, Ohguchi, & Miwa, 2005). These investigations have led to various degrees of successes and challenges in their application in the modern confectionery industry.

Maltitol has organoleptic and technological properties close to those of sucrose (Portmann & Kilcast, 1996). Its low hygroscopic character gives it the advantage of allowing the refining of chocolates under the same conditions as with sucrose and conching at temperatures up to 80 °C (Olinger, 1994). It has 95% of the sweetness of sucrose, reducing the need for its combination with an intense sweetener, and has been used mainly in the manufacture of sugar-free chocolate, sweet coatings and chewing gum (Sicard & Le Bot, 1994). Isomalt has only 40% of the sweetness of sucrose, so intense sweeteners must be used along with isomalt in chocolates (Wijers & Sträter, 2001). The use of isomalt in chocolate results in a higher viscosity compared to maltitol, sucrose, and xylitol after 18 h conching at 50 °C but in a lower viscosity compared to xylitol when conched at 60 °C. Different conching temperatures for chocolates with different sugar alcohols have therefore been advised (Olinger, 1994). Especially for isomalt, a lower conching temperature is suggested due to its high content of water of crystallization that may result in agglomeration during conching.

Consumers may reject chocolate containing xylitol due to xylitol's intense cooling effect in mouth, although this can be masked by addition of other bulk sweeteners (Olinger, 1994). This cooling effect is however absent in isomalt and maltitol (Kato & Moskowitz, 2001; Wijers & Sträter, 2001). Xylitol has 95% of the sweetness of sucrose and no additional intense sweeteners may be needed (Kato & Moskowitz, 2001).

Erythritol also serves as sugar substitute in confectionery compositions, in particular chocolates. It has a sweet taste and delivers considerably less calories than sucrose but its use suffers from the perception of a cooling effect and/or a burning aftertaste. When erythritol is used as a sugar substitute, the melting of chocolate in the mouth causes an unpleasant feeling of cold. US Pat. No. 6,875,460 tries to reduce the cooling effect of erythritol by adding hydrogenated maltodextrin. However, the observed effect is considered as a dilution effect. Other inventions have tried eliminating this cooling effect by using fibers (preferably dietary fibers and in particular, water-soluble dietary fibers) and/or sugar esters. Brown *et al*. (2008) stated that erythritol is commonly combined with inulin and fructo oligosaccharide (FOS) which offer a complementary positive heat of solution. Therefore, there is a continued need to identify and provide agents, by means of which the cooling effect of polyols can be reduced or eliminated.

The time–intensity method has become a useful tool in the comparison of the perception of sucrose sweetness over time with that of other sweeteners. Melo *et al*. (2007) applied the time–intensity analysis in the sweetness perception of diabetic milk chocolates. They concluded that chocolates sweetened with sucrose and sucralose presented similar results with regard to sweetness profile. This was, however, not the case for chocolates sweetened with stevioside (Melo *et al*., 2007). Palazzo *et al*. (2011) determined isosweetness concentrations of sucralose, rebaudioside and neotame as sucrose substitutes in new diet chocolate formulations using the time–intensity method. Sucrose was replaced by polydextrose and erythritol as bulking agents together with the above mentioned sweeteners. Sucralose presented the best result as compared with the traditional sample containing sucrose. The sweetness of rebaudioside decreased with increase in concentration. Neotame as a sweetener presented less satisfactory replacement in milk chocolates. The authors therefore stressed the importance of studying each sweetener in foods they could be used because their sweetness potencies depend on the dispersion matrices in which they are found.

Processing conditions have been known to have great effect on sugar substituted chocolates. Zumbe (1992) mentioned that, in view of the use of polydextrose as bulking agents in sugar-free chocolates, the temperature during conching should be kept below that at which the water of crystallization inherently present in these ingredients is released. This avoids any undesirable increase in viscosity or agglomeration of the mixture. Some sugar-free chocolates use inulin with other bulk sweeteners such as erythritol and isomalt resulting in products of good eating quality and well tolerated by consumers. Golob *et al.* (2004) studied the influence of inulin and fructose on the sensory characteristics of chocolate and found that sucrose replacement with inulin in milk chocolate formulation did not result in perceived sensory differences compared to the control by a consumer panel. The most common functional benefits of inulin in chocolate include modulation of the cooling effect during melting in the mouth and improvement of the chocolate flavor. A major obstacle to the use of inulin as bulking agent however is the presence of various amounts of glucose and fructose, which is naturally contained therein making it difficult to dry, handle and store. When such inulin products are manipulated in the mouth, a sticky, hard substance is formed caused by the insolubility at body temperature in the saliva (Berghofer, 1993).

Rheologically, chocolate properties are mainly influenced by particle size distribution and ingredients composition. Viscosity of suspensions can be greatly modified by changing particle size distribution (PSD) while maintaining the same solid content. Sokmen and Gunes (2006) investigated the influence of bulk sweeteners on rheological properties of chocolate. Sucrose was totally replaced with maltitol, isomalt or xylitol of different particle size intervals (PSI) of 38–20, 53–38 and 106–53 μm. The chocolate samples were conched at 65 °C for 3 h in a paraffin bath and all rheological properties of the chocolate samples were measured using a shear-controlled rheometer with a concentric cylinder system. The Herschel–Bulkley model fitted the data (viscosity, yield stress, flow behavior index) more appropriately although Casson model is widely used and recommended by IOCCC to describe flow behavior of chocolate. Chocolates made with xylitol and maltitol resulted in similar plastic viscosity as the reference chocolate made with sucrose. The plastic viscosity of chocolate with isomalt was significantly higher and the difference was more apparent at lower particle sizes. Sokmen and Gunes (2006) associated this with isomalt's higher solid volume fraction in chocolate because the density of isomalt was 1.50 g/cm^3, slightly lower than the other sugar alcohols, 1.63 and 1.52 g/cm^3 for maltitol and xylitol, respectively. This implies that chocolate with isomalt had more solids and a larger surface area since all sweeteners were added to the chocolate mix on a weight basis. The higher plastic viscosity caused by isomalt may also be associated with its other physical properties such as specific surface area, crystallinity and hygroscopicity that were not evaluated in their study.

Yield stress of chocolate with maltitol was significantly higher than chocolate with isomalt. The authors associated this with maltitols PSD which contained higher amounts of smaller particles out of range than the other sucrose substitutes. The yield stress also decreased significantly with increase in particle size with interactions between PSI and bulk sweetener type being significant ($P = 0.001$).

The average flow behavior index (n) was 1.003, 1.001 and 1.033 for maltitol, isomalt and xylitol, respectively. A flow behavior index greater than 1 indicates slight shear thickening behavior above the yield stresses. Overall, chocolates with xylitol had a higher flow index. The flow behavior index also increased with decrease in particle size. The results of the apparent viscosity were in agreement with that of the plastic viscosity with isomalt chocolate recording higher value than sucrose and maltitol chocolates. The effect of bulk sweeteners on apparent viscosity was more apparent with finer particles. As particle sizes decreased, the apparent viscosity increased substantially. The authors concluded that large particle sizes result in better rheological properties for manufacturing processes but may adversely affect sensory properties. A better control of PSD of bulk sweeteners, chocolate mix and conching conditions is therefore needful to determine the effects of bulk sweeteners on physical and sensory properties. Consequently, addition of bulk sweeteners on volumetric basis may reflect their effect on rheological properties more accurately.

Farzanmehr and Abbasi (2009) evaluated the effects of sugar substitutes on rheological characteristics of prebiotic milk chocolate formulations. Sucrose was replaced with different levels (0–100%) of inulin, polydextrose, and maltodextrin as bulking agents. The Casson model showed the best fitting for predicting rheological properties and all chocolates showed thixotropic and shear thinning behaviors. Chocolate formulations containing high levels of sugar substitutes had higher moisture content, Casson viscosity and yield stress than the control sample made with sucrose. In contrast, the lowest moisture content, Casson viscosity and yield stress, were observed for chocolates with moderate amounts of sugar substitutes. In the physical analyses, formulations with high ratios of polydextrose and maltodextrin were more moist and softer than the control. Lowest moisture content and highest hardness were observed when moderate ratios of polydextrose and maltodextrin were used. Farzanmehr and Abbasi (2009) attributed this to the higher hygroscopicity of maltodextrin and polydextrose. In contrast, inulin due to its low hygroscopicity did only influence the moisture content at very high levels. Chocolate formulation with ratios of 50:25:25% for inulin, polydextrose and maltodextrin, respectively, was the hardest chocolate. Hardness of chocolates formulated with 100% inulin was similar to the control sample. In the sensory analysis, chocolate formulations with high ratios of maltodextrin were very sticky and, after consumption, created a short thin-layer film on the surface of the tongue and mouth hole. This probably accounted for the low melting rate, mouth coating and overall acceptability scores recorded for formulations with high ratios of maltodextrin. Melting rate score however increased with increasing inulin and polydextrose contents and reached its highest values at the highest levels of inulin and polydextrose. Similar trends were observed regarding mouth coating and overall acceptability (Farzanmehr & Abbasi, 2009). The authors concluded that, the type and ratio of sugar substitutes induced various effects on physicochemical, textural and sensory properties of low-calorie milk chocolate. Higher inulin and polydextrose and lower proportions of maltodextrin greatly improved sensory attributes of the milk chocolates. Inulin, polydextrose and maltodextrin concentrations of 14–32% and 71–84%, 7–26% and 67–77%, and 0–20% respectively, were stated as the optimum applicable range for the sugar substitutes. This indicates that inulin and polydextrose can be used in various ratios and owing to their noticeable effects can improve chocolate properties even at very low ratios, whereas maltodextrin should only be added at low ratios (<20%) (Farzanmehr & Abbasi, 2009).

Shah *et al.* (2010) replaced sucrose with inulin (HP, HPX and GR) with different degrees of polymerization and polydextrose as bulking agents together with the intense sweetener stevia in the development of sugar-free chocolates. Inulin HP (average DP $\geq$ 23, long chain inulin), inulin HPX (average DP $\geq$ 23, long chain inulin with low solubility) and inulin GR (average DP $\geq$ 10) were used. Replacement of sucrose by the above ingredients resulted in darker chocolates. Shah *et al.* (2010) attributed the differences in color (L* values) to changes in surface properties, mainly roughness, of chocolate caused by the sugar substitutes since processing conditions were the same for all samples. Smoother surfaces always provide for lighter colors of chocolate products (Briones, Aguilera, & Brown, 2006). The melting point temperature of all chocolate samples ranged from 30.8 °C to 32.6 °C with the control sample and milk chocolates with inulin HP having significantly higher melting temperature compared to the other samples. The authors gave two explanations to the differences in melting temperature. Firstly, the fat in chocolates made with sucrose and inulin HP are in the form of V B_2 triple chained crystals, the most stable form of cocoa butter, produced in a well tempered chocolate. The second possibility is the effect of inulin and its average degree of polymerization. Increase in melting point with increasing average degree of polymerization of inulin has been reported by Blecker *et al.* (2003). Hébette, Delcour, and Koch (1998) also suggested the occurrence of two crystal populations differentiated by crystalline thicknesses, and with thicker crystals having a higher melting point, as the reason for complex melting behavior of inulin. Replacement of sucrose by stevia as a sweetening agent and inulin and polydextrose as bulking agents had no substantial effect on chocolate hardness except for chocolates made with inulin HPX which was less hard than the other samples. Several factors including composition, manufacturing conditions and tempering and consequently fat crystal polymorphism would influence the final hardness of chocolate (Afoakwa, 2010; Beckett, 2008). Shah *et al.* (2010) explained the hardness behavior of inulin HPX as likely to be the result of poor tempering since the authors later found that chocolates made with inulin HPX had a melting point of 30.8 °C. Hardness is a useful indicator of good tempering or the degree to which a fat crystal network has been formed. The authors therefore recommended the modification of the standard operating tempering procedure for inulin HPX since all samples were tempered using the same procedure. In the rheological analysis, the Herschel–Bulkley model showed the best fitting for predicting rheological properties. Chocolates with inulin HPX and HP exhibited higher plastic viscosity than the control. The plastic viscosity of chocolate with inulin GR was however lower than the control. The plastic viscosity thus increased with increase in degree of polymerization of inulin. The authors associated the higher plastic viscosity of chocolates made with inulin HPX and HP to their higher solid volume fraction in chocolate because the density of inulin HPX (470 g L^{-1}) and HP (490 g L^{-1}) was slightly lower than that of inulin GR (580 g L^{-1}). The yield stress of chocolate with inulin HPX was slightly higher than the control whiles the other samples were slightly lower.

Flow behavior is very important in determining the stability of chocolate products. Overall, sucrose replacement with inulin HPX or HP resulted in a higher flow behavior index than the others. This could be due to the fact that the consistency coefficient of chocolate with inulin HPX and inulin HP decreased slightly as the shearing time increased and as a result, flow behavior index increased. Another possibility is that, presence of more crystals in the chocolate with inulin HPX and inulin HP could have caused difficulty in crystal alignment during the chocolate manufacturing process resulting in a slight increase in flow behavior index (Briggs & Wang, 2004).

The viscoelastic behavior of chocolate is directly related to cooling rate of chocolate as fat in chocolate solidifies in a specific way. Replacement of sucrose with stevia as a sweetening agent and inulin and polydextrose as bulking agents had no major impact on elastic behavior of chocolate mixes during the initial stages of tempering. More evident effects were observed during the second cooling stage below 20 °C and were apparently affected by degree of polymerization of inulin. Addition of inulins with lower degree of polymerization resulted in lower elasticity of solidified chocolate whereas inulin HP had similar elastic behavior in comparison to that of the control. Due to the effect of temperature on inulin solubility, the lower viscoelasticity observed in the samples may be due to interference of more soluble (short chain) inulins with fat crystallization. In the sensory analysis with untrained consumer panel, panelists preferred the control chocolate over the sucrose-free types but their next preference was chocolate containing inulin with the highest DP. Sucrose replacement with inulin significantly lowered the smoothness acceptability and mouthfeel. Flavor/taste acceptability decreased with decrease in inulin DP. Shah *et al.* (2010), as part of their conclusions, recommended inulin HP (high DP) as suitable for sucrose-free chocolate formulations since chocolate with inulin HP in combination with stevia and polydextrose resulted in very similar physicochemical and sensory characteristics in comparison to sucrose sweetened milk chocolate. Inulin addition to sucrose-free chocolate formulations had no major effects on particle size, melting point and composition. Inulin HPX and GR, due to their shorter chain length in comparison with inulin HP, did not result in the same physicochemical, rheological and sensory properties as inulin HP.

Conclusion

Development of high-quality sugar-free chocolate requires the use of the most appropriate ingredients that could completely replace sugar without negatively affecting the rheological, physical and sensory properties. In chocolate, sugar is not only added to promote sweetness but, as well, it exerts many functional properties that make it useful as a bulking agent, texture modifier, mouthfeel modifier, flavor enhancer and preservative. Sucrose substitution by high-intensity sweeteners such as saccharin, acesulfame-K, sucralose, stevioside, thaumatin, and sugar alcohols as well as bulking agents such as polydextrose, maltodextrin and inulin has great potential for the successful manufacture of sugar-free chocolate products with the desirable quality – appearance, texture, taste and flavor, very similar to that of their sugar counterparts. Extensive knowledge on the characteristics of the major types of intense and bulk sweeteners has been reviewed. Understanding these factors would lead to the development of sugar-free chocolates that meets the pre-informed quality characteristics and healthy products expected by the global consuming populace.

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