Opportunities and challenges for sugar replacement in chocolate: A review

by

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Executive Summary

This review explores the current landscape of sugar reduction in chocolate, focusing on the challenges and opportunities presented by various sweetener alternatives. Sucrose, which comprises nearly half of a chocolate's composition, plays a multifaceted role as a sweetener, bulking agent, and modulator of mouthfeel and rheology. Traditional sugar substitutes such as polyols (maltitol, xylitol, isomalt, sorbitol) and fibers (inulin, polydextrose, maltodextrin) are widely used, often in combination with high-intensity sweeteners to mimic the physical and sensory properties of sucrose. While polyols and fibers can partially replicate the functionality of sucrose, their use is generally limited by digestive discomfort and the need for complex ingredient blends. Recent research has explored novel alternatives including rare sugars such as tagatose and allulose, palm and coconut sugars, mulberry molasses microcapsules, red beetroot powder, and date powder, each offering unique benefits and challenges in terms of rheology, microstructure, and consumer acceptability.

Studies consistently show that no single substitute can fully match all the sensory and physical attributes of traditional sucrose-sweetened chocolate. Optimal results are achieved through meticulously crafted blends of bulk sweeteners and high-intensity sweeteners, with ingredient selection influenced by chocolate type (white, milk, or dark) and desired consumer target. Sensory evaluations highlight the importance of balancing sweetness, texture, and flavor, while instrumental analyses reveal significant impacts on viscosity, hardness, and fat and sugar crystallization. This review concludes that further research is needed to identify novel ingredient combinations that more closely replicate the properties of sucrose, minimize gastrointestinal impact, and meet consumer expectations for taste and health-consciousness in reduced-sugar chocolate products.

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Introduction

Consumers are becoming increasingly aware of the detrimental health effects associated with sugar overconsumption and are therefore driving sugar reduction trends in snacks and confections. Excessive sugar intake is associated with conditions such as obesity, diabetes, and dental caries, but overconsumption of typical sugar alcohols and fibers may also be perceived negatively by consumers due to undesirable laxative effects. Witkowski et al. (2023) recently claimed that consumption of erythritol, a commonly used sugar alcohol, may pose an elevated risk of cardiovascular events. Mazi and Stanhope (2023), however, quickly argued that additional research is necessary to support these claims. Nonetheless, the industry is tasked with identifying consumer label-friendly alternative sweeteners whose consumption is not associated with gastrointestinal discomfort or other physiological side effects and also possess properties similar enough to sucrose to enable production of sensorially acceptable, reduced sugar foods.

Sugar reduction in chocolate is especially challenging. At nearly fifty percent of a chocolate's composition, sucrose not only serves as the sweetening agent but also as a bulking agent, mouthfeel modulator, and primary contributor to chocolate's rheological properties. Sugar reduction in chocolate has historically been achieved using ingredients such as sugar alcohols and fibers, which typically need to be used in conjunction with high-intensity sweeteners in order to mimic the sweetness of a sucrose-sweetened chocolate. More recently, additional efforts have been made with alternatively-sourced sugars such as palm and coconut, or rare sugars such as tagatose. In other food matrices, researchers have even explored strategies such as aroma-induced sweetening, which aims at modulating sweetness perception through olfactory sensations (Zhao et al., 2024). Many techniques could be employed in chocolate sugar reduction efforts, but few result in confections which match all the physical and sensory characteristics of a full sugar chocolate.

This review aims to compare current widely used bulk sugar substitutes in chocolate matrices and their effects on key attributes such as rheology (as an indicator of production suitability), microstructure, and sensory characteristics (consumer acceptability). Though additional ingredients such as high-intensity sweeteners are heavily used in this field of research, as they do not contribute bulk and factor into two of the main attributes of this review – rheology and microstructure – they will not be addressed independently, and will instead be referenced only as they appear within the other bulk sweetener studies. Through this review, it will become evident that novel sugar substitutes may be more adequate replacements for sugar in chocolate, but further research is needed to confirm their suitability in the chocolate matrix for processing and sensory considerations. The discovery of such substitutes will enable production of great tasting, guilt-free, low-sugar or sugar-free chocolate alternatives.

Types of Chocolate

In the United States, certain foods must meet a specific *Statement of Identity* (SOI) to be labeled in a particular manner. SOIs were first introduced in 1939 for products such as milk, ketchup, and peanut butter and are intended to serve as a way of preventing economic adulteration of foods (US Food and Drug Administration, 2025). These statements of identity typically outline methods in which a food must be processed, a prescribed composition of the food, or a combination of the two. For chocolate in particular, there are SOIs for milk, sweet, and white. Milk chocolate must contain at least 10% chocolate liquor, 12% milk solids, and 3.39% milk fat (Milk Chocolate, 21 CFR§163.130, 2025). Further, chocolate liquor has an SOI describing it as a solid or semiplastic food prepared from ground cacao nibs which requires no less than 50% and no more than 60% cacao fat (Chocolate Liquor, 21 CFR§163.111, 2025). Sweet chocolate must contain at least 15% chocolate liquor and less than 12% milk solids and can be further classified as "semisweet" or "bittersweet" chocolate given that it contains at least 35% chocolate liquor and meets all other requirements (Sweet Chocolate, 21 CFR§163.123, 2025). This designation is more typically seen in the baking chip category rather than ready-to-eat tablet bars, which are more commonly referred to as *dark* chocolates when they consist of a higher proportion of cacao-based ingredients, though no specific standard of identity is set forth by the FDA for this labeling designation. Finally, white chocolates must contain at least 14% total milk solids, 3.5% milkfat, 20% cocoa butter, and no more than 55% nutritive carbohydrate sweeteners (Sweet Chocolate, 21 CFR§163.123, 2025). Chocolates may also contain emulsifiers such as soy or sunflower lecithin and polyglycerol polyricinoleate, salt, or spices as stated in their SOIs. When chocolates do not meet any of the prescribed statements of identity, manufacturers typically add labeling terms such as “chocolatey” or “compound” to signal their likeness to the reference product but nonconformance to the standard.

These labeling terms are often referenced in the literature but are not always indicative of the study material meeting the standard of identity requirements for commercial sale, nor should it be assumed that an SOI or non-SOI chocolate is inherently more well-liked by consumers than the other. Historically, one could assume that the SOI designation made chocolates more appealing as they signaled quality and familiarity to the consumer. However, as today’s market has heavily involved even since the introduction of the latest chocolate definition – white chocolate – in 2002, and now includes a large variety of products ranging from traditional SOI chocolates, to sugar-reduced chocolates, to functional or single-origin chocolates and more, it’s likely that updated research may be required to understand the impact of this labeling designation on consumer appeal.

In this review, “milk” and “white” chocolate will be used as chocolate designations but do not necessarily imply that the studied formulations perfectly comply with the formal standards; rather, they will be used to identify the reference formulations which the studies aim to emulate. Likewise, “dark” will be used to identify formulations lacking a milk component and otherwise aligning with typical “dark” chocolates seen in the marketplace. In fact, typical sugar-free formulations do not meet any SOI criteria at all as they contain ingredients not listed in the CFR and may not be marketed in the same manner as their full-sugar counterparts. Nevertheless, this body of research is critical to understanding how different sugar replacement options impact different chocolate matrices and are or may someday be used by chocolate manufacturers to create healthier alternatives to typical chocolate offerings.

Chocolate Quality Parameters

Chocolate quality can be described in a myriad of ways but is typically tied back to a chocolate's appearance, flavor, texture, microstructure, and flow behavior. Initial perception is often based on aroma, color, and gloss. Aroma and color are impacted by the ingredients and processing while the gloss is directly related to the quality of the chocolate temper. Temper relates to the proper crystallization and polymorphic form of cocoa fat, and it is the crystallization of this fat during controlled cooling and re-heating steps prior to moulding that gives chocolate its characteristic bite, snap, and shiny appearance. The flavors associated with cocoa and chocolate liquor are largely determined by processing of cocoa including post-harvest fermentation and drying, roasting, and conching, but are also influenced by the growing regions from which the beans originated (Ziegleder, 2017). When combined with the other ingredients in chocolate, the overall product flavor is influenced by ingredient selection and processing. Beckett (2008) details how the particle size distribution, viscosity, and hardness of chocolate influence the perceived taste. Likewise, the quality and flavors associated with other ingredients in the matrix such as milk powder or sweetener, the ratios of combined ingredients, processing method, and age of the chocolate all factor into its resulting taste. These flavor characteristics are just one piece of the chocolate quality puzzle.

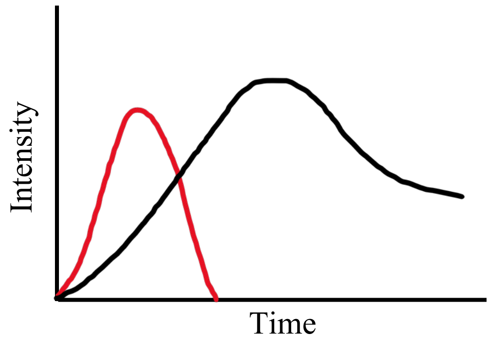
The texture and microstructure of chocolate are also tied heavily to ingredient selection and processing. Chocolate itself is a dispersion of solid particles in fat, which depends on the types and ratios of fats present and the network of sugar that is created upon production. In a study by Glicerina et al. (2016), it was demonstrated that chocolate formulation is highly impactful to microstructure and rheology. In white chocolate samples, which contained the highest amount of fat, the authors observed the smallest particles, a less dense crystalline network, and reduced particle-particle interactions. Dark chocolate samples conversely had the highest amount of aggregation and least amount of void space between particles. Milk chocolate, by formulation being an intermediate of the two, exhibited an intermediary microstructure. The more aggregated structure of the milk compared to the white was also attributed to the lack of emulsifier, which typically coats sugar particles and promotes their dispersion. It was clear that the interaction of the ingredients and the proper suspension of particles were highly impactful to the structural properties, illustrating how different the types of chocolates and even formulations within a single chocolate type could be.

The viscosity or flow behavior of chocolate dictates not only mouthfeel and flavor release, but also processability and potential usage (moulding, enrobing). It is impacted by factors such as fat content, particle size distribution, presence (or absence) of emulsifiers, conching efficiency, and moisture content. Chocolate viscosity is complex due to its Non-Newtonian nature, meaning that its viscosity is dependent upon the rate of shear (Beckett, 2017). Single point measurements therefore do not paint the entire picture of a chocolate's behavior. Rather, it is necessary to measure chocolate viscosity at shear rates similar to those it will experience during production. For example, the shear experienced during depositing into a mould is fast while that experienced while a coating chocolate flows off a wafer is much slower (Beckett, 2017). For chocolate, the internationally accepted and often cited method of measuring chocolate viscosity is ICA Method 46 or a modification thereof. This method involves measurement at 40°C using a rotational rheometer with coaxial cylinder geometry wherein the sample is pre-sheared at 5 s^{-1} to stabilize viscosity and temperature, then sheared in an increasing ramp from 2-50 s^{-1}, held at 50 s^{-1}, then sheared in a decreasing ramp from 50-2 s^{-1}. Hysteresis, related to the ability of the sample to regain its original structure after shear, can then be determined by differences in the up and down shear ramps. By using standard methodology, chocolates can be compared across formulations, processing methods, and researchers. Mathematical models can then be applied to calculate parameters such as plastic viscosity and yield stress, which are important attributes for the chocolate industry. Models include Herschel-Bulkley, Windhab, Casson, and NCA/CMA Casson, though the Casson model is widely used for chocolate rheology. There are limitations, of course, such as how different rheometers measure and calculate rheological attributes, the impact of pre-conditioning on sample types, and the suspension and size of particles in the matrix, but using the standard methodology is a reasonable way to understand basic differences among chocolates.

Challenges in Chocolate Quality Related to Sugar Substitution

The chocolate industry is faced with many challenges when it comes to the substitution of sugar in the chocolate matrix. Using sugars that are already finely ground typically do not meet sensory expectations due to the lack of amorphous sugar, which is created during refining. Amorphous surfaces absorb flavor components and play a significant role in the distinctive taste of the finished chocolate (Kruger, 2017). Thus, the incoming particle size of any sweetener and its tendency (or not) to amorphize during chocolate manufacture will influence overall sensory qualities. The shape of the crystals further impacts the sensory characteristics and whether particles may easily flow past one another or tend to aggregate. Likewise, sweetness perception is important to the overall sensory character of a chocolate. The overall intensity and sweetness duration are critical when choosing a sweetener other than sucrose. Often, the degree of sweetness of a sugar is compared to sucrose, which is regarded as the gold standard or a sweetness equivalency of 100% (Kruger, 2017). However, despite the initial intensity of sweetness, the temporal effects of different sweeteners tend to differ and result in different sweetening characters. This is especially true in the case of high-intensity sweeteners, which may have a different onset, peak, and duration than typical table sugar and are often used in sugar-free formulations to provide additional sweetening to less sweet bulking ingredients (Figure 1).

Figure 1. Sugar sweetness temporality (in red) compared to an example of a high-intensity sweetener.



One must also consider sweetener synergies, cooling effects, lingering aftertastes, and how the other ingredients in the matrix such as fat may influence the sweetness delivery in the final product. Sweetener solubility and melting point will influence its tendency to agglomerate at the high temperatures of conching, and this agglomeration could lead to higher rheological values and unsuitability for chocolate processing. Further, if the chocolate could be processed despite the rheological differences, these differences could present themselves in different sensory qualities as flavor delivery relies heavily on the dispersion and movement of the particles in the fat matrix. As evidenced in the work by Glicerina et al. (2016), any differences in the way the sugar replacer breaks down during processing, crystallizes, or packs together can also influence the ultimate quality of a chocolate. It is critical that these factors are taken into consideration when investigating novel sugar replacement options and that physicochemical and sensory qualities are given appropriate attention to assess the sweetener system's suitability for use.

Sugar Alcohols

Background

Sugar alcohols, or polyols, are commonly used sugar substitutes with a wide range of sweetness intensities, cooling sensations, and other physical properties (Kearsley & Deis, 2006). They are especially attractive to food manufacturers due to their chemical similarities to sucrose and are attractive to consumers due to their low caloric value, noncariogenicity, and low glycemic response. A few common polyols used in chocolates are **maltitol, xylitol, isomalt,** and **sorbitol**. Maltitol is roughly 90% as sweet as sucrose and has a similar heat of solution, so there is no noticeable cooling effect in the mouth (Kearsley & Deis, 2006). Isomalt also has a low cooling effect, but its sweetness is less than half that of sucrose. Xylitol has nearly the same sweetness as sucrose, but it has a higher heat of solution and thus a noticeable cooling. Cooling effects may be moderated through the addition of other ingredients, but this adds complexity for both the manufacturer during production and the consumer during label interpretation. For the chocolate manufacturer, maltitol closely mimics many of the properties of sucrose that affect its processing suitability such as molecular weight, solubility, melting point, and hygroscopicity (Kearsley & Deis, 2006). As the alcoholic form of glucose, sorbitol is a chemically similar molecule naturally found in fruits and vegetables (Loghmani et al., 2022). It provides roughly 60% the sweetness of sucrose and therefore must be used in combination with other sweeteners to meet the expected sweetness profile with the same amount of bulk. To overcome the disadvantages associated with the use of a single polyol, other polyols or bulking agents such as polydextrose and inulin are often used in combination. While a one-for-one ingredient replacement is more straightforward for the manufacturer and results in a simpler label for the consumer, there is not a single polyol that completely mimics the properties of sucrose.

One of the main disadvantages to using polyols is their low digestibility. While this is beneficial from a caloric standpoint, overconsumption of polyols can lead to digestive discomfort (Kearsley & Deis, 2006). All polyols are about half as caloric as sucrose, though some countries have different caloric values assigned to individual polyols for nutritional labeling purposes. The EU, for example, has a base value of 2.4 kcal/g for most polyols. The United States, on the other hand, has assigned values for the various polyols which range from 0.2 kcal/g (erythritol) to 3.6 kcal/g (maltitol and polyglycitol). These values relate back to their digestive breakdown, which in turn relates to their potential to cause laxation if consumed in excess. In general, when the molecular weight of the polyol is higher, the laxative effect is lessened (Kearsley & Deis, 2006). However, individual tolerances are highly influenced by factors that include age, gender, health, and diet. Low digestibility and varying consumer tolerances therefore limit polyols' overall use in foods.

Dark Chocolate

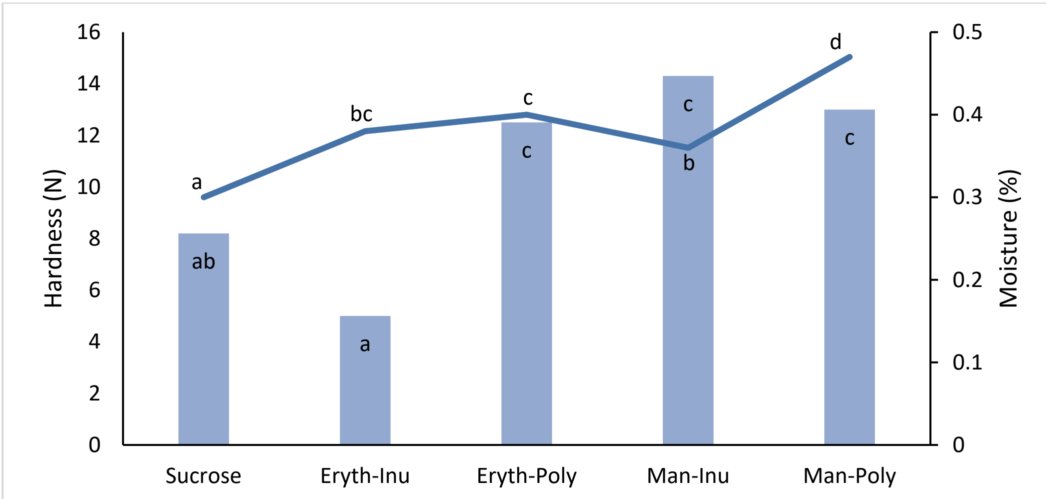
Pirouzian et al. (2025) investigated the optimal formulation of sugar-free dark chocolate using a mixture design incorporating **maltitol**, **lactitol**, and **xylitol** as sucrose substitutes based on their physical attributes. Xylitol exhibited greater hygroscopic behavior than the other polyols and sucrose, evidenced by its higher moisture content when used in increasing amounts. As moisture is critical to the rheology and hardness of chocolate, this finding was in agreement with the results of the other physical analyses. Mean particle size was greatest for high xylitol-containing samples while the 100% lactitol sample was closest to the control. This was attributed to high solubility and intermolecular bonding between active hydroxyl groups causing gritty agglomerates. Conversely, for the maltitol and lactitol samples, the authors indicated that there were fewer intermolecular interactions and more intramolecular interactions due to the positions of the sweeteners' hydroxyl groups and this allowed the particle sizes to remain smaller.

Casson plastic viscosity was highest for high xylitol-containing samples and lowest for high lactitol-containing samples, though the authors note that all viscosity values recorded were within acceptable limits for dark chocolate. An inverse relationship was described for the yield values, but the higher value seen in the 100% lactitol-containing sample was closest to that of the sucrose control. The authors note that the smaller particle sizes lead to increased specific surface area and increased interaction between the particles and the continuous fat phase, leading to increased yield stress. Lastly, the hardness values were greatest for the lactitol samples, then maltitol, then xylitol due to their differences in moisture content, particle size, and density. The authors ultimately concluded that the ideal proportions were 29.49%, 51.46%, and 19.05%, respectively, for the given physical attributes studied. Further investigation could explore whether these optimal physical traits are matched with similar sensory qualities or if further optimization would be required for a commercially acceptable sugar free dark chocolate.

Wong et al. (2024) investigated the use of **erythritol**, **mannitol**, or tagatose in combination with inulin or polydextrose and found that hygroscopicity, crystal shape, and particle size significantly impacted the rheology and texture of sugar-free dark compound chocolates but did not alter fat crystallization or melting characteristics. Rheology was measured with concentric cylinder geometry using the ICA 46 method, with data then fitted to the Casson model. Sucrose-free samples had significantly higher plastic viscosity and yield values than the sucrose control, likely due to the differences in particle size distributions. Further, the authors found that the erythritol and tagatose containing samples had more thixotropic behavior which could be due to higher moisture contents and particle agglomeration. On the other hand, the mannitol sample exhibited much lower thixotropy which the authors attributed to its elongated crystal shape which could reduce agglomeration. In DSC analysis, all samples exhibited two melting peaks, indicative of multiple fat crystal types, and similar crystal stability. No significant differences were found in the high temperature melting peaks, but within the low temperature peaks, the sucrose control showed the highest temperature onset and melting enthalpy compared to the sugar-free samples. The authors suspected that this could be due to the larger particle size changing the fatty acid distribution within the matrix as the components could be more mobile, affecting the crystallization of the chocolate. Likewise, X-ray diffraction analysis revealed an additional polymorph in the sucrose sample only, which the authors believe is the result of a eutectic effect between the fats used – HPKO and cocoa butter. They suspect this was not the case for the sucrose-free samples due to their higher solid packing intensity and reduced movement of fat.

Polydextrose-containing samples had higher moisture content than the inulin-containing samples with the same sweetener. This was due to the higher hygroscopicity of polydextrose than inulin, which was in agreement with other cited studies. Overall, there was a minimal difference in moisture between the sucrose and sucrose-free samples. Sucrose-free samples had significantly smaller particle size and increased specific surface area with a narrower size distribution than the sucrose sample, though the authors attributed this more to the milling process than other factors. This, in combination with higher moisture values, led to higher hardness values due to higher solid packing intensity and particle-particle interactions (Figure 2).

Figure 2. Moisture and hardness values of sugar alcohol-containing dark chocolates, adapted from Wong et al. (2024).



Erythritol-polydextrose mixtures resulted in similar Casson yield to the sucrose control and exhibited a non-elongated crystal shape and therefore could be a potential sucrose replacement option for dark compound chocolate. Samples with mannitol had the highest rheology, attributed to high moisture content, small particle size, and elongated crystal shape. Due to these factors, the authors deemed it likely unsuitable for sucrose replacement in dark compound chocolate. Further research could explore the sensory implications of this sucrose replacement mixture or the impact of different fat systems on rheology and texture.

Milk Chocolate

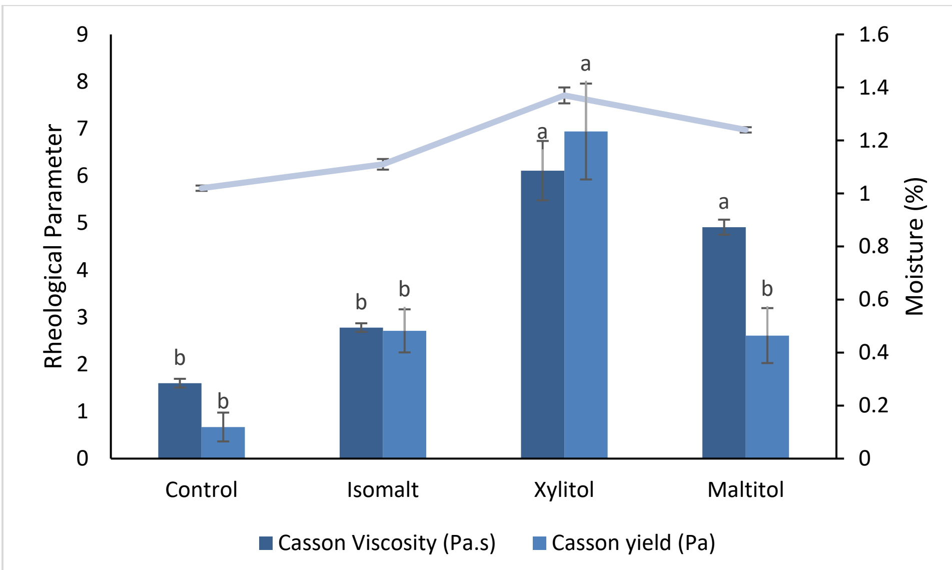
Pirouzian (2022) investigated the use of **xylitol** and **maltitol** as sugar substitutes in milk chocolate and determined that the optimal blend for the most desirable chocolate rheology and sensory characteristics is 85.58% maltitol and 14.42% xylitol. In this study, high ratios of maltitol were preferred over xylitol in terms of rheological and sensorial impact. Chocolates with high maltitol had lower Casson viscosity values as well as increased Casson yield values, both of which were closer to the sucrose control (Table 1). The authors attributed these qualities to the low moisture content of the chocolates and high molecular mass of maltitol, respectively, in addition to a lower mean particle size than the high xylitol chocolates (Table 1). These rheological similarities correlated to optimal mouthfeel during sensory analysis. Similarly, high ratios of maltitol resulted in chocolates with similar texture as the full-sugar control and were preferred over high xylitol formulations in terms of aroma, odor, and taste. The author found no significant differences in appearance, texture, and melting among the chocolates but found a directional preference for the maltitol-containing chocolates. The results as a whole suggest that a blend rather than a single polyol will provide the best physical and sensory characteristics for a milk chocolate.

Table 1. Physicochemical properties of chocolates by increasing xylitol content, adapted from Pirouzian et al. (2022).

Maltitol	**Xylitol**	**Moisture (%)**	**Particle Size (μm)**	**Casson viscosity (Pa.s)**	**Casson yield (Pa)**	**Hardness (N)**
100%	0%	0.88	27.7	1.62	4.136	6.75
75%	25%	0.98	29.7	2.014	3.367	6.08
50%	50%	1.05	31.5	2.326	2.724	5.50
25%	75%	1.09	33.5	2.537	2.216	5.07
0%	100%	1.17	35.5	2.646	1.837	4.81
Control		0.92	27.3	1.718	3.823	6.43

Homayouni Rad et al. (2019) found similar rheological effects of polyols to what Pirouzian (2022) found in their study of **maltitol**, **xylitol**, and **isomalt** in sugar-free milk chocolates. Casson viscosities of the isomalt chocolates were similar to those of the sucrose control while xylitol chocolates exhibited the highest viscosities. The yield stresses of the isomalt and maltitol chocolates were not statistically different from the control, but the yield stress of the xylitol chocolate was significantly higher. The authors suspected that the high hygroscopicity of xylitol paired with the ineffective moisture removal of the ball mill production process caused the higher rheological values in the xylitol-containing chocolates (Figure 3), but they proposed that these properties could be fixed with the appropriate emulsifiers. Scanning electron microscopy revealed particle agglomeration, which supports the authors' theory, along with comparatively large, sharp-edged crystals in the sucrose chocolate along with more interaction between particles in the sucrose-free chocolates.

Figure 3. Rheological and moisture values of sugar alcohol-containing milk chocolates, adapted from Homayouni Rad et al. (2019).



Unlike the previous study, Homayouni Rad et al. (2019) found that xylitol improved overall sensory acceptability in sucrose-free milk chocolate more isomalt or maltitol did. The xylitol chocolate scored the best in all sensory parameters studied (appearance, aroma, taste, structure/firmness, melting rate, and overall acceptability) while isomalt scored the lowest in taste and overall acceptability. All of the sucrose-free chocolates were harder than the sucrose-sweetened chocolate, but the xylitol chocolates were found to be the most similar to the control while the maltitol chocolates were the hardest. The taste of the xylitol sample was also deemed most similar to the sucrose control due to its high sweetness. This sample also exhibited high cooling, which led the researchers to claim that using a sweetener like xylitol, which exhibits a cooling effect, could increase sweetness attributes through ingredient synergies. It is important to note that the maltitol and isomalt samples in this study contained stevia, a high-intensity sweetener, to compensate for their lower sweetness compared to xylitol and sucrose, while no high-intensity sweeteners were used in the previous study. The authors believe that the stevia could have influenced some of the differences in taste perception due to its inherent bitterness and astringency, which could also explain the difference in sensory preferences between the two studies. Overall, Homayouni Rad et al. (2019) concluded that combinations of bulk sweeteners — not a single polyol — could be used to create sucrose-free chocolates with the preferred eating characteristics.

White Chocolate

Sweetening agents (sucrose and rebaudioside A [with **maltitol** and FOS]) and colors (red, blue, yellow, and green) in a white chocolate matrix were investigated in a study by Zukowska et al. (2025) among Polish and Brazilian consumers. Descriptive sensory analysis performed by a trained panel of 25 participants. Panelists generated attribute terms relating to the appearance, aroma, texture, and flavor of the samples, and a final list of attributes and reference standards was created after two consensus meetings with agreement from all panelists. Attributes for each sample were ultimately recorded for fourteen selected panelists. Later, consumer sensory analysis was performed for acceptance based on a 9-cm unstructured hedonic scale, JAR sweetness scoring and purchase intention, and check-all-that-apply emotional perceptions.

The researchers found no significant differences in sweetness or melting profile among samples but found that metallic aftertaste was associated with samples containing reb A regardless of the color of the chocolate. Interestingly, the researchers noted that there were no significant differences in flavor acceptance between samples of the same color sweetened with rebaudioside A or sucrose, suggesting that color modification may be able to promote acceptance of rebaudioside A, especially when considering red, blue, or green natural colorants. This paper provided significant insight into consumer perceptions of flavor and overall acceptance when impacted by color and demonstrated that it may be possible to improve the acceptance of sweetening alternatives with typically undesirable aftertastes simply by modulating the color of the product.

Konar et al. (2018) investigated the viability of probiotic strains and general chocolate quality characteristics in both conventional and sugar-free white chocolates, the latter of which consisted of a **maltitol**-containing base. The authors found that the maltitol-based chocolates generally exhibited lower hardness values compared to the sucrose controls, which was not significantly impacted by the degree of polymerization of inulin or strain of probiotic used, suggesting it served as a stable textural base for experimentation. The maltitol chocolates also demonstrated higher end melting temperatures and lower enthalpy, which the authors attributed to a higher moisture content. Rheologically, the maltitol-containing chocolates had higher plastic viscosity and yield values compared to the sucrose control, which the authors also believe is related to its higher moisture content and also different particle shapes of the maltitol compared to the sucrose, which may have increased particle-particle interactions and friction leading to a higher viscosity. These higher values may not be desirable in terms of processing and sensory perception due to resistance during pumping and mixing operations and higher potential for stickiness upon consumption, respectively. It would be interesting to see how the results of the inulin and probiotic additions impact the white chocolate matrices differently when other sugar replacement options may be considered as well as how the resulting chocolates may be perceived by a human sensory panel.

Fibers

Background

In addition to polyols, fibers such as **inulin, polydextrose**, and **maltodextrin** are popular sugar replacement options for chocolates. Inulin is a polymer of fructose units with a terminal glucose molecule (Anderson-Dekkers et al., 2021). It can vary in degree of polymerization (DP) from 2-60 fructose units, which is dependent upon the source of the inulin. For example, chicory root, which is the most common source of industrial inulin, has a range of DP from 2-50 while inulin from onion only ranges from 2-12. Inulin has a low caloric value, low glycemic response, and lower sweetness than sucrose. Typically, native or short-chain inulins (DP 8-13 and 7-10, respectively) are used for confectionery applications due to their texturizing and sensory properties. In chocolate specifically, inulin can be added in a sweetening system with polyols to improve texture and eating properties. Polydextrose is a non-sweet, randomly bonded glucose polysaccharide with small amounts of sorbitol (Auerbach et al., 2006). It can be used with sugar alcohols to combat excessive cooling due to its high heat of solution and can synergistically enhance perceived sweetness. It is stable at typical conching temperatures, so it does not present additional technical challenges for chocolate. Lastly, maltodextrin is a non-sweet, partially hydrolyzed starch with a dextrose equivalency below 20 that has also been studied as a bulk sugar replacer in chocolates (Gerschenson et al., 2022). Like polyols, overconsumption of fibers may also lead to gastrointestinal discomfort due to their low digestibility (Auerbach et al., 2006; Kearsley & Deis, 2006). All of these fibers are suitable for bulk replacement but do not themselves replicate the sweetness of sugar-containing chocolates.

Dark Chocolate

Loghmani et al. (2022) investigated the impact of sorbitol, isomalt, and **inulin** substitutes on the steady state and dynamic rheological properties of liquid sugar-free dark chocolates. Because inulin and isomalt are only half as sweet as sucrose and sorbitol only 60% as sweet, stevia was added for additional sweetening impact, though sensory qualities were not evaluated in this study.

Rheological properties were assessed using a stress-strain rheometer equipped with parallel plate geometry and a Peltier temperature control system. For steady state evaluation of thixotropy and apparent viscosity, the authors used a modified ICA46 (2000) chocolate method. All samples exhibited yield stress and shear-thinning behavior, which are expected in chocolate matrices. The lowest yield stress was observed in the inulin-containing sample, which the authors attributed to branched inulin structures causing void spaces, allowing for mobilization of cocoa butter and reduced viscosity. They also noted that the higher viscosity of isomalt-containing samples could be attributed to its higher solid volume fraction and lower density. In addition to higher viscosity, the isomalt-containing samples also had the largest hysteresis loop area, meaning that they required the longest post-shearing time to recover their internal structure. To assess dynamic behavior, samples were subjected to a strain sweep of 100-0.1% at 11 rad/s frequency to determine the linear viscoelastic range (LVR), followed by a frequency sweep from 0.01-100 rad/s within the LVR. This data suggested a liquid-like behavior in inulin- and isomalt-containing dark chocolates but a weak gel-like behavior in sorbitol-containing chocolate, which was more similar to the sucrose control.

The authors concluded that sugar substitution had a large effect on dark chocolate structure, highly impacted by ingredient quality and attributes such as particle size, amount and distribution of fat, the presence of emulsifier, and the presence and shape of solid particles. In these particular samples, the observed differences were attributed to the different molecular structures, solid volume fractions, and decreased particle-particle interactions and contact points. To achieve the most ideal rheological dark chocolate qualities, the authors recommended a mixture of these bulk sweeteners.

Aidoo et al. (2014) investigated mixtures of **inulin** and **polydextrose** in dark chocolate and suggested that the ideal concentrations to optimize rheological and physical characteristics were 24.64% inulin and 73.36% polydextrose. Inulin was found to increase Casson viscosity (Table 2), which the authors believe to be due to the dense packing of large crystals observed by microscopy. The authors' findings led them to conclude that inulin cannot be used alone in sugar-free chocolate, but rather complete sugar replacement by polydextrose could optimize plastic viscosity. Increased inulin and decreased polydextrose were also found to decrease Casson yield stress (Table 2). The authors suspected that this was due to a decreased bimodality in the particle size distribution of high polydextrose-containing chocolates since the increased particle-particle interactions of unimodally distributed chocolates lead to a corresponding increase in yield stress. These ideas were supported by microscopic analysis, which revealed large crystals with dense smaller particles in polydextrose chocolates. Complete replacement by either inulin or polydextrose led to harder chocolates, but inulin was seen to have a greater effect on hardening than polydextrose (Table 2). The blend proposed by the authors would optimize Casson viscosity, yield values, and hardness to more closely resemble sucrose-sweetened chocolate.

Table 2. Physicochemical properties of chocolates by increasing inulin content, adapted from Aidoo et al. (2014).

Inulin	**Polydextrose**	**Casson viscosity (Pa.s)**	**Casson yield (Pa)**	**Hardness (N)**	**Moisture (%)**
0	100	2.20	13.53	4.57	0.71
25	75	2.42	11.95	4.13	0.72
50	50	3.83	10.45	3.81	0.80
75	25	4.05	9.52	4.99	0.65
100	0	4.64	8.85	5.38	0.73
Control		2.40	10.20	3.79	0.46

OPTIMUM MODEL OUTPUT				
24.64	75.36	2.77	11.68	4.11

Milk Chocolate

Sarfarazi and Mohebbi (2020) investigated three ratios of **inulin** and **maltodextrin** (25:75, 50:50, 75:25) as sugar replacers in milk chocolate. Typically, chocolate rheological characteristics are determined by using data generated from a shear rate sweep, which is then fit to the Casson model. In this study, yield stress was instead assessed using a stress sweep test. The highest yield stress was observed in the control, and the yield decreased as inulin was increased, indicating a weakening effect of inulin on the chocolate structural network (Sarfarazi & Mohebbi, 2020). The authors associated the decreased flow resistance at higher inulin concentrations to larger particle sizes, fewer particle-particle interactions, and lack of a crystal network. Replacement with inulin and maltodextrin significantly increased chocolate hardness according to instrumental analysis, but no linear correlation was noted between inulin concentration and chocolate hardness. The elevated hardness values of the reduced sugar samples were attributed in part to higher solids packing intensities and increased particle sizes.

The researchers additionally assessed a variety of sensory attributes through quantitative descriptive analysis and found that the 25:75 mixture of inulin and maltodextrin was the closest to the control in terms of mouth coating and chewiness but that the 50:50 blend was closest in crumbliness (Sarfarazi & Mohebbi, 2020). The specific maltodextrin used in this study was based on preliminary sensory evaluation in which the organoleptic properties of maltodextrin with DE 14-16 was preferred over maltodextrin with DE 10-12 and 18-20. Unlike previously reviewed studies, the researchers chose to use the high-intensity sweetener sucralose to compensate for the non-sweet bulking ingredients. Sensory analysis indicated that the control was the hardest, which was not in agreement with the instrumental methods used, but also that the highest inulin-containing sample was the hardest of the sugar-free chocolates, which was in agreement with instrumental analysis. These results demonstrated that different fiber blends were needed to optimize different sensory attributes.

De Melo et al. (2009) investigated the use of **polydextrose**/lactitol bulking mixtures in combination with sucralose and stevioside on the sensory acceptability of reduced sugar milk chocolates. To create the milk chocolate mixtures, the authors leveraged a 60/40 blend of polydextrose and lactitol and compensated for missing sweetness based on the respective sweetening power of sucralose or stevioside to be as sweet as the sucrose control. It is unclear how the authors arrived at this bulking agent mixture or the impact it may have had on the texture of the chocolates and their resulting flavor delivery. Similarly, it should be noted that some high-intensity sweeteners, while calorie free, are associated with undesirable flavors and aftertastes, especially bitterness.

Sensory evaluation was performed in two parts. First, qualitative descriptive analysis was performed by a 10-member trained panel. Panelists generated 16 attribute terms and were trained on each term using references, then evaluated the samples based on these references using a 9-cm line scale for each attribute. Next, consumer testing was conducted by 116 participants. Consumers were not provided with product information or chocolate formulation, so results were based solely on sensory characteristics. Consumer results revealed a general flavor preference for the control chocolates followed by the sucralose-containing chocolate, which were deemed more acceptable than the stevioside-containing chocolate. The authors attribute this to the bitterness commonly associated with stevioside, though both the sucralose and stevioside were noted as having increased bitterness and bitter aftertaste at a similar magnitude. This bitterness was a crucial driver of disliking and contributed to the overall conclusion that consumers preferred conventional chocolates based on sensory perception alone, in the absence of additional product formulation or health claims. Within the high intensity sweeteners, the acceptability was higher for sucralose than stevioside. Different steviol glycosides, the sweetening agents present in the stevia plant leaves, possess varying degrees of sweetening power, bitterness, and artificial taste (Orellana-Paucar 2023). Had the authors used, for example, rebaudioside A over stevioside, it is possible that the bitterness perception could have been reduced to be more in line with the sucralose-sweetened sample. Further research could therefore investigate different high-intensity sweeteners or explore the impact of health information on consumer preference and whether the health benefits are enough to overcome the sensory differences between the reduced sugar and full-sugar chocolates to drive consumer interest.

White Chocolate

Loncarevic et al. (2021) investigated **resistant starch** addition from 5-15% in white chocolate for its impact on sensory and physical quality characteristics. Viscosity increased with increasing resistant starch content, with all values statistically differing from one another (Figure 4). Likewise, yield stress also increased significantly with resistant starch addition, which the authors attributed to reduced fat causing higher particle interactions, though this was likely also tied to the subsequent increase in moisture from 0.71% in the control to 1.81% in the 15% resistant starch sample (Figure 5). Hardness decreased with resistant starch but not significantly (Figure 4), which was again attributed to a decrease in fat content. All of the white chocolate samples had melting profiles in the anticipated range for white chocolates.

Figure 4. Rheology and hardness parameters of white chocolates with resistant starch, adapted from Loncarevic et al. (2021).

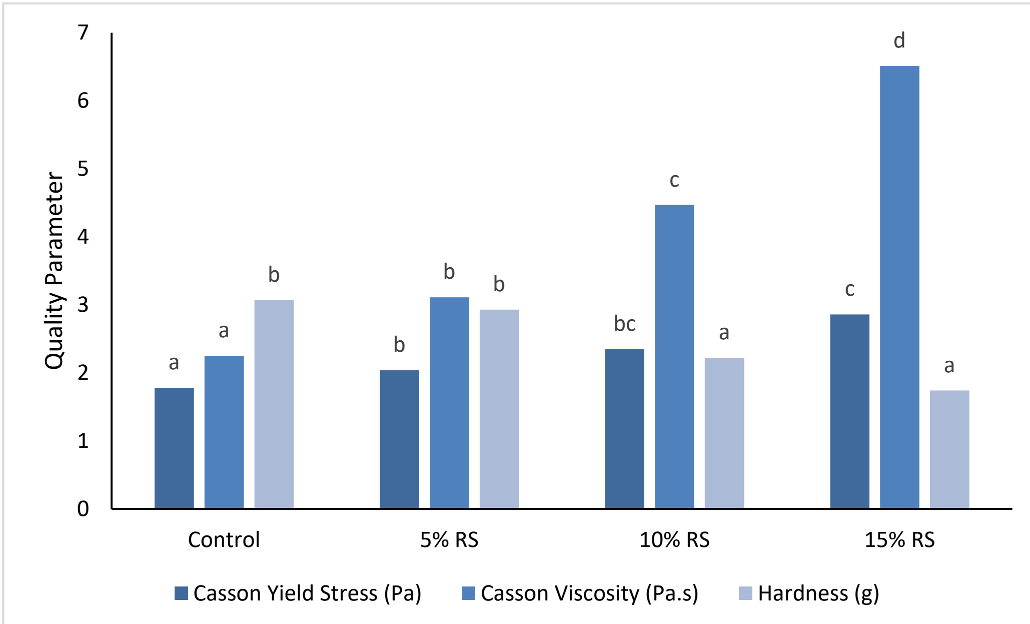
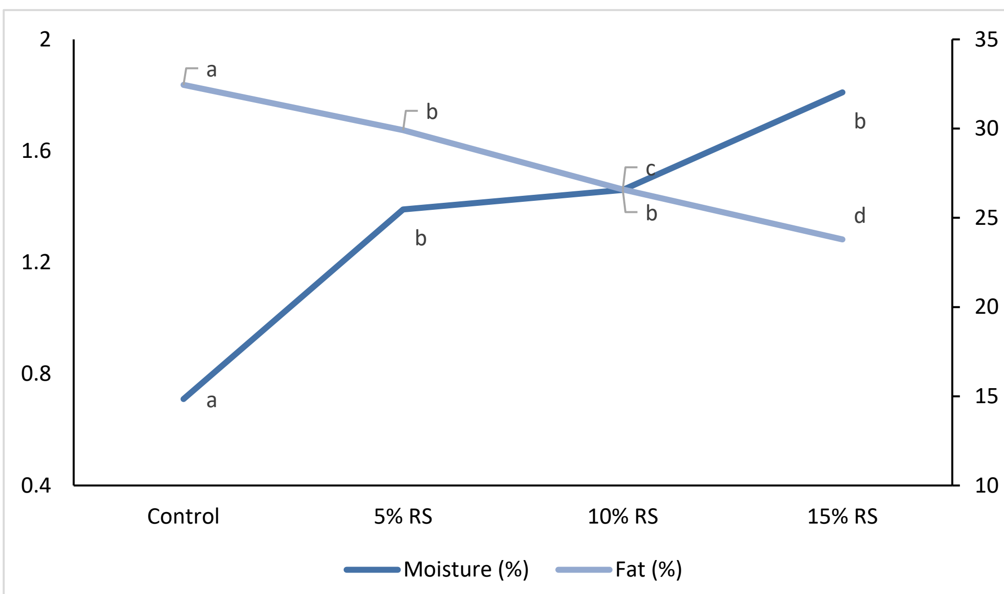


Figure 5. Moisture and fat values of white chocolates with resistant starch, adapted from Loncarevic et al. (2021).



The chocolates were assessed sensorially by an 8-person panel consisting of food technologists. The panel collectively determined 10 attributes comprising appearance, aroma, flavor, and texture, and proceeded to rate samples on a 7-point scale. The authors found that the surface characteristics were not significantly altered with resistant starch addition. Hardness decreased with resistant starch addition, which was in line with the instrumental findings. All samples were perceived to have a pleasant taste by the panel, but with a mild floury taste due to the lower fat proportion. The researchers ultimately concluded that resistant starch could be added in white chocolate up to 15% without negatively impacting sensory qualities. Further research could investigate the impact of resistant starch on the white chocolate matrix when the fat content remains consistent as well as opening sensory analysis to consumers rather than a trained panel.

A 2016 study by Morais Ferreira et al. aimed to develop a healthier, functional white chocolate by incorporating goji berry as an antioxidant source and replacing traditional sucrose with high-intensity sweeteners (sucralose and rebaudioside A) and filling bulk with **fructooligosaccharides**. The authors first determined the ideal sweetness level for white chocolate to set the sucrose level for the control sample, which became 40.46%. Then, high intensity sweeteners were incorporated at levels designed to match this sweetness level in addition to building back the bulk lost from sucrose replacement with fructooligosaccharides. As sensory qualities were the target of the study, physical quality parameters were not assessed. The authors ultimately concluded that either sucralose or rebaudioside A could be reasonably substituted for the sweetening component of sucrose in white chocolate, but sucralose more closely mimicked the time-intensity profile of the sucrose control. Future research could investigate the impact of goji berry and fructooligosaccharides on the physicochemical properties of the white chocolates and how they may be further optimized for optimum market viability.

Newer Ingredients of Interest

Dark Chocolate

Rare sugars are relatively newer in the realm of sugar replacement options and are defined by the International Society of Rare Sugars as monosaccharides and their derivatives which rarely exist in nature (ISRS, 2019). These include sugars such as **L-glucose, D-allose, D-allulose, D-tagatose,** and **L-ribose**. Allulose specifically has risen in interest thanks to the 2020 FDA Final Guidance that it shall be excluded from Total and Added Sugars on nutrition facts panels and shall be counted as just 0.4 calories/gram when creating the nutrition facts label (US Food and Drug Administration, 2020a). While published literature is scarce regarding the inclusion of allulose in chocolate, recent dark chocolate product development and patent applications by confectionery companies suggest that efforts are being made to include allulose in sugar reduction strategies, though it may pose its own challenges in incorporation into the chocolate matrix (St. John et al., 2024; Wang et al., 2024). Unlike allulose, tagatose is not exempt from inclusion in Added Sugar labeling according to the US FDA's 2020 notice on "sugars that are metabolized differently than traditional sugars" (U.S. Food and Drug Administration, 2020b). However, the FDA has also ruled that while it must be labeled with added sugar, manufacturers may use a decreased caloric content of only 1.5 calories per gram when calculating the calories from tagatose (U.S. Food and Drug Administration, 2023). As the landscape continues to evolve, the regulatory perspective on rare sugars will undoubtedly continue to adapt to align with literature findings.

Shourideh et al. (2012) investigated the effects of inulin and **tagatose** on the physicochemical and rheological properties of dark chocolate and concluded that increased tagatose concentrations resulted in chocolates with similar properties as sucrose-sweetened chocolates. Increased tagatose concentration led to lower apparent and plastic viscosities but higher yield stress, similar to the sucrose control (Figure 6). The authors attributed these rheological findings to structural similarities between the two sugars. Likewise, the reduction of yield stress with increased inulin concentration was attributed to differences in structure between inulin and tagatose and weaker interaction forces between particles, which was in agreement with the findings of Aidoo et al. (2014) and Sarafazi and Mohebbi (2020). However, Shourideh et al. (2012) also revealed that as tagatose concentration increased, chocolate hardness reached a final value similar to the sucrose control, while increasing inulin concentration led to softer chocolates (Figure 7). This seemingly contradicts the findings of Aidoo et al. (2014) and Sarafazi and Mohebbi (2020). Shourideh et al. (2012) attributed the softness of the high inulin sample to the absorption of water. It is possible that the inherent moisture in the other ingredients or even differences in production environments could have contributed to the conflicting results among studies.

Figure 6. Rheological values of dark chocolates adapted from Shourideh et al. (2012).

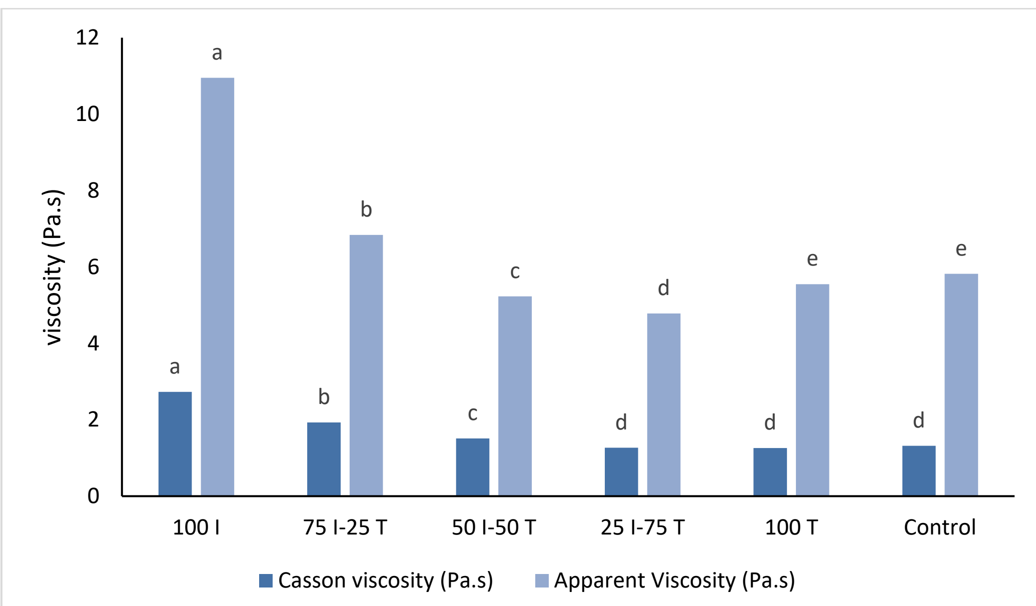
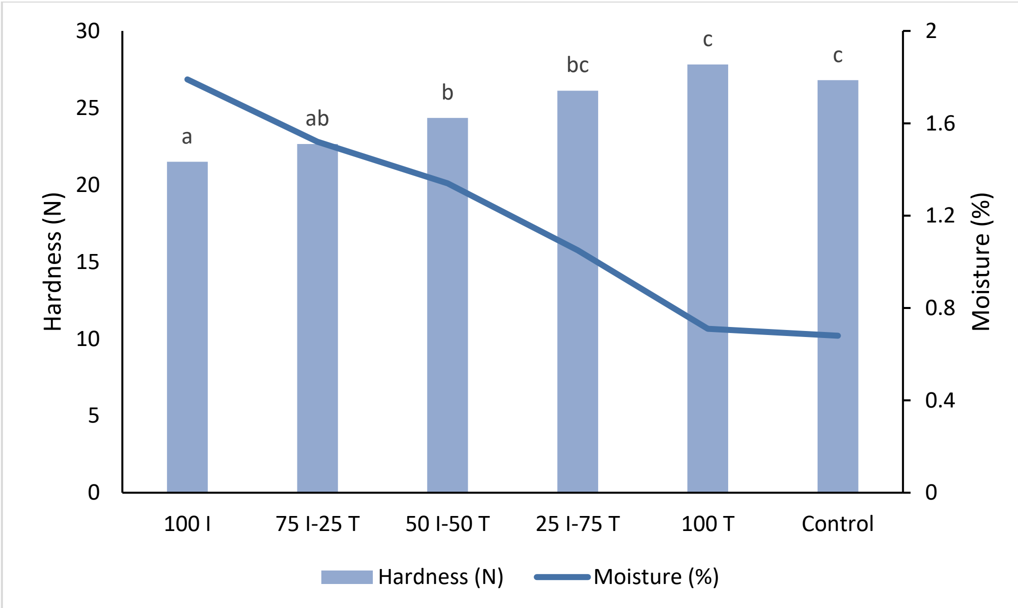


Figure 7. Hardness and moisture values of dark chocolates adapted from Shourideh et al. (2012).



Overall acceptability, which was defined as the sum of sensory ratings including texture, snap, sweetness, taste, melting rate, mouthfeel and color, increased with increasing tagatose (Shourideh et al., 2012). Tagatose has 92% of the sweetness of sucrose and inulin has only 10%, so samples in this study were additionally sweetened with stevia based on the calculated sweetness levels. The samples with 25% inulin-75% tagatose and 100% tagatose were not significantly different from the control in any sensory attribute except color. On the other hand, the sample with 100% inulin received the lowest sensory scores and was significantly different from all other samples. Similar to the results obtained by Homayouni et al. (2019), the sensory ratings for taste and sweetness may have decreased at lower tagatose percentages due to the contribution of bitterness from the increased concentration of stevia. Regardless, the increasing concentration of tagatose seemed to beneficially impact many of the attributes measured in this study, leading the researchers to conclude that 25% inulin-75% tagatose or 100% tagatose were acceptable ratios for sugar replacement in dark chocolate.

Lagast et al. (2018) compared **tagatose** and erythritol (sweetened with stevia) in dark chocolates to commercially available sucrose-sweetened Belgian chocolates according to their sensory attributes and the emotional response invoked by consumers. The authors recruited participants that liked and consumed all types of chocolate (white, milk, and dark) with no food allergies. Participants did not know about reduced sugar content or branding, and samples were provided in the same shape with a randomized 3-digit code to minimize bias. Participants were instructed to evaluate overall liking on first bite using a 7-point hedonic scale, then to select the appropriate emotional terms from a provided list of 24 words. These words were taken from literature review and analysis of frequency of the terms' appearance, with a balance between positive and negative emotions. Other authors suggest that this could have been taken one step further with different lexicon provided based on the participants' PROP taster status (non-taster, medium taster, or super taster) (van Zyl et al., 2023), which could prove interesting for future studies. On second bite, participants were instructed to rate sensory attributes on a 5-point JAR scale. Finally, participants were asked to answer demographic questions and provide information about their diet and restrictions for eating.

Overall liking was significantly lower for chocolate with erythritol and stevia, but no significant difference was found between tagatose and sucrose-containing chocolates. In fact, sensory attribute data suggested that the tagatose-containing chocolate was perceived similarly as the sucrose. Likewise, positive emotions were seen more prominently with the tagatose and sugar samples, and negative emotions were more associated with the erythritol and stevia sample. The tagatose and erythritol samples were perceived differently in terms of texture, sweet flavor, bitter flavor, and duration of aftertaste. Further research with a different bulking agent or a different high intensity sweetener would be interesting to determine if the perception of the erythritol/stevia sample could be improved through taste (namely, bitterness reduction) or texture. Overall, the authors concluded that tagatose is a promising sweetener alternative for sugar in dark chocolate.

Fat bloom is a significant chocolate defect, affecting the appearance of the chocolate surface, fat crystal structure and chocolate texture, and ultimately, consumer perception. It is characterized by a loss of luster and graying wherein polymorphic cocoa butter fat crystals larger than 5 microns rise to the chocolate surface and re-crystallize in form VI from the preferred form V (Son et al., 2018). In 2018, Son et al. investigated the bloom inhibition capabilities of maltitol and **tagatose** as sugar substitutes in dark chocolate formulations. Sweeteners were blended into formulations according to relative sweetness so that all resulting product sweetness levels were identical, then samples were subjected to up to thirty cycles of 18 hours at 18C and 6 hours at 30C to induce bloom for a total of four bloom-inducing periods for each of the three sweeteners. Surfaces were analyzed by stereoscopic microscope and FE-SEM while fat crystals were visualized by X-ray diffraction after the removal of sugar. Texture was analyzed by both instrumental and sensory methods. Sensory information was gathered through Qualitative Descriptive Analysis by a panel trained on 12 sensory terms using a 15-cm line scale.

All samples at the time of production had mainly form V cocoa butter crystals present, which is indicative of good temper. The sucrose group had the fastest conversion to form VI, the type of cocoa butter crystal associated with bloom, followed by the maltitol and tagatose groups, though the latter two were not statistically different from each other. Further, the tagatose samples after 30 bloom-inducing cycles were statistically no different than the sucrose samples after 20 bloom-inducing cycles, indicating a much better resistance to bloom. The authors attribute the increased stability of tagatose crystallization to its decreased blooming progress.

There was significant correlation between instrument- and panelist-derived findings. As bloom progressed, hardness values significantly decreased while whiteness and bloomed area increased. Interestingly, in sensory evaluation, there was no significant difference among the sugars at 30-times bloomed regarding sweet taste aside from tagatose, which was slightly lower. All chocolates were likely to be perceived negatively by the consumer after 20 bloom cycles but as tagatose samples had the relatively smallest change, authors concluded that it had stronger resistance to blooming than sucrose or maltitol, though maltitol also presented increased resistance than sucrose. The authors suggested that either tagatose or maltitol displayed increased bloom resistance throughout the study, and further research could compare the results in dark chocolate to that of milk or white chocolate to determine the impact of other ingredients on the resulting bloom resistance.

Another newer ingredient of interest in chocolate is **palm sap-based sugar,** which is economically appealing due to its geographical proximity to cacao but has not yet been thoroughly investigated as a sucrose replacement in chocolate. Saputro et al. (2017) designed a study in which five sucrose-palm sugar blends were incorporated into dark chocolate in varying ratios to evaluate their potential as sweetening systems. The Casson yield value tended to decrease while hardness increased with increasing levels of palm sugar, which the authors attributed in part to a lower particle density, larger particle size, and higher moisture content of the palm sugar. The authors noted no apparent trends in Casson viscosity values with different sucrose-palm sugar blends despite differences in particle size distributions with increasing levels of palm sugar. These hardness and rheology trends were hypothesized to be influenced by moisture-induced agglomeration because palm-sap sugar has a higher inherent moisture content. The authors used particle size distribution measurements, thixotropic behavior during rheological measurements, and microscopic observations to support this supposition. The authors ultimately concluded that palm sugar substitution influenced the rheological, microstructure, and textural properties due to the higher moisture and chemical impurities of the palm sugar. Further research is needed to understand the suitability of palm sugar in chocolate.

Ramli et al. (2025) also evaluated **palm sugar** in dark chocolate through up to 100% replacement of icing sugar syrup with *Nypa fruticans* syrup, created by a 2:1 ratio of the sugar in water. Palm sugar is very popular in Malaysia; it is rich in vitamins and minerals and predominantly consists of sucrose, glucose, and fructose. With increasing palm sugar substitution, moisture content significantly increased, owing to the hygroscopic nature of its glucose and fructose components and inherent moisture present (Table 3). Energy values decreased as *Nypa fruticans* content increased – evidence of its suitability as a sucrose replacer in terms of caloric health benefits.

The authors used a range of instrumental and sensory methods to provide a comprehensive look at the sweetener's potential as sugar replacement. Hardness and spreadability significantly increased with *Nypa fruticans* addition (Table 3), which the authors attributed to increased agglomeration due to its higher moisture content, hygroscopic nature, and formation of amorphous sugar surfaces during production. However, further addition beyond 50% did not continue to raise the hardness. The authors concluded that the smaller crystals and homogenous agglomeration allowed the sugar to be better distributed in the fat network, leading to the improved spreadability.

The sucrose control exhibited the highest viscosity while the 100% replacement with *Nypa fruticans* sample exhibited the lowest (Table 3). The authors attributed this to the higher reducing sugar content. The authors also note that higher moisture content typically requires more fat to achieve a similar viscosity as a lower moisture containing chocolate, though this is in disagreement with the moisture, fat, and viscosity values obtained (Table 3). The sucrose control had the lowest melting temperature, influenced by particle size, moisture content, and composition of the sugar. The authors suppose that the *Nypa fruticans* samples with higher moisture content may have had enhanced structural integrity and therefore a higher melting point. Nonetheless, all samples had melting points within a reasonable range for dark chocolate. Samples required varying energy input for melting, attributed to their differences in viscosity and moisture content.

Table 3. Proximate, texture, and melting properties of dark chocolates sweetened with palm sugar, adapted from Ramli et al. (2025).

	Energy (kcal/100g)	Reducing Sugar (%)	Moisture (%)	Fat (%)	Hardness (kg)	Viscosity (cP)	Melting Peak (°C)
Control	687.97 ± 11.37[a]	1.11 ± 0.02[e]	1.25 ± 0.01[d]	59.63 ± 2.31[a]	5.24 ± 0.20[b]	7327.87 ± 1.17[a]	37.07
25% Palm Sugar	675.40 ± 2.46[ab]	2.03 ± 0.04[d]	2.91 ± 0.07[c]	58.87 ± 0.57[a]	6.16 ± 0.66[ab]	7068.20 ± 4.01[b]	37.87
50% Palm Sugar	673.35 ± 2.74[ab]	2.21 ± 0.01[c]	3.13 ± 0.06[b]	58.71 ± 0.50[a]	6.39 ± 0.38[a]	6549.58 ± 3.58[c]	37.87
75% Palm Sugar	664.58 ± 10.43[b]	2.55 ± 0.01[b]	3.37 ± 0.02[a]	57.17 ± 2.09[a]	6.28 ± 0.10[a]	5973.81 ± 0.01[d]	36.87
100% Palm Sugar	663.35 ± 1.87[b]	3.04 ± 0.04[a]	3.48 ± 0.06[a]	57.14 ± 0.41[a]	6.28 ± 0.04[a]	5578.45 ± 0.61[e]	36.87

Surface microstructure was assessed using a scanning electron microscope. Samples up to 50% sugar replacement contained larger crystals, with the sucrose control containing sugar crystals with clear edges unlike the 100% *Nypa fruticans* sample which was void of large, distinct crystals. Additionally, as the *Nypa fruticans* syrup was increased to 75% and beyond, particle agglomeration was more evident. The authors note that palm sugar particles contain adhesion-promoting layers between other palm sugar crystals, which could be due to the hygroscopic sugars, increased moisture content, and amorphous material.

Sensory evaluation was completed using a 9-point hedonic scale to assess color, texture, aroma, taste, and overall acceptability using 50 untrained panelists. All samples were deemed acceptable color-wise aside from the 100% *Nypa fruticans* sample, which was visually darker.

Texturally, the 50/50 *Nypa fruticans*/icing sugar blend was directionally the most preferred, though the texture preferences did not significantly differ between samples. The largest sensory difference noted by the panel was in the taste attribute, with the 50/50 sample being the most preferred and the sucrose control being liked less than the moderately substituted (25-75%) samples. Ultimately, the authors concluded that *Nypa fruticans* in a 50/50 blend of icing sugar was a suitable recipe compared to the sucrose control.

Torregrossa et al. (2024) investigated dark chocolates made with stevia, erythritol (44%), and **coconut sugar** (56%), resulting in an 8% calorie and 75% sucrose reduction from the sucrose-sweetened control. Coconut sugar in this case is desirable due to being seen as "less unhealthy" than table sugar. It's mineral, vitamin, protein, and phenol constituents lend more nutritional value to the overall matrix.

Texture was determined by penetration with a texture analyzer. Hardness was noted as the maximum force registered while adhesiveness was the negative force registered. The hardness value for control was higher than the coconut sugar-containing sample, which the authors attributed to high hygroscopicity and presence of inulin in coconut sugar. DSC analysis suggested that the crystallization of cocoa butter was the best in the sucrose-substituted dark chocolate based on the maximum peak temperature. Sugars and their particle size affect cocoa butter crystallization, as they are the seed around which fat crystals grow. This homogenous sugar phase in the sucrose sample led to a higher extent of fat crystallization evidenced by its higher melting enthalpy. Together with the texture analysis, the data suggest that samples with lower melting enthalpy have softer structure at the same temperature.

Rheology was performed following the standard ICA 2000 methodology for chocolate viscosity with data fitted to the Casson model. Yield stress increased almost 70% with sugar substitution while apparent and Casson viscosity also increased but to a much smaller extent.

The sugar-substituted sample exhibited more thixotropy – the role of time in restructuring process after sample is sheared – which can have processing implications. Ultimately, the authors did not recommend coconut sugar as an acceptable replacement based on the instrumental analyses alone. Further sensory evaluation could provide insight as to whether the instrument-derived differences are meaningful to the consumer.

Nurhayati et al. (2022) combined **both palm and coconut sugars** into 65% cacao dark chocolates. Both sugars are claimed as healthier thanks to their vitamin and mineral, protein, and phenol contents; thus, the goal of this study was to increase the phenolic and antioxidant activity of probiotic-enriched dark chocolate. However, the learnings from this study could be applied to sugar reduction efforts without probiotic addition.

The authors first evaluated the caloric content of chocolates, which revealed that the palm sugar chocolate was lower than that of coconut sugar chocolate but not significantly different than sucrose chocolate. One could argue that the minimal decrease could be forgiven due to the additional health benefits offered by the sugar substitutes. Visually, palm and coconut sugar samples had darker colors than sucrose controls, which the authors attributed to Maillard and caramelization reactions. Both contain reducing sugars and proteins that can lead to Maillard reaction progression. Palm sugar was darker than coconut, which was only slightly darker than sucrose.

The viscosity of all samples was measured with a Brookfield viscometer with disc spindle at 20 rpm and 38C. Significant differences were observed between the samples with the coconut sugar sample being the most viscous. The higher viscosities were attributed to increased particle-particle interactions due to lower particle densities and increased agglomeration due to higher moisture content of the substitute sugars. This was further evidenced by sugar agglomeration seen in microscopic analysis.

DSC analysis revealed a lower melting temperature in the sucrose-containing chocolate than the coconut and palm sugar sweetened chocolates, which the authors attributed to particle size, moisture, and sugar composition. The sugar melting temperature, however, was higher due to its lower moisture content. The authors suggest that the lower melting temperature and narrower peak area of the coconut and palm sugar samples were due to high moisture content, amorphous surfaces, agglomeration, and presence of impurities. Sensory analysis and further processing tests would be required to more appropriately vet the coconut and palm sugars' suitability for incorporation into reduced sugar chocolates.

Kongor et al. (2024) investigated the impact of incorporation of up to 30% **red beetroot powder** on physicochemical and sensory properties and consumer acceptability of dark chocolate. Red beetroot powder has low sugar content and contains bioactive compounds such as betalains, flavonoids, dietary nitrate, though it has different physicochemical properties than sugar, making it another interesting candidate for sugar reduction in chocolate.

Increasing red beetroot powder concentration led to increased moisture content, particle size distribution, and hardness. The increased moisture could be counteracted with longer processing times, but the authors noted that even the highest addition level of beetroot powder remained under the 1.5% threshold for acceptable rheology. The increased particle size was attributed to the increased particle size of the powder itself prior to processing. The hardness was also explained by the high moisture content of the powder leading to particle agglomeration, which was supported by the rheological data. This consistent with the findings of Saputro et al. (2017) in which the increasing moisture associated with palm sugar also led to an increase in hardness.

Rheology was assessed by rotational rheometer at 40C using the ICA standard chocolate method and fitted to the Casson model. All samples exhibited typical non-Newtonian plastic liquid behavior during rheological analysis, which is expected of dark chocolate. There was a higher degree of particle agglomeration seen in 15% and 30% samples as evidenced by thixotropy, which was linked to their increased hardness. Increasing beetroot powder concentration additionally led to increased Casson plastic viscosity, yield stress, and apparent viscosity.

To assess sensory attributes, Qualitative Descriptive Analysis was performed by 13 trained panelists. Each attribute was quantified using a 15-cm unstructured line scale. Principal component analysis was then used to visualize the relationship between samples and attributes. Four of the chocolate samples from the study were then chosen for consumer acceptability testing using 100 randomly selected consumers and a 7-point hedonic scale. Consumer testing revealed that the red beetroot samples were more bitter, which was attributed to their polyphenol content. Hardness increased with increasing red beetroot concentration in sensory analysis, in agreement with instrumental techniques. Cocoa flavor was not affected but increasing beetroot addition led to a decrease in sweetness and an increase in saltiness and earthiness. Highest beetroot powder concentration (30%) was rated as least acceptable. The authors ultimately suggested that any red beetroot addition to commercial products should start lower to familiarize consumers with the associated taste and improve their perception before increasing to higher doses. Further research should be conducted to evaluate red beetroot chocolate's shelf life and optimal storage temperature.

Milk Chocolate

Al Qafari et al. (2025) explored the incorporation of Sukkari dates into milk chocolate formulations as an eco-friendly, sustainable, healthier sugar alternative. In Saudi Arabia, roughly 20-30% of dates are wasted annually due to their non-marketability (low quality) or overabundance. As dates contain carbohydrates, fiber, and essential vitamins and minerals, they provide a healthier alternative to straight table sugar and an interesting prospective ingredient for sugar reduction in chocolate. To more wholly assess their suitability, the authors examined **date powder** in both lower-fat moulding chocolates and higher-fat coating chocolates at up to 30% and 60%, respectively, of the total sweetener composition.

Table 4. Initial fat, moisture, and viscosity analyses of date powder-substituted dark chocolates, adapted from Al Qafari et al. (2025)

		Fat (%)	Moisture (%)	Viscosity (Pa.s)
Moulding Chocolates	Control	41.80 ± 1.21^{a}	1.90 ± 0.36^{a}	2545 ± 7.61^{a}
	10% DP	41.84 ± 1.42^{a}	1.62 ± 0.16^{ab}	1228 ± 4.51^{d}
	20% DP	41.93 ± 1.23^{a}	1.29 ± 0.15^{ab}	1650 ± 4.02^{c}
	30% DP	41.95 ± 1.32^{a}	1.15 ± 0.15^{b}	1810 ± 4.02^{b}
Coating Chocolates	Control	50.31 ± 0.33^{a}	3.42 ± 0.17^{a}	606 ± 3.71^{b}
	20% DP	50.34 ± 0.32^{a}	2.95 ± 0.12^{ab}	380 ± 2.71^{d}
	40% DP	50.37 ± 0.37^{a}	2.75 ± 0.13^{ab}	540 ± 3.01^{c}
	60% DP	50.51 ± 0.37^{a}	2.35 ± 0.13^{b}	750 ± 3.92^{a}

Chocolates were evaluated both immediately and in 2-month intervals for the first six months of their shelf life. Moisture content decreased with date powder addition due to its moisture retention capacity (Table 4). Over time, the samples increased in moisture, and the sucrose-sweetened control sample consistently had the highest moisture content at all time intervals. There were no significant differences in fat content among samples, eliminating fat as a confounding factor when discussing attributes such as viscosity and flavor delivery (Table 4). Additionally, the authors found that total energy content decreased as date powder increased, which is positive news for its potential as a healthier sucrose replacement option.

Moulding chocolate in general had a higher apparent viscosity as measured at 40C and 100 rpm by Brookfield viscometer given its lower fat content. Within the different chocolate types, all samples were significantly different from one another, with the control and 10% date powder samples having the highest and lowest viscosities, respectively, in the moulding chocolate group and 60% date powder and 10% date powder-containing samples having the highest and lowest, respectively, of the coating chocolate group (Table 4). Viscosity increased with increasing date powder addition, attributed to higher solid particle content and water-binding capacity.

Finally, sensory analysis was performed by ten trained panelists on attributes such as color, surface appearance, taste, aroma, and overall acceptability, and in the case of moulding chocolate, the texture and snap. Sensory evaluation revealed significant differences in taste, snap, and texture between the sucrose control and 30% date powder moulding chocolate samples, leading to the lowest overall acceptability score for the 30% replacement sample. The 30% replacement sample consistently had the lowest texture scores in particular, which the authors attributed to the date powder containing a proportion of fibers and not strictly sugars. The same trend was noted for the 30% replacement sample's snap. Likewise, this sample also trended lower in taste and aroma values throughout the entire storage period. The authors recommended a total replacement up to 20% with date sugar would not significantly impact the sensory perception and overall acceptability. In coated wafer evaluation, the lowest ratings for taste, aroma, and surface appearance were recorded for the 60% replacement sample throughout the storage period. The 20% and 40% replacement samples were generally acceptable for the same attributes throughout storage. Therefore, replacement up to 40% can be recommended by the authors for coating applications. In addition, the authors suggest further research on processing optimization, glycemic response, and consumer perception before date powder incorporation into the commercial market can be fully recommended.

White Chocolate

Didar (2023) examined the potential of **mulberry molasses microcapsules** – concentrated, encapsulated mulberry fruit juice – in white chocolate from 0 to 50% of the sweetener composition. The author noted that while mulberry fruit itself contains various sugars, the overall sugar content is lower than pure sugar, which makes it an interesting, non-traditional candidate for sugar reduction without resulting in complete sugar replacement. Instrumental analysis revealed that hardness and moisture decreased, but color, Casson yield stress, and Casson viscosity increased as mulberry molasses was added to the matrix (Figure 8, Table 5). Microcapsules were relatively uniform in size but had an increasing effect on the particle size distribution. DSC analysis revealed that the mulberry-containing samples melted at lower temperatures (Table 5), which was suspected to be caused by variations in moisture content and acidity influencing the thermal properties of chocolates. Microstructure assessed by FE-SEM showed more light areas in the mulberry containing samples, thought to be due to the formation of white fat crystals on the chocolate surface, though the sensory analysis via panel did not indicate a higher amount of fat bloom.

Figure 8. Rheology, hardness, and moisture values of white chocolates with mulberry molasses microcapsules adapted from Didar (2023).

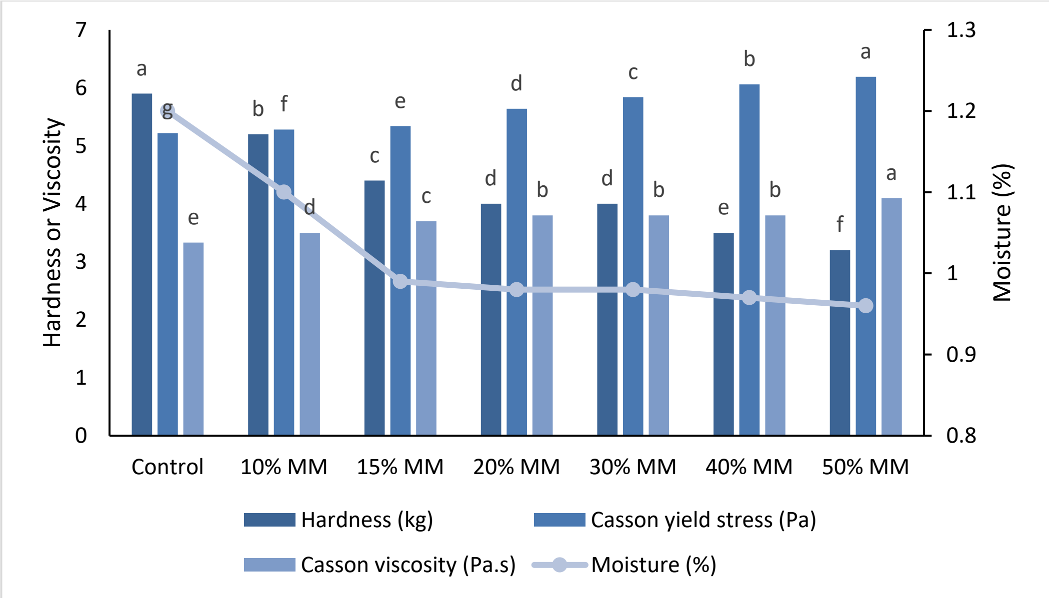


Table 5. Color and thermal properties of white chocolates with mulberry molasses microcapsules, adapted from Didar (2023).

	Color Properties			Thermal Properties
	L*	a*	b*	Melting peak (°C)
Control	73.3±0.03[a]	−1.18±0.1[g]	20.42±0.02[c]	23.99±0.2[a]
10% MM	71.4±0.02[b]	0.7±0.01[f]	20.58±0.03[c]	22.6± 1[b]
15% MM	70.1±0.04[c]	0.9±0.05[e]	21.22±0.02[b]	20.2±0.2[c]
20% MM	65±0.01[d]	1.1±0.02[d]	21.61±0.02[b]	19.1±0.2[d]
30% MM	61.5±0.01[e]	1.5±0.01[c]	22.11±0.03[a]	18.4±0.1[e]
40% MM	59±0.02[f]	1.8±0.02[b]	22.21±0.02[a]	17.5±0.1[f]
50% MM	56±0.01[g]	1.9±0.2[a]	22.25±0.02[a]	16.5±0.1[g]

For sensory analysis, ten panelists rated the chocolates on a variety of attributes such as appearance, color, texture, taste, and overall acceptance on a 7-point hedonic scale. The resulting data indicated similar bitterness, sweetness, and overall acceptability between the mulberry and sugar samples. Hardness agreed with the instrumental analysis in that the mulberry samples were not as hard. Due to overall acceptance being similar, the author concluded that mulberry molasses microcapsules could be a potential tool for lowering overall sugar in white chocolate matrix, though further research should be performed on shelf-life stability and broader consumer perceptions.

Conclusion

Sugar reduction in chocolate is well-studied, but the optimal sweetening system with minimal impact to physical, rheological, and sensory properties of chocolate and a positive perception from consumers has yet to be identified. In dark chocolates, polyols, fibers, or blends of the two show promise for matching rheology and hardness but the hygroscopicity of some polyols can lead to undesirably high moisture and rheological values, impacting processing and sensory qualities, while different molecular structures and particle size distributions of fibers can have a large impact on chocolate structure. Emerging rare sugars are promising contenders for matching sucrose properties in dark chocolate and alternatives such as palm and coconut sugar offer nutritional benefits not typically seen in traditional substitutes, but the moisture content of the latter, like polyols, can also hinder their use in the dark chocolate matrix, and their shelf-life stabilities and consumer impact have yet to be extensively studied. In milk chocolates, polyols may lead to harder texture and increased viscosity but can optimize sensory acceptability under the right conditions. Fibers have also exhibited desirable sensory properties, but different fiber blends may be required depending on the specific chocolate quality attributes desired. Newer alternatives such as date powder may lead to desirable sensory attributes, but their processing behaviors require further studying and optimization. Lastly, in white chocolates, studies suggest that different particle shapes of sugar alcohols may lead to undesirable processing and sensory qualities, but appropriate blends of polyols, fibers, and high intensity sweeteners may be able to match the temporal sweetness impact of sucrose-sweetened white chocolate. Emerging alternatives such as mulberry molasses again show promise in lowering sugar content without reducing acceptability, but similarly as milk chocolate, these alternatives require broader consumer and shelf-life studies before their adoption can be wholly recommended.

Research is still needed to address key questions to fully qualify these sugar replacement options as commercially viable substitutes for sugar in chocolate matrices, namely if there a novel ingredient or blend of ingredients that may be used in chocolate to more closely replicate the physicochemical, rheological, and sensory properties of sucrose-sweetened chocolates with minimal gastrointestinal distress, how these ingredients may be perceived by consumers, how chocolate labeling methodology may adapt to align with changing industry trends and formulation strategies, and how the type of chocolate (white, milk, or dark) influences an ingredient's suitability as a sugar replacement.

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