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Sugar-Free Chocolates: Physical Properties of Brazilian Market Samples

Chocolates sin azúcar: propiedades físicas de muestras del mercado brasileño

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Abstract

Understanding local trends is essential for assessing consumer preferences and openness to new products. This study compared nine commercial dark and milk chocolates (with and without sucrose) from the Brazilian market, evaluating color, calorimetric, rheological, and texture properties. One-way ANOVA assessed overall differences, with significant results ($p < 0.05$) further examined by Tukey's test. Texture, measured via normalized bending stress (σflex) to reduce geometric artifacts, showed dark chocolates with greater breakage resistance than milk chocolates; the xylitol sample (D) was the most resistant. All samples exhibited pseudoplastic behavior, confirmed by the Casson model ($R^2 > 0.98$). Milk chocolates generally showed higher rheological values (Casson yield stress, plastic viscosity, thixotropy), whereas dark chocolate Sample D (xylitol) had a significantly lower plastic viscosity (1.37 Pa·s). Sucrose substitution significantly altered color: dark chocolate Sample C (maltitol) presented a higher b* (8.54 ± 0.25) and lower Whiteness Index (20.59 ± 0.33), while milk chocolate Sample I (maltitol/polydextrose) differed from the control (E) in all color parameters, with a lower L* (31.44 ± 0.26). In calorimetry, sugar-free dark chocolates showed lower carbonization peak temperatures (e.g., 148.72 °C for Sample B) than the sucrose control (A, 219.44 °C), and milk chocolate Samples I and F did not carbonize within the 15–250 °C range. In conclusion, although sweetener choice, formulation, and ingredients induced statistically significant differences ($p < 0.05$) in flow limits and physical characteristics, the commercial products maintained quality control comparable to the sugar-based control commonly sold in Brazil.

Keywords: chocolate, sucrose, rheological properties, Brazilian market.

Resumen

Comprender las tendencias locales es esencial para evaluar preferencias de consumidores y su apertura a nuevos productos. Se compararon nueve chocolates comerciales amargos y con leche (con y sin sacarosa) del mercado brasileño, evaluando color, propiedades calorimétricas, reológicas y de textura. Se aplicó ANOVA de una vía y prueba de Tukey ($p < 0{,}05$). La textura, medida con esfuerzo de flexión normalizado (σflex), mostró que los chocolates amargos fueron más resistentes a la fractura que los de leche; la muestra con xilitol (D) fue la más resistente. Todas las muestras presentaron comportamiento pseudoplástico (modelo de Casson, $R^2 > 0{,}98$). Los chocolates con leche mostraron mayores valores reológicos (esfuerzo de fluencia, viscosidad plástica y tixotropía), mientras que la muestra D tuvo viscosidad plástica significativamente menor (1,37 Pa·s). La sustitución de sacarosa alteró el color: la muestra C (maltitol) presentó mayor b* (8,54 ± 0,25) y menor Índice de Blancura (20,59 ± 0,33), y la muestra I (maltitol/polidextrosa) difirió del control (E) en todos los parámetros, con menor L* (31,44 ± 0,26). En calorimetría, los chocolates amargos sin azúcar mostraron picos de carbonización más bajos (p. ej., 148,72 °C para B) que el control (A, 219,44 °C); las muestras I y F no se carbonizaron en el rango 15–250 °C. En conclusión, aunque el edulcorante y la formulación indujeron diferencias significativas ($p < 0{,}05$) en las propiedades físicas, los productos mantuvieron calidad comparable al chocolate con sacarosa comercializado en Brasil.

Palabras clave: chocolate, sacarosa, propiedades reológicas, mercado brasileño.

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Introduction

The chocolate results from a mix of cocoa (*Theobroma cacao* L.) derivatives and other ingredients, such as sugars, milk, and emulsifiers. According to Brazilian legislation, a product must contain at least 25% (g/100g) of cocoa solids to be classified as chocolate (Brasil, 2022). In a bar of traditional chocolate, the sucrose amount represents approximately 40–50 % of the chocolate solids. It enhances sweetness and affects particle distribution, as well as the rheological and sensory properties. Additionally, it serves as a bulking agent and energy source, providing 394 kcal/100 g from refined sugar (Sarfarazi & Mohebbi, 2020). However, growing awareness of problems, such as being overweight, obesity and diabetes, associated with the high caloric value of chocolate, has led consumers to prefer sugar-free or reduced-sugar options (Selvasekaran & Chidambaram, 2021).

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Of the estimated 1 billion obese individuals, 650 million are adults, 340 million are adolescents, and 39 million are children, with these numbers trending upward (WHO, 2022; WHO, 2023). Global obesity rates have nearly tripled since 1975; 1.9 billion adults (39%) and 381 million children and adolescents are now overweight or obese (Wang, Minton, Zhang, 2020). The World Health Organization (WHO) recommends limiting added sugar intake to 10% of total caloric intake. Addressing obesity is a priority for achieving the Sustainable Development Goals and the European Programme of Work 2020–2025 (WHO, 2022; WHO, 2023).

Recently, sugar-free chocolates have gained appeal and popularity among consumers due to their low calories, non-carcinogenic character, and suitability for diabetics (Sarfarazi & Mohebbi, 2020). This trend is notably driven by increasing health concerns regarding the adverse effects of excessive sugar intake, which has motivated the use of sweeteners that possess a comparable sweetening profile to sucrose in chocolate formulations (Gameiro et al., 2023).

Thus, polymers with low or no digestibility and low-energy edible carbohydrates are used to produce chocolates with low or no sugar content, which satisfy both sweetness and particle size and distribution characteristics (Selvasekaran & Chidambaram, 2021). An innovative alternative to bulk sugar reduction is the use of inhomogeneous sugar distribution, in which chocolates are engineered in layers of varying sugar concentrations to enhance sweetness perception while reducing the overall sucrose content. For example, a layered formulation with a 20% reduction in sugar content achieved the same level of sweetness as the reference chocolate (Dadalı & Elmacı, 2025).

Among sucrose substitutes, polyols are considered good sweetening agents, as some of them, in addition to their sweetening power and flavor preservation capacity, have structural characteristics that can be used individually or combined with some soluble fiber to improve the rheological properties of chocolate (Lipkin et al., 2025). These ingredients contain fewer calories, induce a low glycemic index and are often added to diet chocolates from large industries. It is important to emphasize that the selection of the bulk sweetener is a critical compositional factor, as it significantly influences the final rheological properties of the chocolate mass (Saupi et al., 2025).

The systematic substitution of sucrose with alternative ingredients in dark chocolate formulations constitutes an active research area, with studies focusing on the resulting physicochemical properties, sensorial acceptance, and potential health benefits (Saupi et al., 2025). Therefore, this study aimed to perform a comparative analysis of key physical properties (color, rheology, calorimetry (DSC), and texture) between commercially available sugared and sugar-free milk and dark chocolate samples from the Brazilian market. The sugar-free formulations included maltitol, xylitol, and sucralose as sweeteners, with samples [G], [H], and [I] also incorporating polydextrose as a bulking agent (as shown in Tables 1 and 2). The comparative evaluation of these physical properties was conducted to determine the specific physical influence of the alternative sweeteners and their synergistic effects in the distinct milk and dark chocolate matrices.

Materials and Methods

In this study, nine different chocolates commonly found on the Brazilian market were evaluated. The samples were divided into dark (A, B, C, D) and milk (E, F, G, H, I) chocolates, in which sugared A and E were used as a control for comparison with the other sugar-free samples (Table 1 and 2).

Table 1
List of ingredients for dark chocolate

Chocolates	Cocoa solids content (%)	List of ingredients
A Control	70	cocoa mass, sugar, cocoa butter, cocoa powder, emulsifiers: ricinoleic acid esters interesterified with polyglycerol and soy lecithin and flavoring.
B	70	cocoa mass, cocoa butter, collagen, sweeteners: maltitol and sucralose, emulsifiers: soy lecithin and ricinoleic acid esters interesterified with polyglycerol and flavoring.
C	70	cocoa mass, cocoa butter, cocoa powder, sweetener: maltitol, emulsifier: soy lecithin and flavoring.
D	70	cocoa mass, cocoa butter, whole milk powder for lactose-restricted diets (whole milk, lactase enzyme, vitamins A, C, D and soy lecithin emulsifier), sweetener: xylitol and emulsifier: soy lecithin.

Source: Product labels.

Table 2

List of ingredients for milk chocolates

Chocolates	List of ingredients
E Control	sugar, milk powder, cocoa butter, cocoa mass, vegetable fat, emulsifiers: soy lecithin and ricinoleic acid esters interesterified as polyglycerol and flavoring.
F	milk powder, cocoa butter, cocoa mass, anhydrous milk fat, sweetener: maltitol, emulsifiers: soy lecithin and ricinoleic acid esters interesterified as polyglycerol and flavoring.
G	cocoa butter, whole milk powder, cocoa mass, demineralized whey, collagen, soluble corn fiber, sweeteners: maltitol and sucralose, humectant: polydextrose, emulsifiers: soy lecithin and ricinoleic acid esters interesterified as polyglycerol and flavoring.
H	cocoa butter, whole milk powder, cocoa mass, cream powder, whey powder, sweetener: maltitol, bulking agent: polydextrose, emulsifiers: soy lecithin and ricinoleic acid esters interesterified as polyglycerol.
I	instant whole milk powder for lactose-restricted diets (whole milk, lactase enzyme, vitamins A, C, D and emulsifier soy lecithin), cocoa butter, cocoa mass, polydextrose, sweetener: maltitol and emulsifier: soy lecithin.

Source: Product labels

All measurements were conducted in triplicate for each sample and data were expressed as mean ± standard deviation. Differences among samples were evaluated using one-way analysis of variance (ANOVA) with a significance level of 0.05. When ANOVA indicated significant differences, Tukey's Honestly Significant Difference (HSD) post hoc test was applied for multiple comparisons between group means. These statistical analyses were performed using R version 4.4.1 (R Core Team, 2024) within the RStudio environment (RStudio Team, 2025). The samples were not tempered before the analysis but were only melted at 40 °C. Color and texture measurements were performed at ambient temperature and humidity.

Colorimetry

Colorimetric analysis of market samples (dark and milk chocolate) was performed using the Colorium2 colorimeter (Delta Color, Rio Grande do Sul, Brazil) to assess the *L**, *a**, and *b** parameters in the CIELAB D65/10º color space. Measurements were conducted at ambient temperature (25 °C) and humidity (60% RH). Data processing was carried out using Lab7 software (Delta Color, Rio Grande do Sul, Brazil).

Rheology

A rotational test was performed using a MARS II Rheometer (Thermo Scientific, Germany), with the Rheowin software and a C35/2 rotor (d=35 mm, 2° angle) and a 0.105 mm gap. The controlled rate (CR) test was conducted in three phases: (1) Gradual increase in the rate from 0.00 to 65.00 rotations per second (1/s) over 180 seconds; (2) Maintaining the rate at 65.00 1/s for 60 seconds; (3) Gradual decrease from 65.00 1/s to 0.00 1/s over 180 seconds at 40 °C, after pre-conditioning the sample at the same temperature. Samples were not tempered before analysis but were melted at 40 °C. A sufficient sample volume was used to fill the space between the rotor and base. The Casson model was fitted to the flow curves using the Rheowin software's built-in regression analysis, which employs the least squares method. Model fit quality was evaluated based on the coefficient of determination (R^2), with $R^2 > 0.95$ considered indicative of adequate fit. Results were applied to the Casson equation for plastic viscosity and yield stress data (Beckett, 2008; Agibert, Lannes, 2018). Thixotropy values were determined based on the area of the hysteresis loop formed.

Texture

To analyze the breaking strength of the chocolates, a break force test was performed on each sample (milk and dark chocolate), both controls (with sucrose) and sweetened with different sweeteners. The samples were pre-conditioned at 25 °C, and the test was conducted using a Brookfield CTX texture analyzer (AMETEK, Brookfield, Middleboro, MA, USA) with a TA-TPB probe. The parameters used were: (a)trigger speed: 1 mm/s, (b)target speed: 2 mm/s, and (c)speed: 17 mm/s, distance: 4 mm, load cell: 50 kg, compression force: 0.05 N. Data were collected using Texture Pro V1.0 Build 15 software. Considering these were market samples, they had different areas and thicknesses, though all were rectangular. After measuring the breaking force, the Section Modulus was calculated (Equation 1).

$$S = \frac{b \cdot h^2}{6} \tag{1}$$

Where:

S: Section Modulus; b: Width; h: Thickness.

The section modulus S directly depends on the geometry of the chocolate's cross-section, including its thickness, and for a rectangular shape (assuming the chocolate's section is approximately rectangular).

Followed by the Bending Moment (Equation 2).

$$M = \frac{F \cdot L}{4} \tag{2}$$

Where:

M: Bending Moment; F: Breaking force; L: Length.

The bending moment is the force required to break the chocolate multiplied by the distance to the breaking point (assuming the force is applied at the center of the bar).

Finally, the bending stress was determined (Equation 3) to compare values regardless of the chocolate bar's geometry.

$$\sigma_{\text{flex}} = \frac{M}{S} \quad (3)$$

Where:

σ_{flex}: Bending Stress; M: Bending Moment; S: Section Modulus.

The bending stress (σflex) is directly related to the force F and the length L, and inversely related to the width b and the square of the thickness h. The higher the bending stress value, the greater the chocolate's resistance to breaking, regardless of its dimensions. Measurements were conducted at ambient temperature (25 °C) and humidity (60% RH). For the texture parameters used to calculate the bending stress values see the Appendix Table A1.

Calorimetry

Differential Scanning Calorimetry (DSC) analyses were conducted using a DSCi Series device (Instrument Specialists Incorporated, I Series, Twin Lakes, WI, USA). The equipment was calibrated at a scanning rate of 20 °C/min using an aluminum pan as a reference. Samples (3 mg) were placed in aluminum pans with a volume of 40 µL and sealed with lids using a crimper. The samples were heated at 20 °C/min from 15 °C to 250 °C under a nitrogen atmosphere (N_2). The heating curve was obtained using Infinity Pro-Thermal Analysis software (Instrument Specialists Incorporated, Twin Lakes, WI, USA), based on data from the Acquire program, allowing for the determination of melting properties (start, peak, and end temperatures), caramelization, and carbonization.

Results and Discussion

The evaluation of commercially available products, while essential for providing a realistic perspective on market trends, imposes a critical methodological limitation on the interpretation of results. The statistically significant differences (p-value < 0.05) observed across all physicochemical parameters (Color, Rheology, and Calorimetry) cannot be solely attributed to the type of sweetener or fiber used. Each analyzed sample represents a unique commercial formulation, where industrial processing parameters (such as conching time and temperature, degree of particle size reduction) and the exact composition of secondary ingredients (e.g., cocoa mass origin, fat content, type of emulsifier) are uncontrolled variables in this study. Consequently, the results reflect the combined, synergistic influence of the entire manufacturing matrix and ingredient composition. This inherent variability in market samples must be considered when interpreting cause-and-effect relationships, as the differences observed stem from the overall formulation, and not just the sucrose substitute in isolation.

Colorimetry

The sample C showed the greatest statistically significant difference (p-value < 0.05) in color parameters compared to the control sample A. This sample, which uses only maltitol as a substitute for sucrose, demonstrated significant differences in the *b** color component, h° hue angle, and WI. Sample D also showed a significant difference compared to sample A in *a** color component and *h*° hue angle, with the latter being similar to sample C, as shown in Table 3.

Table 3

Color characteristics of sugar-free and sugared dark chocolates

Color space	A •	B	C	D
*L**	23.69 ± 1.06^{a}	21.88 ± 1.14^{a}	21.71 ± 0.26^{a}	22.36 ± 0.27^{a}
*a**	10.41 ± 0.48^{a}	9.56 ± 0.78^{a}	10.21 ± 0.42^{a}	8.30 ± 0.0^{b}
*b**	6.83 ± 0.49^{a}	7.51 ± 0.58^{a}	8.54 ± 0.25^{b}	7.67 ± 0.6^{ab}
*C**	12.46 ± 0.50^{a}	12.18 ± 0.51^{a}	13.31 ± 0.48^{a}	11.40 ± 0.40^{a}
h°	33.26 ± 2.13^{a}	38.18 ± 3.87^{a}	39.90 ± 0.49^{b}	42.74 ± 1.35^{b}
WI	22.68 ± 1.00^{a}	20.94 ± 1.20^{ab}	20.59 ± 0.33^{b}	21.54 ± 0.23^{ab}

Sweetener–A: Sucrose; B: maltitol and sucralose; C: maltitol; D: Xylitol. The same letter in the same row does not indicate a significant difference between the samples (p-value>0.05). n:3 *L*:* completely black (0), completely white (100); *a*:* green (-120), red (+120), and *b*:* blue (-120), yellow (+120). (•) indicating sugar-free chocolate. n:3 Same letter in the same line means no significant difference in 5% (p-value > 0.05)

Milk chocolates exhibited a greater statistically significant difference (p-value < 0.05) in the color parameters of the sugar-free samples compared to the control E. All samples significantly differed in at least two parameters, with sample I showing differences in all parameters compared to the control E (Table 4).

Table 4

Color characteristics of sugar-free and sugared milk chocolates

Color space	E •	F	G	H	I
*L**	42.22 ± 8.74a	42.00 ± 0.65a	37.71 ± 0.25b	41.34 ± 0.08a	31.44 ± 0.26c
*a**	15.11 ± 0.28a	16.49 ± 0.03b	13.33 ± 0.08c	16.20 ± 0.02b	13.14 ± 0.02c
*b**	15.22 ± 0.65a	16.51 ± 0.03ad	13.56 ± 0.10b	17.24 ± 2.05d	10.91 ± 0.16c
*C**	21.47 ± 0.21a	23.34 ± 0.13b	19.00 ± 0.09c	23.18 ± 0.17b	18.08 ± 0.38c
h°	45.19 ± 2.51a	45.04 ± 0.56a	45.44 ± 1.37a	45.66 ± 0.93a	39.72 ± 0.71b
WI	38.35 ± 7.60a	37.48 ±0.63ab	34.87 ± 0.22b	36.74 ± 0.04ab	29.34 ± 0.20c

Sweetener–E: Sucrose; F: maltitol; G: maltitol, sucralose, and polydextrose; H: maltitol and polydextrose; I: maltitol and polydextrose. The same letter in the same row does not indicate a significant difference between the samples (p-value>0.05). n:3 L*: completely black (0), completely white (100); a*: green (-120), red (+120), and b*: blue (-120), yellow (+120). (•) indicating sugar-free chocolate. n:3. Same letter in the same line means no significant difference in 5% (p-value > 0.05)

The results suggest that dark chocolates tend to present a more reddish coloration. Among all samples, chocolate D, containing the sweetener xylitol, showed the least tendency towards a reddish color, and the chocolates with maltitol showed more tendency toward a yellowish coloration. The whiteness index of chocolate C (maltitol) presented a lower value and a significant difference from the other samples, making maltitol only a good option for producing a product with fewer light spots on the surface. For a dark chocolate, the appropriate whiteness index is approximately 20 ± 1, immediately after the chocolate is produced (Marcus, 2013).

Due to the milk solids, the whiteness index values of milk chocolates were higher than those of dark chocolates. The choice of milk powder used in chocolate may likely influence its coloration, increasing the Whiteness Index (WI) (Son et al., 2018). Thus, it is possible to associate the significant statistical differences (p-value < 0.05) with the fact that each formulation has different processes, ingredients, and formulations that may influence the color of chocolates.

The L*, a*, and b* values varied much more among milk chocolate samples than dark chocolate ones, with the Maillard reaction influencing the non-enzymatic browning of some samples due to the presence of lactose (a reducing sugar) in most of them (Liang & Hartel, 2004).

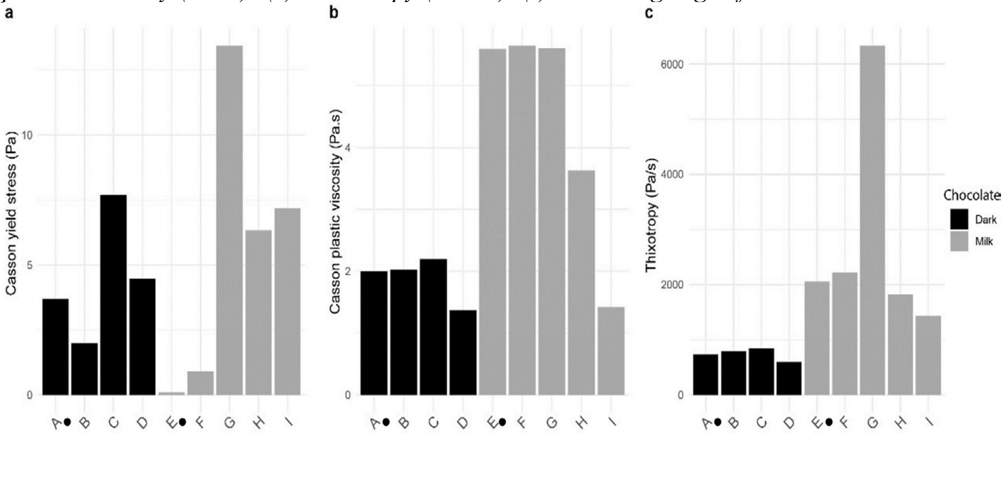
The whiteness index measurement is used to identify the appearance of fat bloom or sugar bloom, as the higher this index, the whitish the surface color (Son et al., 2018). In the evaluated samples, no fat or sugar migration defects were observed, allowing us to conclude that the significant difference found between the samples is due to their having different formulations and processes. Comparing both samples, the Whiteness Index of the control sample with sucrose, for both dark and milk chocolates, was higher than those using sweeteners, highlighting that the presence of sucrose crystals in the system, even if practically imperceptible to the naked eye, results in an increase in WI.

Rheology

In general, milk chocolates expressed greater values for the three rheological parameters evaluated in contrast with dark chocolates. Conversely, the milk chocolates E and F, both without polydextrose (fiber with a complex and compact structure), in their formulation, unlike the other milk chocolate samples, showed lower Casson yield stress than all dark chocolates; and sample I, presented lower or the same values of Casson plastic viscosity, contrasting with dark chocolates. Regarding thixotropy, sample G, which shows the most complex structure (Liang & Hartel, 2004), exhibited the highest values among other chocolates (Figure 1).

Figure 1

Chocolates rheological parameters evaluated: (a) Casson yield stress (Pa); (b) Casson plastic viscosity (Pa·s); (c) Thixotropy (Pa·s^{-1}). (•) indicating sugar-free chocolates.



Thixotropy is characterized as a property of a non-Newtonian and pseudoplastic fluid, manifesting a temporal change in its viscosity. In other words, a thixotropic fluid requires a finite time to reach equilibrium viscosity after an abrupt change in shear rate. The factors that affect shear and consequently thixotropy are particle size, fat content, and lecithin content (Rad et al., 2019; Ayres, 2019). The dark chocolate samples showed thixotropy values between 550 and 850 $Pa \cdot s^{-1}$, with the lowest value obtained from chocolate D (xylitol) and the highest from chocolate C (maltitol). As for milk chocolates, the only one that differed within the group was chocolate G (maltitol, sucralose, corn fiber, and polydextrose), which showed an extremely higher thixotropy value due to its complex structure, with two sweeteners and two soluble fibers.

For milk chocolates, only sample F (maltitol) did not differ significantly (p-value > 0.05) regarding the initial Casson yield stress from the control E (sucrose). This is possibly a result of the absence of polydextrose, a fiber with a complex and compact structure, in its formulation, unlike the other samples. Samples containing polydextrose required a higher initial yield stress.

Milk chocolates with added sweeteners showed a higher Casson yield stress compared to the sugar control. However, Casson viscosity did not follow a consistent pattern, with F (maltitol) and G (maltitol, sucralose, and polydextrose) showing statistical similarity (p-value > 0.05) to the control, while I and H (maltitol and polydextrose) showed a significant difference (p-value < 0.05) compared to the control. In dark chocolates, a higher shear stress was observed for chocolate C formulated with 100% maltitol than the others. In terms of viscosity, the chocolates did not present a statistically significant difference (p-value > 0.05) between them, except for sample D, made with 100% xylitol, which showed a viscosity of 1.37 Pa·s, a value lower than the others.

Sweetener crystals partially dissolve when in contact with water, forming a delicate syrup layer on their surface (Konar et al., 2018). This increases the internal friction between the sweetener particles, resulting in a viscosity increase. This occurs due to the non-Newtonian pseudoplastic behavior of chocolate: the more force applied, the more viscous it becomes. However, the fact that we observe different rheological characteristics for different types of chocolates (even those using the same sweetener to replace sucrose) can be explained by various factors, such as different processing parameters, ingredient quality, and the qualitative and quantitative composition of the ingredients in the formulation.

Low-sugar chocolates developed with maltitol exhibited significant variations in rheological properties compared to sugared chocolates, across different conching temperatures (Konar, 2012). This study concludes that, in addition to the influence of the concentration and type of sweetener, optimizing the conching process and other processing parameters plays a crucial role in achieving high-quality rheological properties in chocolate. This means that the same chocolate, with the same formulation or using the same sucrose substitutes, can present statistical differences in its rheology when using different processing parameters.

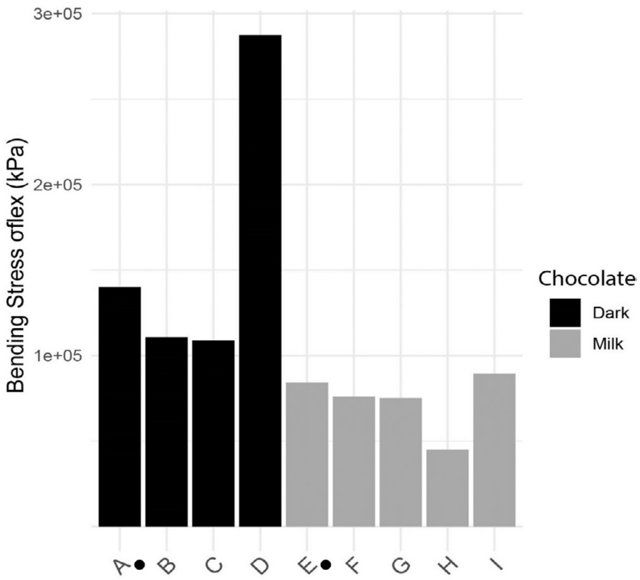
The sugar-free milk chocolate samples H and I were produced by replacing sucrose with a mixture of maltitol and polydextrose. Both chocolates showed reduced Casson viscosity and higher shear stress, which is consistent with the study observed in the literature, which produced dark chocolate with different concentrations of maltitol and polydextrose. Chocolates with a high polydextrose content tend to require higher shear stress to flow (Aidoo, Afoakwa & Dewettinck, 2014).

Texture

According to the calculated bending stress, dark chocolates presented greater breakage resistance than milk chocolates. The D sample showed the greatest resistance among all other chocolates (Figure 2), Bending stress (σflex) increases with the force and length, while it decreases with the width and the square of the thickness. A higher value of bending stress indicates greater resistance of the chocolate to breaking, irrespective of its dimensions.

Figure 2

Bar plot describing bending stress required to break each sample chocolate



Sweetener–A: Sucrose; B: maltitol and sucralose; C: maltitol; D: xylitol, E: Sucrose; F: maltitol; G: maltitol, sucralose, corn fiber and polydextrose; H: maltitol and polydextrose; I: maltitol and polydextrose. (•) indicating sugar-free chocolates.

Formulations containing a high concentration of polyols result in hardening effects in the final chocolates, which is attributed to the presence of highly hydrophilic active sites in polyols that are involved in the formation of intermolecular bonds (Cordeiro, Chagas, Dala-Paula, 2021). These hydroxyl groups become highly active during the chocolate manufacturing process and induce non-polar (intermolecular) interactions between the particles present throughout the chocolate matrix, making sugar-free chocolates generally harder. However, this was observed in this study only for chocolate D (xylitol), which showed a significantly higher hardness value compared to all the other chocolates.

In general, both dark and milk chocolates that use maltitol or a mixture of maltitol with another sweetener or fiber as a sugar substitute have greater similarity to control sugar-containing chocolates. Xylitol, however, is not the best option for sugar substitution if the goal of the development is to parity with sugar-containing chocolate.

Calorimetry

The sugar-free dark chocolates are carbonized at a lower temperature than dark chocolate with sugar. A significant difference (p-value < 0.05) was observed between chocolate B (sweetened with maltitol and sucralose) and control Chocolate A (sweetened with sucrose) in the melting peak. However, the other chocolates did not show significant differences compared to either of the two mentioned chocolates. Only Control chocolate A (sucrose) exhibited a caramelization peak. Additionally, the carbonization peak of Control Chocolate A (sucrose) differed statistically (p-value < 0.05) from the samples containing sweeteners, according to Table 5.

Table 5

Calorimetric properties of dark chocolates with sugar and sugar-free.

Mark	Melting peak (°C)	Caramelization peak (°C)	Carbonization peak (°C)
A	35.74 ± 0.53^{a}	182.91 ± 7.23^{a}	219.44 ± 3.25^{a}
B	34.42 ± 0.22^{b}	*	148.72 ± 0.18^{b}
C	34.93 ± 0.20^{ab}	*	150.38 ± 0.34^{b}
D	34.56 ± 0.89^{ab}	*	155.91 ± 7.82^{b}

Sweetener–A: Sucrose; B: maltitol and sucralose; C: maltitol; D: xylitol. Same letter in the same column means no significant difference in 5% (p-value > 0.05)

Except for sample F (containing maltitol), all sugar-free milk chocolates showed statistically significant differences (p-value < 0.05) in the melting peak versus the Control E (sugared) sample; however, no significant differences (p-value > 0.05) were observed among them, likely due to the addition of polydextrose, a fiber with a high melting point (Costa & Lannes, 2022). Among the sugar-free samples, only chocolates H and G exhibited caramelization peaks, which were significantly different (p-value < 0.05) from each other and from the Control. This could be attributed to Chocolate H containing a higher concentration of lactose-providing ingredients (milk powder, whey, and cream) than the other samples, and to Chocolate G containing sucralose in its formulation, both of which have caramelization potential (Beckett, 2008). Chocolate H did not differ significantly (p-value > 0.05) in carbonization from the control E, whereas chocolate G showed a statistically significant difference (p-value < 0.05). The other chocolates (I and F) did not carbonize within the tested temperature range (15–250 °C), suggesting their suitability for baking within this range (Table 6; Figure 3).

Table 6

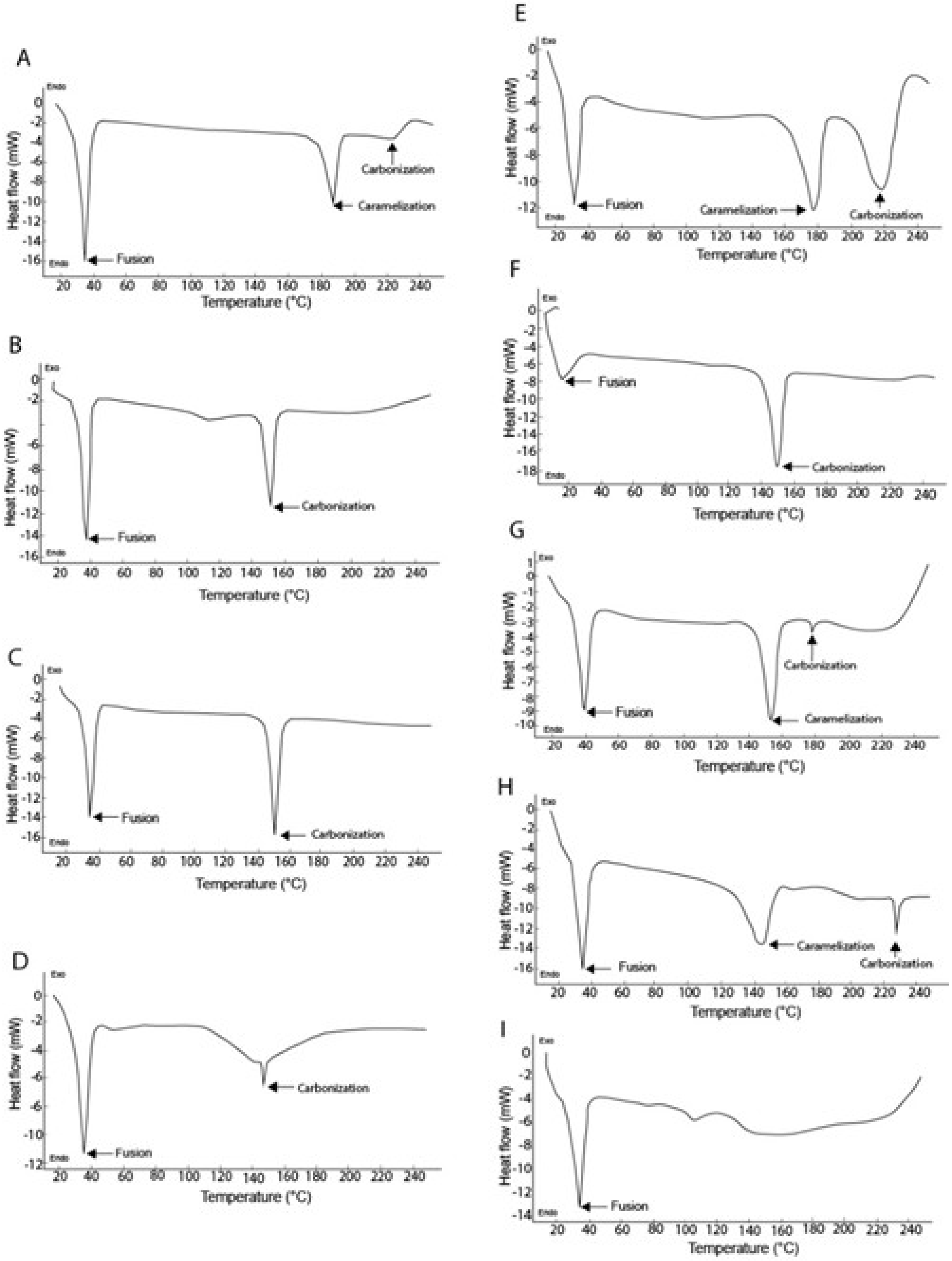
Calorimetric properties of milk chocolates with sugar and sugar-free

Mark	Melting peak (°C)	Caramelization peak (°C)	Carbonization peak (°C)
E	16.63 ± 1.10^{a}	180.68 ± 1.92^{a}	221.11 ± 1.31^{a}
F	17.15 ± 1.00^{a}	148.83 ± 0.42^{c}	**
G	34.69 ± 0.56^{b}	151.09 ± 1.21^{b}	185.06 ± 7.45^{b}
H	33.08 ± 1.32^{b}	141.48 ± 6.55^{c}	227.78 ± 7.53^{a}
I	34.90 ± 0.24^{b}	*	**

Sweetener–E: Sucrose; F: maltitol; G: maltitol, sucralose, corn fiber and polydextrose; H: maltitol and polydextrose; I: maltitol and polydextrose. Same letter in the same column means no significant difference in 5% (p-value > 0.05)

Figure 3

Calorimetric profile of the analyzed chocolates. Dark Chocolates sweetener–A: Sucrose; B: maltitol and sucralose; C: maltitol; D: xylitol. Milk Chocolates sweetener–E: Sucrose; F: maltitol; G: maltitol, sucralose, corn fiber and polydextrose; H: maltitol and polydextrose; I: maltitol and polydextrose



Conclusions

The variations observed in color, rheology, calorimetry, and texture are fundamentally related to the type of sweetener and soluble fiber incorporated into the chocolates, leading to the following main conclusions:

Main Findings

Texture and Rheology by Substitute: Xylitol imparts a peculiar crystallization characteristic that results in significantly harder and more compact chocolates with a lower thixotropy value. In contrast, maltitol, whether used alone or in combination with other ingredients, tends to maintain the product's hardness and flow properties similar to those of traditional sucrose-containing chocolate. Fiber Influence and Thermal Stability: The incorporation of soluble fibers (such as polydextrose and corn fiber) serves as a key structural factor, significantly increasing both thixotropy and initial Casson yield stress. Thermally, chocolates without sucrose tend to carbonize at a lower temperature; however, formulations containing maltitol and polydextrose exhibited a higher melting temperature. Optimal Replacement Strategy: A single ideal substitute does not exist. The combination of maltitol and polydextrose proved to be the most advantageous in terms of cost and calorimetric behavior (melting/processing), whereas substitution with xylitol was the optimal choice for achieving parity in color (reddish hue) and viscosity with the sucrose control.

Study Limitations

The study's scope is limited by the lack of sensory data, hindering the direct assessment of consumer acceptance based on physicochemical findings. Furthermore, the methodological approach utilizing commercial samples introduces complexity, as observed variations reflect the synergistic influence of the unique ingredient matrix and uncontrolled processing parameters, rather than the isolated effect of the sucrose substitute.

Future Research Directions

As a continuation of these findings, the following research lines are proposed: Sensory Studies: Conduct detailed sensory analyses to correlate the significant differences in texture (xylitol hardness) and color (reddish/yellowish hues) with consumer perception and acceptability. Microstructural Analysis: Develop microstructural studies (e.g., using Scanning Electron Microscopy) to visualize the crystallization morphology of the polyols and the fiber interaction, which would help explain the observed variations in hardness and thixotropy at a fundamental level.

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Appendix

Table A1. Raw dimensional and strength parameters used for texture analysis (Strength, Length, Width, Thickness) and the calculated values for Section Modulus (m^3), Bending Moment M (Nm) and mean Bending Stress (σflex) for samples A through I. Samples A and E serve as controls. Superscript letters in the Bending Stress column indicate the results of the Tukey's HSD post-hoc test. Values sharing the same letter are not significantly different (p-value > 0.05), while values with different letters are significantly different (p-value < 0.05).

Dark samples	Strength (N)	Length (m)	Width (m)	Thickness (m)	Section Modulus S (m^3)	Bending Moment M (Nm)	Bending Stress σflex (Pa)
A – Control	18.67 ± 0.54	0.0080	0.0025	0.0008	2.67×10^{-10}	0.0373	140,025.000[a]
B	19.51 ± 0.53	0.0069	0.0029	0.0008	3.09×10^{-10}	0.0336	108,797.683[b]
C	44.12 ± 0.55	0.0065	0.0023	0.0013	6.48×10^{-10}	0.0717	110,668.896[b]
D	11.35 ± 1.75	0.0079	0.0013	0.0006	7.80×10^{-11}	0.0224	287,387.821[c]

Milk samples	Strength (N)	Length (m)	Width (m)	Thickness (m)	Section Modulus S (m^3)	Bending Moment M (Nm)	Bending Stress σflex (Pa)
E – Control	5.42 ± 0.13	0.0082	0.0022	0.0006	1.32×10^{-10}	0.0111	84,174.242[a]
F	4.90 ± 0.33	0.0082	0.0022	0.0006	1.32×10^{-10}	0.0100	76,098.485[b]
G	5.69 ± 1.15	0.0092	0.0029	0.0006	1.74×10^{-10}	0.0131	75,212.644[b]
H	17.94 ± 0.35	0.0065	0.0023	0.0013	6.48×10^{-10}	0.0291	45,000.000[c]
I	5.76 ± 0.06	0.0082	0.0022	0.0006	1.32×10^{-10}	0.0118	89,454.545[a]