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Optimization of the Formulation of Prebiotic Milk Chocolate Based on Rheological Properties

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Summary

Rheological properties are very important parameters in the production of products with high-quality and desirable texture. So far, many attempts to produce low-calorie milk chocolate have not succeeded. Therefore, the present study aims to evaluate the effects of sugar substitutes on rheological characteristics of prebiotic milk chocolate using Simplex-lattice mixture design. For doing this, a prebiotic compound (inulin) with two bulking agents (polydextrose and maltodextrin) at different levels (0–100 %) along with sucralose were used. Fifteen formulations covering the entire range of a triangular simplex were examined in order to find the optimum levels. All chocolates showed thixotropic and shear thinning behaviour and among the evaluated mathematical models, Casson model showed the best fitting for predicting rheological properties. According to our findings, chocolate formulations containing high levels of sugar substitutes (where a single component predominated) had higher moisture content, Casson viscosity and yield stress than others, including the control. In contrast, the lowest moisture content, Casson viscosity and yield stress were observed at medium levels. Therefore, the optimum values for substitution of sucrose and production of a low-calorie prebiotic milk chocolate are 8–28 % and 67–86 % for inulin, 0–19 % and 31–69 % for polydextrose and 0–47 % for maltodextrin, respectively.

Key words: chocolate, sugar substitutes, simplex-lattice mixture design, rheology, prebiotic

Introduction

Within the past few years, increasing health and nutrition care and public demands have motivated the production of low-calorie, low-fat and reduced sugar products (*1*). Moreover, consumption of low sugar products is recommended for diabetes, weight control and prevention of dental cavities (*2*). In addition, studies are showing that sugar substitutes may play an essential role in the development of products with health promoting properties. In this regard, the possibility to combine sweeteners with fibres and prebiotic compounds (*e.g.* inulin) and their applications in production of dietetic foods can be pointed out (*3,4*).

In general, melted chocolate represents a suspension of sugar, cocoa and milk powder in a liquid matrix of mainly cocoa butter (*5*), exhibiting non-Newtonian flow behaviour with a yield stress (*6,7*). Moreover, rheological characteristics are important in manufacturing process for obtaining high-quality product with well-defined texture depending on composition, processing strategy and particle size distribution (*8*). These characteristics can be described with some mathematical models (constitutive equations) (*6*). The International Office of Cocoa, Chocolate and Sugar Confectionery (IOCCC) suggests the use of rotational viscometers equipped with concentric cylinder (bob and cup geometry) at shear rate between 5 and 60 s^{-1} and Casson equation for rheological measurement of ordinary chocolates (*6,7,9*). However, the major challenge at present is how to match the functions of sugar using sugar substitutes on various aspects, particularly rheological properties of the finished

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*Corresponding author; Phone: ++98 21 4458 0500 (2321); Fax: ++98 21 4419 6524; E-mail: sabbasifood@modares.ac.ir product (*10*). Hence, the question arises whether replacing the sugar with various combinations of sugar substitutes in order to produce low sugar chocolate would have any influence on the rheological properties or not. If yes, would these changes affect the fitting of mathematical models as well or not? It is believed that optimization of a formulation can be achieved through different experimental designs and it is an alternative to minimize the number of experiments. In addition, mixture experiments are well suited for products with more than one ingredient.

Therefore, the aim of the present study is to verify the effects of replacing the sugar in milk chocolates with different combinations of inulin (IN), polydextrose (PD), maltodextrin (MD) and sucralose on rheological properties, mathemathical model fittings, as well as finding the optimum levels of these compounds, using a simplex-lattice mixture design.

Materials and Methods

Materials

The ingredients including cocoa powder (Delfi Cocoa, Johor Darul Takzim, Malaysia), cocoa butter (Cargill, Kuala Lumpur, Malaysia), lecithin (ADM, IL, USA), skimmed milk powder (BinaRazan, Razan, Iran), IN Frutafit® IQ, TEX, CLR (Sensus, Roosendaal, the Netherlands), PD Litess® Ultra (Danisco Deutschland GmbH, Bönningstedt, Germany), MD (DE=18) (SCT, Bangkok, Thailand), sucralose Splenda® (Tate and Lyle, AL, USA), sucrose (Iran sugar Co., Tehran, Iran), and vanilla powder (Golha Foods, Tehran, Iran) were used for the production of milk chocolates.

Size reduction

Using a domestic mill (Cogen Electric, Japan), sucrose, IN, PD, MD and skimmed milk granules were milled. Then, the powder was sieved using a nest of shaking sieves (pore sizes 53, 45, 38 and 20 μm), and distinct particles (+20 and –38 μm) were used for the production of chocolates.

Milk chocolate production

In order to prepare milk chocolate (100 g), cocoa butter (23 g) was initially melted in an oven at 60 °C, then cocoa powder (11.86 g), sugar (41.8 g) or its substitutes (including IN, PD, and MD according to the experimental design), sucralose (0.04 g) and skimmed milk powder (14 g) were added to the molten cocoa butter. The mixture was then transferred to a paraffin bath (65 °C) and conched using a vane mixer (designed in our laboratory, diameter of blades 50 mm) at 50 rpm for 3.5 h. After that, lecithin (0.3 g) and the rest of the cocoa butter (9 g) were added, and conching was continued for 30 min (*6*). Then, the molten chocolate was stored in an incubator overnight at 50 °C. The next day, milk chocolates were tempered (cooled down to 20 °C in 20–25 min, stored for 10 min, heated up to 30 °C and stored for 5 min) before casting into plastic moulds (50×20×10 mm). These plastic dies were then placed in water bath (15 °C) for 30 min for demoulding purposes. The finished chocolate bars were wrapped in aluminium foils and stored in a fridge prior to analysis. It needs to be noted that the control sample contained sucrose instead of sugar substitutes.

Rheological measurements

Rheological properties of milk chocolates were determined using a rheometer (Physica UDS 200, Physica Messtechnik GmbH, Stuttgart, Germany) operating in a controlled shear rate rotation mode. In order to melt them, chocolate samples were incubated at 50 °C for 75 min, then transferred to a cup (concentric cylinder geometry, Z3 DIN) and presheared (10 min, shear rate=5 s^{-1}) at 40 °C before measurement cycles started. Afterwards, shear stress was measured as a function of shear rate over a wide range (0.01 to 60 s^{-1} upward and downward, each measurement took 180 s) at 40 °C. The fitting of the collected data with mathematical models including Bingham, Casson, Power law and Herschel-Bulkley was done. The best fitting was selected by statistical analysis based on the coefficient of determination (R^2) and standard error (S.E.) values. Moreover, the rheological parameters including viscosity and yield stress values of the selected models were calculated.

Statistical analysis

The simplex-lattice mixture design was used to investigate the effects of replacing the sugar with IN, PD and MD on rheological properties of prebiotic milk chocolates as well as to determine the optimum formulations. Moreover, the JMP Software (v. 5.1, SAS Institute Inc., Cary NC, USA) was used for experimental designs, to calculate equations and statistical evaluations. Using the JMP software, over a wide range of ratios (0–100), only fifteen combinations of three sugar substitutes (IN, PD, and MD) were tested (Table 1). Mathematical model

Table 1. Mass fraction and quantity of sugar substitutes in various formulations of prebiotic milk chocolates

Sample no.	Level/%			*w*(IN)/g	*w*(PD)/g	*w*(MD)/g
	X_1	X_2	X_3			
1	0	0	100	0	0	41.80
2	0	25	75	0	10.45	31.35
3	0	50	50	0	20.90	20.90
4	0	75	25	0	31.35	10.45
5	0	100	0	0	41.80	0
6	25	0	75	1 0.45	0	31.35
7	25	25	50	10.45	10.45	20.90
8	25	50	25	10.45	20.90	10.45
9	25	75	0	10.45	31.35	0
10	50	0	50	20.90	0	20.90
11	50	25	25	20.90	10.45	10.45
12	50	50	0	20.90	20.90	0
13	75	0	25	31.35	0	10.45
14	75	25	0	31.35	10.45	0
15	100	0	0	41.80	0	0

IN=inulin, PD=polydextrose, MD=maltodextrine fittings were evaluated with linear and nonlinear regression analysis of rheological data using SigmaPlot 2001 v. 7.02 (SPSS Inc., Chicago, IL, USA) (*11*). The prediction equation for each parameter was obtained and contour plots were generated. To achieve the optimum region, contour plots of the predicted equations for each parameter were superimposed (*12*). The least significant difference (LSD) test was also used ($p<0.05$) to detect differences between mean values using SPSS software (v. 14.0, SPSS Inc., Chicago, IL, USA).

Results and Discussion

Rheograms of control and prebiotic milk chocolates are shown in Fig. 1. Hysteresis loops were observed in all chocolate formulations during upward and downward shear rate sweeps. The presence of this behaviour was confirmed by shearing at a constant shear rate for a few minutes, which decreased the viscosity of chocolate formulations. It was reported that the hysteresis loop alone is not a cause for thixotropic behaviour unless the sample shows shear thinning behaviour at constant shear rate as well (*9,13*). It is notable that the shift between ascending and descending curves can be reduced with sufficient waiting time at each shear rate (*9*). Moreover, this phenomenon can be an artifact of slippage on the walls of geometry (*9,13,14*). These findings show that any variation in sugar content and its replacement with various amounts of sugar replacers cannot affect the thixotropic behaviour of chocolates.

Shear thinning behaviour of chocolate formulations is shown in Fig. 2. As it can be seen, at low shear rates, the apparent viscosity was reasonably high, whereas with increasing the shear rate, they dropped almost 2 log

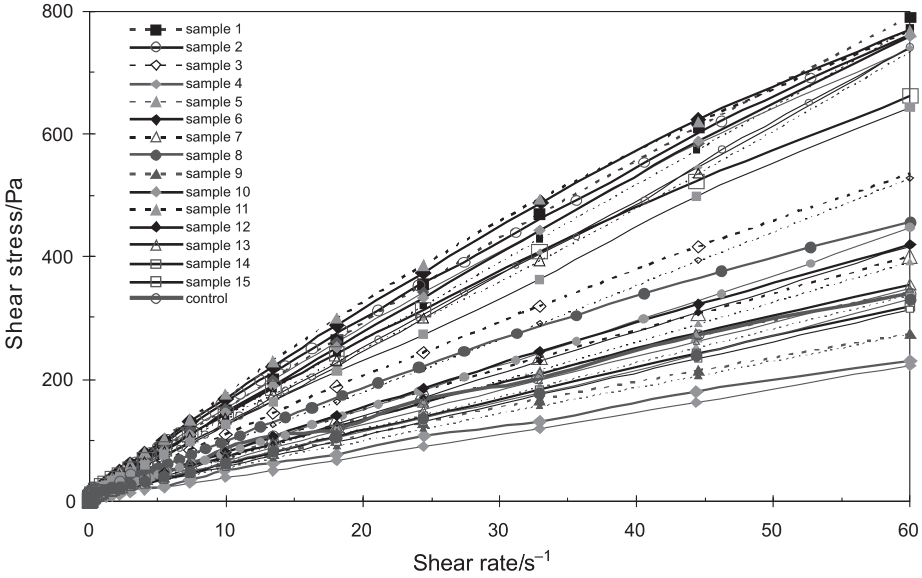

Fig 1. Effects of sugar substitutes on shear stress–shear rate rheograms of prebiotic milk chocolates

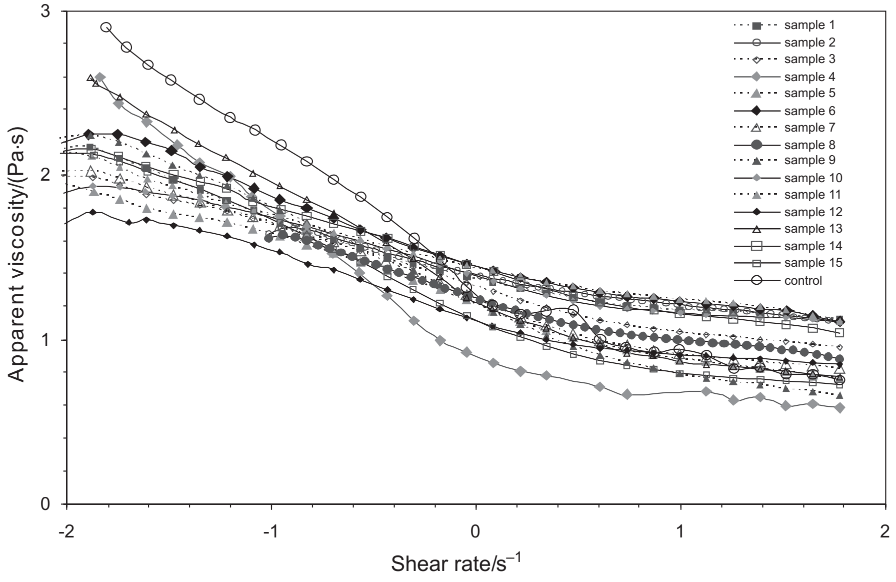

Fig 2. Effects of sugar substitutes on apparent viscosity–shear rate rheograms of prebiotic milk chocolates

cyles and any further increase of shear rate did not show any substantial effect on this parameter.

In the next step, in order to elucidate the influences of various combinations of sugar replacers on the rheological behaviour of prebiotic milk chocolates, their shear stress *vs.* shear rate data was fitted with some well known mathematical models including Bingham (Eq. 1), Casson (Eq. 2), Power law (Eq. 3) and Herschel-Bulkley (Eq. 4):

$$\sigma=\eta_{\mathrm{pl}}(\gamma)+\sigma_0 \qquad /1/$$

$$(\sigma)^{0.5}=K_1(\gamma)^{0.5}+(\sigma_0)^{0.5} \qquad /2/$$

$$\sigma=K\gamma^{\mathrm{n}} \qquad /3/$$

$$\sigma=K\gamma^{\mathrm{n}}+\sigma_0 \qquad /4/$$

where σ is shear stress (Pa), η_{pl} is plastic viscosity (Pa·s), γ is shear rate (s^{-1}), σ_0 is yield stress (Pa), K_1 is Casson viscosity [$(\mathrm{Pa\cdot s})^{0.5}$], K is consistency coefficient ($\mathrm{Pa\cdot s^n}$) and n is flow behaviour index (dimensionless). The fitting of experimental data with models was evaluated on the basis of the coefficient of determination (R^2) and standard error (S.E.) parameters. Based on statistical calculations, the Bingham and Casson models, despite providing the highest R^2 values, were not chosen as appropriate models as the further evaluation of standard errors revealed that the Casson model showed the best fitting for all chocolate formulations due to providing the highest R^2 as well as the lowest S.E. values (Table 2). As a result, it can be said that the substitution of sucrose, in spite of having influence on the rheological parameters, had no effect on mathematical model fitting and the same model

Table 2. Effects of sugar substitutes on fitting of experimental data with mathematical models based on determination coefficient and standard error parameters

Sample no.	Mathematical model	R^2	S.E.	Sample no.	Mathematical model	R^2	S.E.
1	Bingham	0.998	6.530	9	Bingham	0.995	4.390
	Casson	0.996	0.153		Casson	0.995	1.910
	Power law	0.989	0.196		Power law	0.979	0.204
	Herschel-Bulkley	0.980	0.318		Herschel-Bulkley	0.976	0.495
2	Bingham	0.997	7.640	10	Bingham	0.999	5.410
	Casson	0.999	0.228		Casson	0.998	0.287
	Power	0.997	0.082		Power law	0.994	0.147
	Herschel-Bulkley	0.977	0.074		Herschel-Bulkley	0.970	0.334
3	Bingham	0.997	6.030	11	Bingham	0.998	6.260
	Casson	0.997	0.299		Casson	0.997	0.373
	Power law	0.995	0.129		Power law	0.995	0.136
	Herschel-Bulkley	0.959	0.396		Herschel-Bulkley	0.993	0.161
4	Bingham	0.998	2.390	12	Bingham	0.999	2.860
	Casson	0.989	0.376		Casson	0.998	0.198
	Power law	0.902	0.398		Power law	0.991	0.181
	Herschel-Bulkley	0.865	0.698		Herschel-Bulkley	0.991	0.179
5	Bingham	0.995	5.310	13	Bingham	0.997	4.620
	Casson	0.995	0.330		Casson	0.996	0.271
	Power law	0.995	0.138		Power law	0.981	0.206
	Herschel-Bulkley	0.959	0.369		Herschel-Bulkley	0.969	0.316
6	Bingham	0.994	14.300	14	Bingham	0.996	9.940
	Casson	0.998	0.233		Casson	0.997	0.327
	Power law	0.979	0.247		Power law	0.993	0.144
	Herschel-Bulkley	0.990	0.200		Herschel-Bulkley	0.964	0.376
7	Bingham	0.998	4.260	15	Bingham	0.998	2.460
	Casson	0.996	0.321		Casson	0.997	0.239
	Power law	0.990	0.169		Power law	0.975	0.247
	Herschel-Bulkley	0.986	0.196		Herschel-Bulkley	0.959	0.284
8	Bingham	0.997	5.330	Control	Bingham	0.995	5.170
	Casson	0.998	0.175		Casson	0.991	0.387
	Power law	0.988	0.148		Power law	0.977	0.219
	Herschel-Bulkley	0.996	0.096		Herschel-Bulkley	0.948	0.378

R^2=determination coefficient, S.E.=standard error can be used for the prediction of rheological behaviour of control and prebiotic milk chocolates. Casson model is recommended by IOCCC and has been used as an internationally accepted standard model for determination of viscosity. It is now accepted and applied as an appropriate mathematical model for predicting flow behaviour and rheological analysis of different kinds of chocolates (*9,15*).

The effects of various combinations of sugar substitutes on the mean values of moisture content, apparent viscosity, Casson viscosity, and yield stress are shown in Table 3. As it can be seen, there are significant differences ($p<0.05$) between the moisture content of some formulations and control, but the lowest values belong to samples 7, 8, 11 and control. In contrast, chocolates with 100 % MD (sample no. 1) and 100 % PD (sample no. 5) have the highest moisture content ($p<0.05$). In general, the moisture content of formulations can be attributed to high and low hygroscopicity of bulking agents (*i.e.* MD and PD) and IN, respectively (Tables 1 and 3).

The Casson viscosity and yield stress values are calculated using $\sigma^{0.5}$ *vs.* $\gamma^{0.5}$ curves, where the slope and square of the intercept belong to the Casson viscosity and yield stress values, respectively (Table 3). These results revealed significant differences ($p<0.05$) in which sample no. 7 had the same Casson viscosity as the control and the lowest values belonged to samples nos. 8 and 11. Again, similar explanation was given for moisture content; the reason for low Casson viscosity values is related to the various hygroscopicity of sugar replacers. As it can be seen, there is direct relationship between moisture content and Casson viscosity, in which with the increase or decrease of the former, the latter rises or descends, respectively. The Casson viscosity values ranged from 1.81–4.71 $(Pa\cdot s)^{0.5}$, which is in a very good agreement with what was reported by Aeschlimann and Beckett (*16*) for milk chocolate (2.2–5.5 $(Pa\cdot s)^{0.5}$).

Table 3. Influence of various combinations of sugar substitutes on mean values of moisture content and some rheological parameters based on Casson model of prebiotic milk chocolates

Sample no.	Moisture content %	Apparent viscosity* Pa·s	Casson viscosity $(Pa\cdot s)^{0.5}$	Yield stress Pa
1	0.921^{a}	14.30^{a}	4.71^{a}	4.41^{b}
2	0.870^{b}	13.40^{b}	3.32^{d}	3.69^{c}
3	0.843^{bc}	13.00^{c}	3.11^{d}	2.56^{de}
4	0.841^{bc}	13.30^{c}	3.10^{d}	2.62^{d}
5	0.901^{a}	13.70^{bc}	3.62^{c}	2.56^{de}
6	0.862^{b}	13.90^{ab}	4.10^{b}	3.80^{c}
7	0.540^{hi}	6.11^{j}	2.12^{hi}	1.44^{h}
8	0.542^{hi}	4.94^{k}	1.93^{ij}	1.39^{h}
9	0.753^{ef}	11.90^{d}	2.82^{e}	2.34^{e}
10	0.594^{g}	6.55^{ij}	2.40^{fg}	1.90^{fg}
11	0.540^{hi}	4.62^{hi}	1.81^{j}	1.32^{h}
12	0.582^{gh}	6.62^{hi}	2.23^{gh}	1.72^{g}
13	0.720^{ef}	7.01^{gh}	2.40^{fg}	1.93^{fg}
14	0.712^{f}	7.33^{g}	2.52^{f}	1.99^{fg}
15	0.763^{de}	9.48^{e}	2.83^{e}	2.04^{f}
Control	0.531^{i}	6.32^{j}	2.12^{hi}	6.40^{a}

*apparent viscosities are reported at a constant shear rate (40 s^{-1}) for comparison purposes

different letters within columns indicate significant differences ($p<0.05$)

With regard to the yield stress, there was a direct relationship between moisture content and this parameter, except for the control ($p<0.05$). Aeschlimann and Beckett (*16*) reported a wide range (2–18 Pa) of yield stress values for milk chocolates. In the case of the present study, the yield stress values of some samples (nos. 7, 8 and 11) are situated slightly out of the lower part of the range given in Table 3. Although there have not been any particle size measurements in this study, such difference can be attributed to the various particle size and shapes of sugar substitutes in comparison with sugar used in the control formulation. To support this assumption, Nebesny and Żyżelewicz (*17*) in a study on sucrose-free chocolates confirmed the role of isomalt particle shape in lowering the yield in comparison with control. They pointed out that round edges of isomalt particles can improve the flow behaviour of sucrose-free chocolates.

The apparent viscosities (shear rate=40 s^{-1}) of prebiotic milk chocolates were between 4.62–14.3 Pa·s (Table 3). The trend of variations is similar to the trends noted with Casson viscosity and significant differences ($p<0.05$) were observed among formulations.

Taking into account the above-mentioned explanations and in order to find the optimized conditions, the moisture content and rheological parameters were subjected to analysis and prediction equations (Eqs. 5–8) were developed for each parameter (moisture content, Casson viscosity, yield stress and apparent viscosity, respectively) as follows:

$$y=0.823x_1+0.935x_2+0.992x_3-1.32x_1x_2-1.14x_1x_3-0.707x_2x_3;\ R^2=0.91 \tag{5}$$

$$y=2.88x_1+3.77x_2+4.95x_3-4.71x_1x_2-5.25x_1x_3-6.25x_2x_3;\ R^2=0.92 \tag{6}$$

$$y=2.22x_1+2.87x_2+4.98x_3-3.35x_1x_2-6.02x_1x_3-6.17x_2x_3;\ R^2=0.90 \tag{7}$$

$$y=9.57x_1+15.2x_2+16.2x_3-23.2x_1x_2-22.9x_1x_3-16.6x_2x_3;\ R^2=0.78 \tag{8}$$

After that, parameters with R^2 values of ≥0.85 (moisture content, Casson viscosity and yield stress) were included in the optimization model. Afterwards, their contour plots and predicted profiles were drawn where their details will be discussed in the following subsections.

Moisture content contour

As it is shown in Figs. 3 and 4a, the increase of sugar substitutes leads to a proportional increase in moisture content. Due to various levels of hygroscopicity, the formulations with high proportions of MD, PD and IN showed higher moisture content. Moreover, the moisture content in the presence of inulin (up to 50 %) diminished, whereas with its further increase, the moisture content was conversely increased. In terms of MD and PD, the increase of moisture content started at lower levels (<50 %), where the highest moisture content was

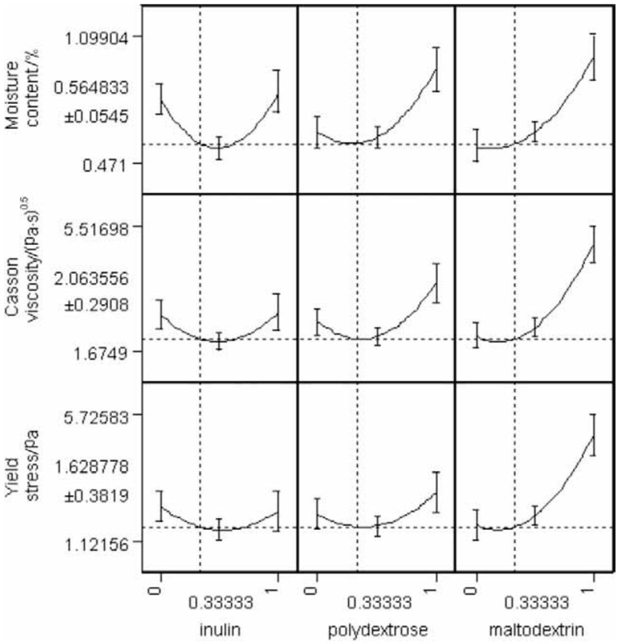

Fig 3. Predicted profiles for demonstrating the effects of individual sugar substitutes on the moisture content and two rheological properties

observed in samples containing high mass fractions of MD (Figs. 3 and 4a). It is reported that maltodextrin is a very hygroscopic ingredient (*18*) and this property is directly related to dextrose equivalent (DE) value due to the presence of low molecular mass saccharides (*19*). The hygroscopic property of polydextrose is also noted in studies on reduced calorie frozen dessert (*18*) and biscuit (*20*). It can be said that in comparison with other sugar substitutes, inulin had the lowest hygroscopicity and could increase the moisture content only at very high mass fractions, possibly through water binding capacity. Similarly, Cardarelli *et al.* (*21*) reported that petit-suisse cheese with high levels of inulin had higher moisture content.

Casson viscosity contour

According to Figs. 3 and 4b, increasing the proportions of any single sugar substitutes, Casson viscosity increased and the highest values were observed in chocolates containing high levels of MD, PD and IN, respectively. In contrast, the lowest values were related to the medium proportions of sugar substitutes, particularly inulin. The reduction of Casson viscosity was reported by Bolenz *et al.* (*22*) in chocolates containing 20 % of inulin as well. Based on our observations (Figs. 3 and 4b), the Casson viscosity reduced with the increase of IN (up to 50 %) and its further increase caused only a minor change in Casson viscosity, whereas in the case of MD and PD, these changes were very significant. This behaviour can also be related to low hygroscopicity of IN and its low water binding capacity, which leads to moisture reduction during conching process. Similar results were reported by Akin *et al.* (*23*) on the effect of inulin on rheological properties of yoghurt and ice cream. Moreover, Rapaille *et al.* (*24*) observed significant increase

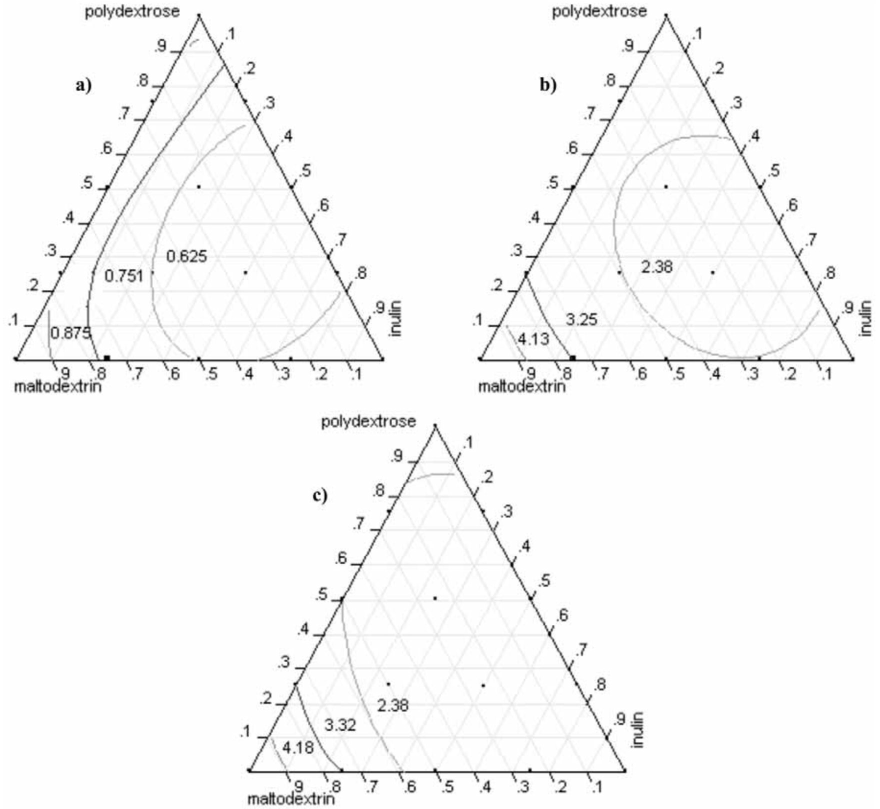

Fig 4. Ternary plots for illustrating the synchronized effects of inulin, polydextrose and maltodextrin on (a) moisture content, (b) Casson viscosity and (c) yield stress of prebiotic milk chocolates

in viscosity of chocolates containing PD, whereas chocolates with inulin showed a slight increase in viscosity and better rheological properties.

In terms of PD and MD, very significant increase in Casson viscosity was detected at higher proportions (Figs. 3 and 4b). These behaviours can be related mostly to their hygroscopicity and possibly to the molecular mass and saccharide content of these ingredients. In line with our observations and justifications, Ozdemir and Sadikoglu (*25*) pointed out that one of the reasons for viscosity increase of systems containing PD is their high molecular mass. Moreover, Dokic-Baucal *et al*. (*26*) also attributed the high Casson viscosity of formulations to high levels of MD with depletion flocculation mechanism in emulsion systems. In addition, Klinkesorn *et al*. (*27*) reported a considerable increase in relative viscosity of oil-in-water emulsions in the presence of higher concentrations (above critical level) of MD due to depletion flocculation. They explained that in the flocculated droplets, the effective volume fraction of particles is increased due to entrapping the continuous phase between droplets within flocs, and as a result of this process, the relative viscosity of the emulsion increases. It seems that in the present study, despite the differences between the oil-in-water emulsions and the formulation of chocolate, the same phenomenon has happened and the critical concentration of MD for depletion flocculation is probably about 50 %.

Yield stress contour

The same as Casson viscosity, yield stress values also increased with the increase of the content of MD, PD and IN, and the highest yield stress values were detected in formulations containing high proportions of these compounds (Figs. 3 and 4c). The lowest yield stress values were also observed in the presence of medium ratios of these ingredients. As it can be seen, the increase in the IN content (up to 50 %) reduced the yield stress, and at any higher proportions (>50 %), it changed only slightly. Bolenz *et al*. (*22*) in their study on chocolates containing IN also reported a significant reduction in yield stress. Moreover, yield stress values of chocolates were increased when the ratio of MD exceeded 30 % and high proportions of MD caused a considerable increase in this parameter (Fig. 3). The hygroscopic properties of MD and PD, high molecular mass of PD and depletion flocculation by MD are possible reasons for the behaviour discussed in the previous sections.

Optimal values

On the basis of our findings on prediction equations, the best acceptance limits for moisture content, Casson viscosity and yield stress, which show the highest similarity to control, were 0.682, 2.5 and 2, respectively. To obtain the optimal region, contour plots with these limits were superimposed (Fig. 5). The white region in these figures indicates that any point within this region represents an optimum combination of IN, PD and MD, which results in a desirable moisture content, Casson viscosity and yield stress in prebiotic milk chocolates. As a consequence, the optimum values were 8–28 and 67–86 % for IN, 0–19 and 31–69 % for PD and 0–47 % for MD.

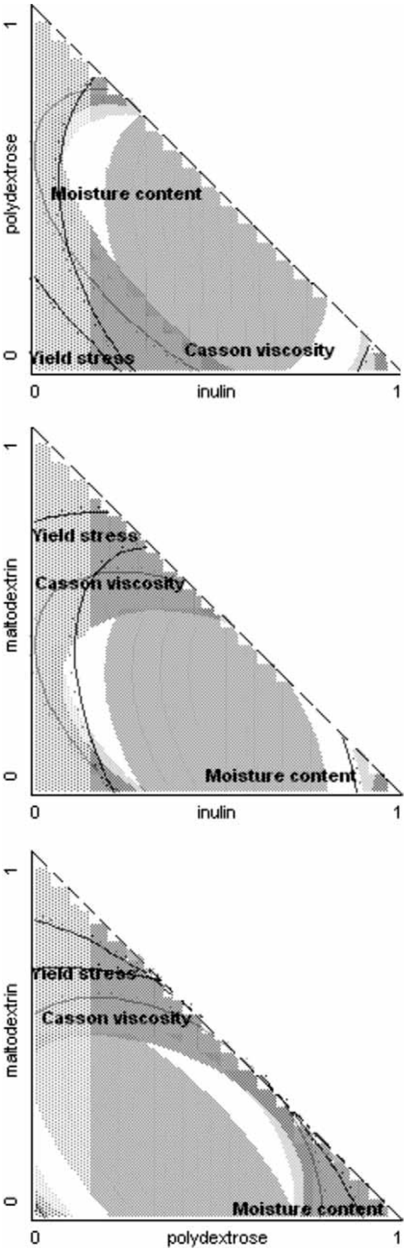

Fig 5. Superimposed contour plots showing optimal regions of sugar substitutes

These findings show that the formulations containing high ratios of IN, PD and MD did not represent desirable rheological properties due to their high moisture content, Casson viscosity and yield stress. With respect to the above-mentioned values, it can be concluded that IN and PD can be used in reasonably wide ratios in which they are capable of improving the rheological properties of prebiotic milk chocolate, even at low proportions. However, MD can only be used up to 47 % and above this value it cannot improve the rheological properties.

Conclusions

Various formulations of prebiotic milk chocolate showed thixotropic properties and shear thinning behaviour. Among the evaluated mathematical equations, Casson model demonstrated the best fitting for predicting rheological properties of prebiotic milk chocolate. The type and ratio of sugar substitutes had different effects on moisture content and rheological properties. Sugar replacement with high mass fractions of sugar substitutes resulted in high moisture content, Casson viscosity and yield stress. The lowest moisture content, Casson viscosity and yield stress were observed at medium mass fractions of sugar substitutes. In general, the use of a simplex-lattice mixture design showed to be a valuable tool for finding the optimum combination of IN, PD and MD, and producing a low-calorie prebiotic milk chocolate with close similarity in characteristics to the ordinary chocolate. Additional studies should be conducted focusing on the influences of different particle sizes of sugar substitutes and different fat contents on rheological properties of chocolate and possibility of further calorie reduction.

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References

1. L.M. Bullock, A.P. Handel, S. Segall, P.A. Wasserman, Replacement of simple sugars in cookie dough, *Food Technol. 46* (1992) 82–86.

2. S.C.F. Iop, R.S.F. Silva, A.P. Beleia, Formulation and evaluation of dry dessert mix containing sweetener combination using mixture response methodology, *Food Chem. 66* (1999) 167–171.

3. D. Pszczola, Sweet beginnings to a new year, *Food Technol. 53* (1999) 70–74.

4. H. Farzanmehr, S. Abbasi, Effects of inulin and bulking agents on some physicochemical, textural and sensory properties of milk chocolate, *J. Texture Stud. 40* (2009) 536–553.

5. B. Schantz, H. Rohm, Influence of lecithin-PGPR on the rheological properties of chocolate, *LWT-Food Sci. Technol. 38* (2005) 41–45.

6. A. Sokmen, G. Gunes, Influence of some bulk sweeteners on rheological properties of chocolate, *LWT-Food Sci. Technol. 39* (2006) 1053–1058.

7. E.O. Afoakwa, A. Paterson, M. Fowler, Effects of particle size distribution and composition on rheological properties of dark chocolate, *Eur. Food Res. Technol. 226* (2008) 1259–1268.

8. E.O. Afoakwa, A. Paterson, M. Fowler, Factors influencing rheological and textural qualities in chocolate – A review, *Trends Food Sci. Technol. 18* (2007) 290–298.

9. J. Chevalley: Chocolate Flow Properties. In: *Industrial Chocolate Manufacture and Use*, S.T. Beckett (Ed.), Blackie Academic and Professional, London, UK (1994) pp. 139–155.

10. R. Chetana, S. Krishnamurthy, S.R.Y. Reddy, Rheological behavior of syrups containing sugar substitutes, *Eur. Food Res. Technol. 218* (2004) 345–348.

11. J.R. Zamecnik, C.L. Crawford, D.C. Koopman: *Large Scale Vitrification of 241-AN-102*, Sawannah River Technology Center, Aiken, SC, USA (2002) (*http://sti.srs.gov/fulltext/tr2002093/tr2002093.pdf*).

12. Ö. Zorba, Ş. Kurt, Optimization of emulsion characteristics of beef, chicken and turkey meat mixtures in model system using mixture design, *Meat Sci. 73* (2006) 611–618.

13. J.F. Steffe: *Rheological Methods in Food Processing Engineering*, Freeman Press, East Lansing, MI, USA (1996) pp. 1–93.

14. S. Abbasi: *Handbook of Elementary Rheology*, Marzedanesh Publishers, Tehran, Iran (2008) (in Farsi).

15. S. Abbasi: *Food Texture and Viscosity: Concept and Measurement*, Marzedanesh Publishers, Tehran, Iran (2007) (in Farsi).

16. J.M. Aeschlimann, S.T. Beckett, International inter-laboratory trials to determine the factors affecting the measurement of chocolate viscosity, *J. Texture Stud. 31* (2000) 541–576.

17. E. Nebesny, D. Żyżelewicz, Effect of lecithin concentration on properties of sucrose-free chocolate masses sweetened with isomalt, *Eur. Food Res. Technol. 220* (2005) 131–135.

18. S.E. Specter, C.S. Sester, Sensory and physical properties of a reduced-calorie frozen dessert system made with milk fat and sucrose substitutes, *J. Dairy Sci. 77* (1994) 708–717.

19. M. Zheng, Z. Jin, Y. Zhang, Effect of cross-linking and esterification on hygroscopicity and surface activity of cassava maltodextrins, *Food Chem. 103* (2007) 1375–1379.

20. P. Stanyon, C. Costello, Effects of wheat bran and polydextrose on the sensory characteristics of biscuits, *Cereal Chem. 67* (1990) 545–547.

21. H.R. Cardarelli, F.C.A. Buriti, I.A. Castro, S.M.I. Saad, Inulin and oligofructose improve sensory quality and increase probiotic viable count in potentially synbiotic *petit-suisse* cheese, *LWT-Food Sci. Technol. 41* (2008) 1037–1046.

22. S. Bolenz, K. Amtsberg, R. Schäpe, The broader usage of sugars and fillers in milk chocolate made possible by the new EC cocoa directive, *Int. J. Food Sci. Technol. 41* (2006) 45–55.

23. M.B. Akin, M.S. Akin, Z. Kırmacı, Effects of inulin and sugar levels on the viability of yoghurt and probiotic bacteria and the physical and sensory characteristics in probiotic ice-cream, *Food Chem. 104* (2007) 93–99.

24. A. Rapaille, M. Gonze, F. Van der Schueren, Formulating sugar-free chocolate products with maltitol, *Food Technol. 49* (1995) 51–54.

25. M. Ozdemir, H. Sadikoglu, Characterization of rheological properties of systems containing sugar substitutes and carrageenan, *Int. J. Food Sci. Technol. 33* (1998) 439–444.

26. L. Dokic-Baucal, P. Dokic, J. Jakovljevic, Influence of maltodextrins on properties of O/W emulsions, *Food Hydrocoll. 18* (2004) 233–239.

27. U. Klinkesorn, P. Sophanodora, P. Chinachoti, D.J. McClements, Stability and rheology of corn oil-in-water emulsions containing maltodextrin, *Food Res. Int. 37* (2004) 851–859.