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Relationship between smoothing temperature, storage time, syneresis and rheological properties of stirred yogurt

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Highlights

- Smoothing at 10°C minimizes syneresis compared to higher temperature (15-30°C)
- Rheological properties were improved for yogurt smoothed at 25 and 30°C.
- Flow time through a Posthumus funnel could predict firmness of stirred yogurt.

Abstract

Six different smoothing temperatures were compared for nonfat yogurt and the changes in syneresis and rheological properties observed for up to 22 days. Multiple linear regressions were used to describe the syneresis, firmness, flow time, viscosity, and flow resistance and the relationship between these properties, the smoothing temperature and the storage time. During storage, viscosity, firmness, and flow time increased; syneresis and flow resistance remained stable. Syneresis increased significantly ($P \geq 0.05$) with smoothing temperature (10 - 35 °C). Other properties increased slightly ($P > 0.05$), and properties started to decrease above 30 °C. Syneresis, viscosity, and flow resistance were more sensitive to smoothing temperature; firmness and flow time were more sensitive to storage time. Lower smoothing temperature (10 °C) should

be used to minimize syneresis while smoothing temperature ranging from 25 to 30 °C is better to improve rheological properties. Storage time must be considered to optimize these properties.

1 Introduction

Between 2005 and 2016, Canadian consumption of yogurts (set and stirred) increased significantly (by 42.6%) (Canadian Dairy Information Centre, 2018). Unlike in set yogurt, the additional operations of stirring, smoothing, and cooling to produce stirred yogurt break the acid gel into a dispersion of brittle gel particles in the whey (Rasmussen, Janhoj, & Ipsen, 2007; Zoon, 2003). This breakdown of the gel can affect the sensory quality of stirred yogurt in various ways, such as expulsion of whey, decreased firmness and viscosity, and the appearance of lumps that can be perceived in the mouth (Lucey, 2004).

Recently, results obtained by Guénard-Lampron, St-Gelais, Villeneuve, & Turgeon, (2019) using a technical scale unit (30 L), have demonstrated that the smoothing and cooling operations, comparatively to stirring and pumping, contribute most to the modulation of stirred yogurt properties after 1 day of storage. . Several authors have also observed that smoothing is crucial to obtaining a smooth yogurt, but this operation causes a significant breakdown in the protein structure, which leads to lower values of viscosity of the yogurt (Cayot, Schenker, Houzé, Sulmont-Rossé, & Colas, 2008; Mokoonlall, Nöbel, & Hinrichs, 2016; Rasmussen et al., 2007). The temperature of the yogurt during shearing is also critical in order to avoid viscosity loss (Mokoonlall et al., 2016). For example, Abu-Jdayil, Nasser, & Ghannam (2013) showed that the higher the viscosity of the yogurt, the larger the viscosity loss observed during a shear treatment. De Lorenzi, Pricl, & Torriano (1995) observed that temperature variations (between 4 and 20 °C) during the frequency sweep test of a full fat yogurt did not modified the G* values, but a decrease of G* was observed at 28 °C. Also, Afonso & Maia (1999) demonstrated that viscosity of yogurt decreases when the temperature was increased (between 5 and 45 °C) and that this effect was more pronounced for temperature above 25 °C. So far, the literature has agreed that the smoothing operation must be carried out at about 20 °C in order to obtain a yogurt with acceptable properties (Robinson, Lucey, & Tamime, 2007; A. Y. Tamime & Robinson, 2007). Lucey (2004) observed that yogurt should not be smoothed when the gel is too warm because the structure of the protein network would be too fragile. The smoothing of cooled yogurt (10 °C) would also not be appropriate, comparatively to a yogurt cooled at 20°C which is less viscous and therefore undergoes less damage by the mechanical stress. (Tamime & Robinson, 2007). Guénard-Lampron, St-Gelais, Villeneuve, & Turgeon (2020) studied the impact of the stirring operations, such as the smoothing temperature, on syneresis and rheological properties of yogurts up to 22 days of storage. This study compared two smoothing temperature (38 and 20 °C), but they were also linked to the operational sequence: smoothing performed before the cooling (38 °C) or after the cooling (20 °C). Yogurt smoothed at 38 °C, comparatively to those smoothed at 20 °C, showed higher flow time. However, this study did not allow to dissociate the impact of the smoothing temperature from the impact of the operational sequence. The literature does not include more specific data on the impact of smoothing at different temperatures between a warm yogurt (ex: at the incubation temperature, 40°C) and a cooled yogurt (ex: at the storage temperature, 4 °C). Moreover, the information reported in the literature is based mainly on laboratory-scale stirring and smoothing operations, for example using a syringe, which may not be representative of production conditions on an industrial scale. A better understanding of the effect of different smoothing temperatures on the syneresis and rheological and properties of yogurt in a context closer to the industrial reality is needed to improve stirred yogurt quality. Consequently, the aim of the present study was to describe the syneresis and rheological properties of yogurts smoothed at six different temperatures using a technical scale unit and stored for up to 22 days.

2 Materials and methods

2.1 Milk ingredients and starter

Nonfat yogurts were produced with pasteurized skim milk (Laiterie Chalifoux Inc., Sorel-Tracy, QC, Canada), low-heat skim milk powder (Agropur, Saint-Hyacinthe, QC, Canada), whey protein concentrate (Agropur), and lactose (Saputo Inc., Montreal, QC, CA). A non-ropy lyophilized culture of *Streptococcus thermophilus* and *Lactobacillus delbrueckii* ssp. *bulgaricus* was used as described by Guénard-Lampron et al. (2019) to prepare the starter (Yo-Dolce; Biena, Saint-Hyacinthe, QC, Canada). A non-ropy culture and a nonfat yogurt were chosen in order to focus on the impact of the stirring process and more precisely on the smoothing temperature. For all the yogurts produced, the average incubation time for the starter was 297 ± 11 min. Table 1 presents the composition of each ingredient.

2.2 Yogurt production

Skim milk was standardized to obtain a milk mixture at 0% fat, 4% total protein (casein-to-whey-protein ratio of 2.8), and 14% total solids, rehydrated, homogenized in 2 stages (13.80 and 3.45 MPa), and heat-treated (94.5 °C for 5 min) as explained by Guénard-Lampron et al. (2019). Each batch was made of 130 kg of skim milk and amount of each ingredient used is present in Table 1. The treated milk mixture was incubated at 40 °C (Magelis unit; Schneider Electric, Brossard, QC, Canada) in three 30 L cone-shaped spout yogurt vats. Yogurt vat was inoculated with the starter (1.5% v/v), and the pH was measured (portable pH meter, model HI 99161;

Hanna Instruments, Laval, QC, Canada) until 4.7 was reached. The average incubation time for the yogurts was 253 ± 20 min.

2.3 Technical scale unit and stirring operations

The technical scale unit used by Guénard-Lampron et al. (2019) and Guénard-Lampron, St-Gelais, Villeneuve, & Turgeon (2020), which represents each sequential steps of the stirring process (stirring in the yogurt vat, pumping, smoothing and cooling), was adapted to study the effects of smoothing temperature (Fig. 1). A helical blade mixer (Fig.2) was used to perform the stirring operation (10 min at 30 rpm) in the yogurt vat, and removable baffles were used during the first 30 s of mixing, as explained by Guénard-Lampron et al. (2019). After 10 min of stirring, the mixing speed was reduced to 15 rpm, and the yogurt was pumped using a positive gear pump with a flow rate of 1.7 L/min (Seco DANA, model 210; Bronco Industries, BC, Canada) into cylindrical stainless steel pipes (3.4 cm inner diameter, length of 4.4 m). Pressure was measured after the pump by a digital pressure gauge (Distribution Qualtech, Saint-Hyacinthe, QC, Canada) to allow detection of clogging of the smoothing nozzle. The yogurt was then presmoothed (1.4 mm filter nozzle), cooled to one of the six smoothing temperatures under study (10, 15, 20, 25, 30, or 35 °C) with a plate heat exchanger (type A3-HBM; Alfa Laval, Lund, Sweden), smoothed (425 µm filter nozzle), and cooled to 10 °C with a tubular heat exchanger (PG7757/84; Sepak Industries Pty Ltd, Sydney, Australia). The heat exchangers were connected to a cold water system in counterflow, and the temperature was controlled as described by Guénard-Lampron et al. (2019).

The stirred yogurt was collected at the outlet of the technical scale unit in 175 mL containers for all analyses except for the flow time, for which 500 mL containers were required

(Plastipak; GenPak, Boucherville, QC, Canada). The stirred yogurts were stored in a cold room at 4 °C, and containers were chosen randomly for the syneresis and rheological analyses after 1, 3, 13, and 22 days.

2.4 Yogurt analyses

Analytical methods such as the determination of pH, total solids content (desiccation), fat content (Mojonnier method), and total nitrogen, non-protein nitrogen, and non-casein contents (Kjeldahl method) in the ingredients and yogurt milks taken before the heat treatment of the milk mixture were performed as described by Guénard-Lampron et al. (2019). On day 1, 3, 13 and 22 of storage, microbial counts (M17 agar + 0.5% lactose for streptococci and MRS acidified for lactobacilli), syneresis (centrifugation), firmness (TA-XT2 texture analyzer; Texture Technologies Corporation, Scarsdale, NY, USA), apparent viscosity (Physica MCR301 rheometer; Anton Paar GmbH, Ostfildern, Germany), and consistency (Bostwick consistometer) were performed using the methods provided by Guénard-Lampron et al. (2019). However, in the present study, consistency (distance traveled in Bostwick) has been replaced by flow resistance (maximal distance of the device minus distance travelled). The flow time of stirred yogurt through a standard Posthumus funnel (Kutter, Singh, Rauh, & Delgado, 2011; Posthumus, 1954) was added to the yogurt analyses. The flow time for 280 g of yogurt was recorded as a function of mass using a balance (model P-2002, Pinnacle series; Denver Instrument, Mississauga, ON, Canada) that was connected to a data acquisition system. Duplicates were performed for each yogurt.

2.5 Data processing and statistical analyses

An empirical approach was used to describe each variable under study (syneresis, viscosity, firmness, flow resistance, and flow time) depending on the smoothing temperature and the storage time. The following polynomial equation was used:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \quad (1)$$

where β_0, β_1, ... β_{22} represent the regression coefficients, with β_0 as the constant, β_1 and β_2 as the linear effect, β_{11} and β_{22} as the quadratic effect, and β_{12} as the effect of interactions; and X_1 and X_2 are, respectively, the independent variables of smoothing temperature and storage time. In order to determine the regression coefficients and to minimize the error between the values measured in the laboratory and those predicted by the model, the least squares estimation method of β (Eq. 2) was used:

$$\hat{\beta} = (X^1X)^{-1} X^1 y \quad (2)$$

where X^1 corresponds to the transpose of the matrix X, and $(X^1X)^{-1}$ corresponds to the inverse of the matrix X^1X. The input variables were therefore smoothing temperature (°C) and storage time (days), and the output variables were syneresis, viscosity, firmness, flow resistance, and flow time.

The six smoothing temperatures were randomized and repeated three times. Statistical analysis (split-plot statistical design) was carried out to compare the properties of the stirred yogurt after 1, 3, 13, and 22 days of storage. The six temperatures were the main factor, and the number of days of storage was the subplot factor. The GLM (General Linear Model) procedure of the SAS software package (SAS Server Interface, version 2.5.14; SAS Institute Inc., Cary, NC) was used to perform the statistical analyses. Two Pearson correlations were calculated with the CORR procedure of the SAS software. The first one compared processing parameters (smoothing temperature and storage time) and the properties of the stirred yogurt, and the second one compared syneresis, viscosity, and firmness to flow resistance and flow time. Significant differences were tested at $P \leq 0.05$. Correlations were considered for Pearson correlation coefficients over 0.50.

2.6 Sensitivity analysis

In order to analyze the effects of variation of the input variables on the outputs of the model, a sensitivity analysis was carried out using the finite-difference method of Chokmani, Viau, & Bourgeois (2001) and successfully used by (Bergeron Quirion, Villeneuve, Leblanc, & Delaquis, 2012; Mercier, Moresoli, Villeneuve, Mondor, & Marcos, 2013; Villeneuve & Gélinas, 2007). By using a reference scenario, each input parameter was varied within a specific range while keeping the other parameters constant. In this study, smoothing temperature and storage time were the input parameters. The reference scenario was smoothing at 20 °C and storage of 7 days with increments of 1 °C (between 10 and 35 °C) and 1 day (between 1 and 22 days). The outputs of the model were syneresis, viscosity, firmness, flow resistance, and flow time. Critical input parameters were expressed as % change in the model output per unit of change of the input parameter. Relative sensitivity is not influenced by input parameters units or scales.

3 Results

3.1 Composition of yogurt milk

All milk mixtures had the same composition (fat: 0.18 ± 0.01 g/100g; total solids: 14.5 ± 0.1 g/100g; true proteins: 4.25 ± 0.09 g/100g; caseins: 3.13 ± 0.07 g/100g; whey proteins: 1.12 ± 0.01 g/100g; and casein-to-whey-protein ratio: 2.81 ± 0.04).

3.2 Changes in microbial counts and pH

During storage, a significant effect of storage time was observed on changes in bacterial populations and pH. No significant interaction between smoothing temperature and storage time was observed. Between day 1 and 13 of storage at 4 °C, the streptococci (8.40 ± 0.04 Log CFU mL^{-1}) and lactobacilli (7.57 ± 0.09 Log CFU mL^{-1}) populations remained stable. After 22 days, the streptococci decreased slightly to 8.31 ± 0.04 and the lactobacilli decreased to 6.78 ± 0.09 Log CFU mL^{-1}. The pH of the yogurts decreased significantly, from 4.5 to 4.3 ± 0.01, until day 13 and then remained stable.

3.3 Changes in syneresis and rheological properties

The effects of smoothing temperature and storage time on the stirred yogurt properties expressed by the response surface are presented in Fig. 3. The polynomial equations used to describe each property are presented in Table 2. The effect of storage time on syneresis was lower in comparison with the effect of smoothing temperature (Fig. 3A). Syneresis of yogurt increased with smoothing temperature (10 to 35 °C), but between 10 and 15 days of storage, syneresis was similar for yogurts smoothed between 20 and 30 °C. The response surface had two parabolas, the first limited from 10 to 20 °C and the second limited from 20 to 35 °C (Fig. 3A). For both equations, the regression coefficients were much higher for smoothing temperature, and no interaction coefficient was observed between smoothing temperature and storage time, as also confirmed with the statistical analysis (Table 2).

Viscosity (Fig. 3B), flow resistance (Fig. 3C), firmness (Fig. 3D), and flow time (Fig. 3E) increased as the smoothing temperature increased from 10 to 30 °C and then started to decrease at 35 °C. The polynomial equations were therefore limited to smoothing temperatures from 10 to

30 °C. The regression coefficients for smoothing temperature and storage time were similar for the equations for viscosity, flow resistance, and flow time, but for the firmness equation, the regression coefficient for storage time was higher than the regression coefficient for smoothing temperature (Table 2). For these properties, a weak interaction coefficient between smoothing temperature and storage time was observed (Table 2), as also observed in the statistical analysis. Fig. 3B also shows that, between 1 and 15 days of storage at 4 °C, viscosity was higher when the smoothing temperature was between 25 and 30 °C. However, between 15 and 22 days, the highest viscosity values were obtained at temperatures between 15 and 20 °C. Values for flow resistance seemed stable over the 22 days of storage between 20 and 30 °C, whereas for the other smoothing temperatures (10, 15, and 35 °C), a drop in flow resistance was observed after 22 days of storage (Fig. 3C). Firmness (Fig. 3D) and flow time (Fig. 3E) also increased with storage time (1 to 22 days).

3.4 Sensitivity and Pearson correlation coefficients

Fig. 4 presents the relative sensitivities to a variation of 1°C during smoothing (sensitivity to smoothing temperature) and to a variation of 1 day during storage (sensitivity to storage time) of the properties under study. Syneresis, viscosity, and flow resistance were more sensitive to smoothing temperature than to storage time, whereas an opposite trend was observed for firmness and flow time (Fig. 4). These results are in agreement with the Pearson correlation coefficients, presented in Table 3, which indicated that storage time was positively correlated to firmness or flow time (Table 3). In addition, flow time was about seven times more sensitive to storage time than the other properties were. Viscosity and flow resistance were both more sensitive to variations in smoothing temperature (Fig. 4), but no significant correlation was observed between these properties and smoothing temperature (Table 3). Syneresis was very sensitive (Fig. 4) and positively correlated (Table 3) to smoothing temperature. Between 10 and 20 °C, syneresis was 13 times more sensitive to a variation of 1 °C than to a variation of 1 day (Fig. 4). The sensitivity of syneresis to storage time was similar for both smoothing temperature intervals (10–20 °C and 20–35 °C) (Fig. 3).

Fig. 5 presents, more precisely, the relative sensitivity of syneresis to variations in smoothing temperature, as provided by the two quadratic equations. The relative sensitivity of syneresis is therefore presented for each temperature interval between the six temperatures studied.The sensitivity of syneresis in the interval from 16 to 20 °C was 1.5 times higher than in the intervals from 10 to 15 °C and 21 to 25 °C; 3 times higher than in the interval from 26 to 30 °C; and 10 times higher than in the interval from 31 to 35 °C. Syneresis was therefore much less sensitive to variations in smoothing temperature above 30 °C.

Table 5 presents the Pearson correlation coefficients for the comparison of syneresis, viscosity, and firmness to flow time and flow resistance. The coefficients of correlation indicate that flow resistance and flow time were positively correlated to viscosity and that flow time was even more positively correlated to firmness.

4 Discussion

During storage, syneresis and rheological properties of stirred yogurt depend on the entire shear history that occurred during stirring operations (Fangary, Barigou, & Seville, 1999; Guénard-Lampron et al., 2019; Mokoonlall et al., 2016; Sodini, Remeuf, Haddad, & Corrieu, 2004). In the present study, surface response, sensitivity analysis, and Pearson correlation indicate clearly that syneresis was affected most by smoothing temperature. Even though post-acidification for all the yogurts was similar, it would seem that the smoothing temperature modified the protein network, which subsequently affected the restructuring of yogurt during storage. Mizrahi (2010) explained that temperature, both during gel preparation and after production, changes the strength of hydrogen bonds and hydrophobic interactions, which has the consequence of affecting the association, dissociation, and configuration of the gel particles. In addition, temperature affects osmotic pressure and gel contraction. Hinrichs & Keim (2007) demonstrated that hydrophobic interactions represent 70% of the protein–protein interactions in skim milk yogurt after 7 days of storage. Consequently, the modifications to hydrophobic interactions during smoothing at different temperatures could have a major impact on the restructuring of the protein network and on the expulsion of whey. Gilbert, Rioux, St-Gelais, & Turgeon (2020) also demonstrated that yogurt smoothed in a rheometer at 42 °C had higher syneresis value and more heterogeneous microstructure then yogurt smoothed at 20 °C. In addition, several authors agree that smoothing at 20 °C is ideal for obtaining high-quality yogurt, which is supposed to include lower syneresis values (Robinson et al., 2007; Tamime & Robinson, 1999). In the present study, the lowest syneresis values were obtained for yogurt smoothed at 10 °C, and the sensitivity results indicate a major variation of syneresis for a smoothing temperature near 20 °C.

The smoothing temperature (10 to 30 °C) also increased the viscosity, flow resistance, firmness, and flow time values. A similar observation was reported in the review by Mokoonlall et al. (2016), who described a smaller decrease in viscosity when smoothing was performed at 20 °C in comparison with 6 °C. They also reported that greater loss of structure occurs when the initial viscosity of a microgel suspension is higher. Abu-Jdayil, Nasser, & Ghannam (2013) have also shown that increasing the casein content results in a more structured gel with higher viscosity which result in a yogurt more sensitive to shear conditions. In the present study, the viscosity could increase during cooling at lower temperature before the smoothing and this can lead to a greater breakdown of the protein network during the smoothing at lower temperature and could explain the lower values for rheological properties.

Viscosity, flow resistance, firmness, and flow time values also started to drop at 35 °C, and their values were similar to those obtained at 10 °C. Smoothing yogurt at a temperature close to the incubation temperature would damage the structure of the protein network because the network would still be brittle (Lucey, 2004). In the present study, the yogurts incubated at 40 °C and smoothed at 35 °C were subjected to mechanical stress caused by the plate heat exchanger as well as by the smoothing filter nozzle at 35 °C, which could have greatly affected the brittle protein network by, for example, breaking electrostatic interactions. These phenomena could explain the lower values obtained for rheological properties at 35 °C. For both smoothing temperatures (10 and 35 °C), a difference in temperature of 25 °C (ΔT 25 °C) occurred during the cooling at 10 °C, but at a different step in the stirring operation (after smoothing at 35 °C or before the smoothing at 10 °C). Olsen (2003) observed a similar impact for the comparison of different filling temperatures (10 to 25 °C) before a final cooling step at 5 °C. That author explained that yogurt potted at 25 °C had a denser protein network (higher restructuration) than yogurt potted at 10 °C did, possibly because shearing at a lower temperature implied a higher loss of protein structure. However, Olsen (2003) did not test processing conditions involving cooling above 25 °C. In the present study, it is possible that the protein structure would have difficulty rebuilding when yogurt was smoothed at 10 °C and above 30 °C because of the high temperature difference (high ΔT).

In the present study, as post-acidification increased up to 13 days of storage (decrease of pH from 4.5 to 4.3), viscosity, firmness, and flow time also increased. In addition, firmness and flow time continued to increase up to 22 days. Increase in rheological properties during storage was also observed by Serra, Trujillo, Guamis, & Ferragut (2009) and was related to post-acidification (pH value not specified). During storage, flow resistance and syneresis stayed relatively stable and were not very sensitive to storage time in comparison with the other properties, which increased. The stability of flow resistance over time is difficult to explain but could be due to the fact that the Bostwick consistometer analysis was less sensitive to the structural changes in stirred yogurt. A decrease in syneresis as the pH decreased during storage was also expected owing to the reabsorption of the whey through the gel particles, as reported by several authors. For example, a decrease in syneresis was reported by Lorenzen, Neve, Mautner, & Schlimme (2002) and was related to an increase of the titrable acidity from approximately 40 to 50°SH after 3 weeks of storage and by Prasad, Sherkat, & Shah (2013) for a decrease in pH from 4.5 to 4.2 after 4 weeks of storage.. However, Lucey (2001) reported that the expulsion of whey is a consequence of an excessive rearrangement of gel particles. In the present study, the mechanical stress caused by the stirring operation in the technical scale unit could have contributed to a more stable and dense protein network that was able to maintain its capacity to retain the whey.

5 Conclusions

The present study demonstrated that smoothing temperature is a critical parameter for controlling the syneresis and rheological properties of stirred yogurt during storage. The smoothing temperature had the greatest effect on the syneresis of yogurt. A low smoothing temperature (10 °C) would be better to minimize syneresis. However, this temperature was not optimal for improving all yogurt properties. No matter the storage time (between 1 and 22 days), the viscosity, flow resistance, firmness, and flow time tended to be lower for yogurts smoothed at 10 °C or above 30 °C. In order to improve these properties, a smoothing temperature between 25 and 30 °C could be recommended. The sensitivity analysis also demonstrated that each property exhibited a different level of sensitivity to smoothing temperature and to storage time. A correlation was established between firmness and flow time and could be further investigated to predict the firmness from the Posthumus funnel flow. The next step will be to investigate the relationship between the smoothing temperature and the change in the microstructure of the protein network, which leads to the modification of the syneresis and rheological and properties of stirred yogurt.

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Table 1 Composition of milk ingredients and amount used in each batch.

Ingredients[2]	Components (%)[1]						Amount used in each batch (kg)
	Total N	NPN	Casein	WP	TS	Fat	
Skim milk[3]	3.1 ± 0.2	0.4 ± 0.1	2.0 ± 0.2	0.61 ± 0.03	8.3 ± 0.4	0.15 ± 0.01	130.0
SMP	34.2	0.7	26.7	6.8	97.7	0.007	6.64 ± 0.36
WPC34	34.1	3.4	0.0	30.7	97.4	0.01	1.04 ± 0.02
Lactose	0.0	0.0	0.0	0.0	99.8	0.0	2.27 ± 0.12
Starter	4.1	0.08	3.2	0.8	11.7	0.001	0.45

[1]Total N, total nitrogen; NPN, non-protein nitrogen; WP, whey protein; TS, total solids.

[2]SMP, low-heat skim milk powder; WPC34, 34% whey protein concentrate.

[3]The values for skim milk are averages of the values measured with an FT 120 infrared analyzer (Foss North America, Eden Prairie, MN) in the milk used for all batches.

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Table 2 Polynomial equations describing each property depending on the smoothing temperature (x_1; °C) and the storage time (x_2; days)

Properties	**Limitations**	**Polynomial equations**	R^2
Syneresis (%)	$10 \le x_1 \le 20$	$19.9573 - 2.0184x_1 + 0.0777x_1^2 + 0.1357x_2 - 0.0071x_2^2$	0.81
	$20 \le x_1 \le 35$	$54.6834 - 3.5650x_1 + 0.0682x_1^2 + 0.1525x_2 - 0.0075x_2^2$	0.92
Viscosity (s^{-1})	$10 \le x_1 \le 30$	$1.3702 + 0.0171x_1 + 0.0200x_2 - 0.0007x_1x_2$	0.66
Flow resistance (cm)	$10 \le x_1 \le 30$	$13.2731 + 0.0564x_1 - 0.1213x_2 + 0.0055x_1x_2$	0.67
Firmness (N/m^2)	$10 \le x_1 \le 30$	$260.8744 + 1.9443x_1 + 4.8300x_2 - 0.0739x_1x_2$	0.94
Flow time (min)	$10 \le x_1 \le 30$	$-0.4634 + 0.3422x_1 + 0.1952x_2 + 0.0458x_1x_2$	0.91

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Table 3 Pearson correlation coefficients (r) between processing parameters (smoothing temperature and storage time) and properties of stirred yogurt ($n = 72$)

*** Significant correlation at $P < 0.001$.

	Syneresis	Viscosity	Flow resistance	Firmness	Flow time
Smoothing temperature	**0.55*** **	−0.04	0.19	0.10	0.16
Storage time	−0.02	0.20	−0.10	**0.81*** **	**0.57*** **

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Table 4 Pearson correlation coefficients (r) between syneresis, viscosity, and firmness and flow resistance and flow time (n = 72)

	Flow resistance	Flow time
Syneresis	−0.30**	−0.11
Viscosity	**0.50*****	**0.50*** **
Firmness	−0.03	**0.69*** **

**Significant correlation at $P < 0.005$.

***Significant correlation at $P < 0.001$.

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Figure captions

Fig. 1. Technical scale unit consisting of stirring in the yogurt vat, presmoothing, cooling with a plate heat exchanger (PHX), smoothing, and cooling with a tubular heat exchanger (THX).

Fig.2. Helical blade mixer. The dimensions are: A = 2.5 cm, B = 17.8 cm, C = 40.6 cm, D = 7.6 cm and E = 15.2 cm.

Fig. 3. Response surfaces for the (A) syneresis (%), (B) viscosity (Pa*s), (C) flow resistance (cm), (D) firmness (N/m^2), and (E) flow time (min) of stirred yogurts depending on the smoothing temperature (10, 15, 20, 25, 30 and 35 °C) and the storage time (1 to 22 days).

Fig. 4. Relative sensitivities of syneresis, viscosity, firmness, flow time, and flow resistance as a function of storage time (black) or smoothing temperature (grey).

Fig. 5. Relative sensitivity of syneresis as a function of five smoothing temperature intervals.

Fig. 1

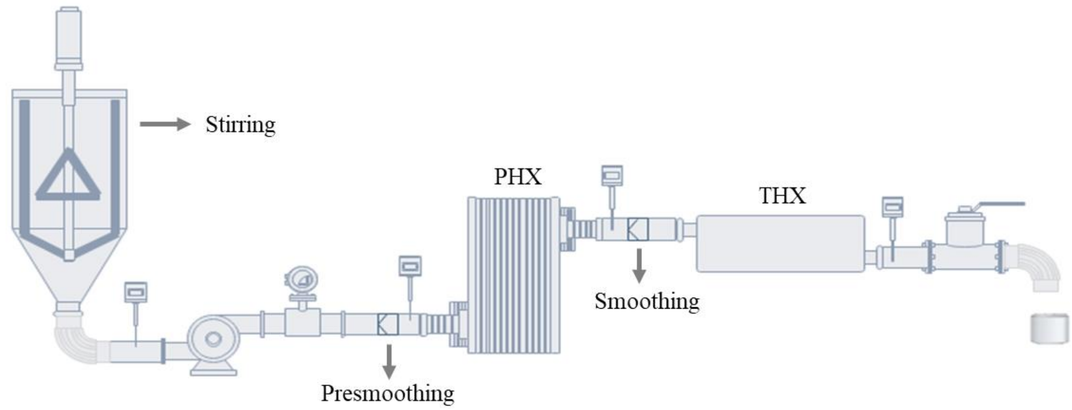

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Fig. 2

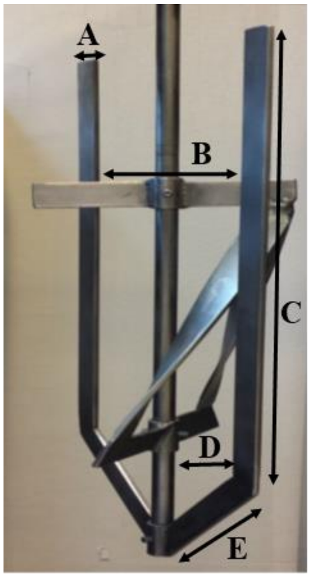

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Fig. 3

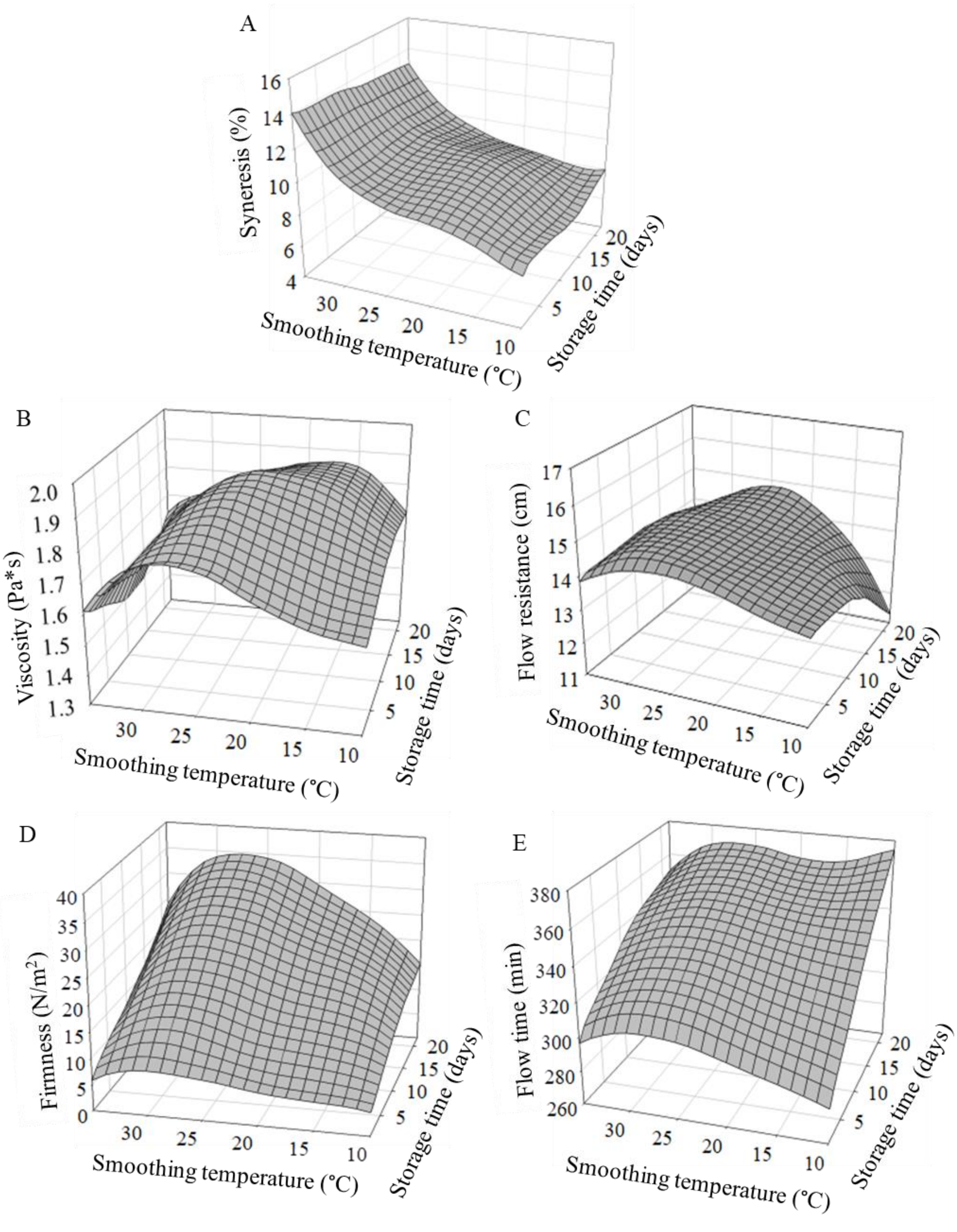

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Fig. 4

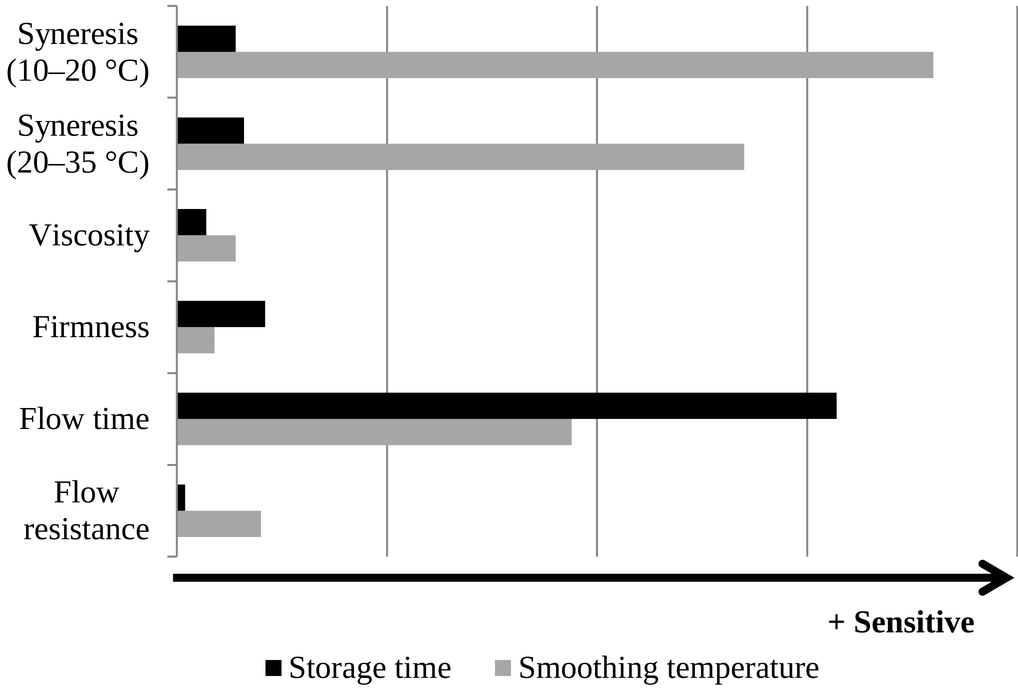

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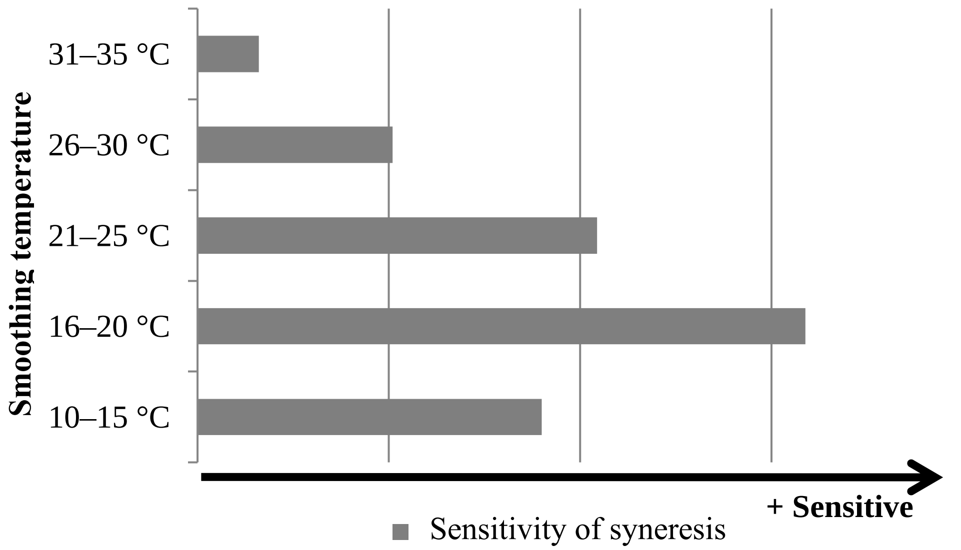
Fig. 5



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