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Rheological, textural and structural properties of dairy cream as affected by some natural stabilizers

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Abstract

The effects of whey protein, basil seed gum (BSG), and κ-carrageenan (CGN) on the structure–rheology interactions of low- and high-fat cream were investigated. Pseudoplastic and thixotropic behavior of cream was found for all the samples and the pseudoplasticity was increased with an increased level of stabilizers. The apparent viscosity (η_a) of the forward curves is greater than that of the backward ones, which may be the result of the breakdown of the fat globule structure under shear stress. The viscosity of cream was reduced, while using a stabilizer (BSG/CGN) can be related to the water binding of hydrocolloid molecules contributing to resistance in flow. For all samples, elastic modulus was greater than viscous modulus, indicating a greater contribution from elastic characteristics. With the increase of BSG/CGN levels, the molecules may be competitively adsorbed onto the surface of fat droplets, thereby changing its surface tension and decreasing its particle size. Increases in whey proteins, fat, and BSG also significantly increased hardness, whereas increases in CGN significantly decreased it. The globular aggregates in the microstructure of high-fat dairy cream were smaller than those in low-fat dairy cream, allowing more water to be retained in the high-fat samples. Therefore, synergistic interactions between polysaccharides and proteins may encourage the formation of a cross-linked network.

Keywords: Dairy cream, Rheology, Whey protein, κ-Carrageenan, Basil seed gum, Physical attributes

Introduction

At the air/water interface, dairy cream is a dispersion of gas bubbles encircled by partly solidified fat and sustained by high viscosity in the serum phase. At least 40% of fat must be in the crystalline state to encourage partial coalescence and increase stiffness to the air bubble interface. The amount of fat, the circumstances of processing, and the use of stabilizers and emulsifiers all have an impact on the structural characteristics of cream [1]. Without these ingredients, the cream's fat level must be at least 30% to promote the production of rigid foam. There have been evaluations of a number of parameters that affect the whippability of creams, including composition, cream tempering, fat globule size, ultrasound, and homogenization [2–9]. For whipping cream, Graf and Müller (1965) suggested a preferred fat globule size of 15–20 μm. Because of this, whipping cream has historically been treated without homogenization, which may cause fat globules to shrink to the point, where they resist partial coalescence and prevent the creation of stiff foam [10].

Cream is improved by adding emulsifier/stabilizer, which also increase foam stability. Through reducing interfacial tension, the low molecular weight emulsifiers encourages the adsorption of partly coalesced fat at the interface [11, 12]. The addition of large molecule polysaccharides causes the aqueous phase's viscosity to increase.

κ-Carrageenan (CGN), which is mostly utilized in the dairy, interacts with casein micelles to generate

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a complex called a casein–glycomacropeptide that strengthens the foam's overall structural integrity by promoting cohesiveness between membranes and serum. As a result, several non-ionic surfactants are used to stabilize proteins, such as Tween 60 and 80 [13], lactic acid ester of mono-glycerides and saturated mono-glycerides [14], which make protein-stabilized emulsions shear sensitive [15, 16]. Furthermore, several studies on the utilization of other stabilizers have been carried out, such as starch and gums [17], Aertex cream stabilizer [18], locust bean gum and λ-carrageenan [19, 20], sodium caseinate and λ-carrageenan [21, 22], sodium caseinate, methylcellulose and hydroxypropyl methylcellulose (HPMC) [23], sodium caseinate and whey proteins [24–26], HPMC and xanthan gum [27], modified whey proteins [28, 29] and Milk fat globule membrane protein (MFGMP) [30]. Protein/polysaccharide systems' foam stability has been assessed to clarify the process, and it has been discovered that they can strengthen the interface as a whole. Therefore, the development and stability of whipped products can benefit from careful surfactant selection for controlled emulsion destabilization [14]. Dairy cream can benefit from the emulsifying and stabilizing abilities of hydrocolloids. Their significance in replacing fat and decreasing some contemporary issues including cardiovascular disease, hypertension, and obesity encourage customers to buy low-fat products. Accordingly, manufacturers have reduced the amount of fat in foamed products and replaced it with polysaccharide or proteins [31]. Whey proteins as fat replacers have exhibited distinctive properties which promote functional performance in food systems similar to the functionality of fat globules [32, 33]. Among various kind of polysaccharides, basil seed gum (BSG), has also found more attentions due to its functional properties, such as stabilizing, emulsifying [34], lubrication [35] and gelling properties [36, 37]. It has been employed as a surface-active polysaccharide that can produce tiny emulsion droplets and stabilize 30% O/W emulsions against phase separation by utilizing little more than 0.3% of protein and comprises mostly glucomanan, xylan, and minor portions of glucan [34]. While it has found that the storage modulus of whipped creams is significantly influenced by the friction between the fat globules and serum phase [38], BSG has demonstrated outstanding lubricant behavior and an extremely low friction coefficient [35]. According to the literature review, a comparison of rheological and structural properties of whipped cream prepared by whey protein, BSG and CGN as stabilizer and fat replacer was not conducted. The novelty of the work is the effect of stabilizer on the rheological, textural and some physicochemical properties of dairy cream. In this context, rheological, physical and structural properties of cream at various levels of fat and stabilizer were evaluated and the structure–rheology relationship was investigated.

Materials and methods

Materials

According to our prior research, BSG was prepared under optimal circumstances [36]. Briefly, following centrifugation (U-320R, BOECO, Germany) at 5000 rpm for 20 min, the extracted mucilage was collected. The gum solutions were cleaned by running them through a 20 µm filter (provided by AMIAD Australia Pty Ltd., Victoria, Australia), drying them in a regular oven at 60 °C, and then milling and sieving with a mesh 18 sifter. BSG powder was stored in hermetic plastic bags prior to the tests. Whey protein concentrate (WPC) containing 80% protein and κ-carrageenan (CGN) were provided by Saputo company (USA Inc.) and Sigma-Aldrich (St. Louis, MO, USA), respectively. From Merck, analytical-grade NaOH and HCl were purchased (Merck KgaA, Dermstadt, Germany). Except where otherwise noted, all additional substances were of analytical quality and came from Sigma-Aldrich (St. Louis, MO, USA).

Whipped cream preparation

By slight changes, dairy cream was manufactured using Sajedi's procedure [28]. By adding the proper amounts of raw skimmed milk (less than 0.1% fat) to full fat cream (40%), the whipped creams' fat contents were changed to 25, 30, and 35%. After fat adjustment, the whipped creams were mixed with BSG powder or CGN at different levels of 0.1 and 0.3%. The whipped cream with 35% fat along with CGN as control was examined here, since the other fat content 25 and 30% were evaluated in our previous work [39]. WPC was also used at different levels of 5 and 10%. Afterward, samples were pasteurized for 5 min in a water bath at 85 °C. They were homogenized for 1 min at 50 °C and 3000 rpm using an Ultra-Turrax homogenizer (Ultra-Turrax, T25, IKA, Germany). The treated samples were kept in the refrigerator overnight at 5 °C to assist in development of fat crystals and structure of the foam during whipping. The whipped cream was able to be aerated after being refrigerated. First, the maximum overrun was calculated by whipping a subset of samples at various timings. The remaining portions of each treatment were then whipped in the preceding stage at the ideal moment. Samples' physical characteristics were assessed in triplicates.

Rheological measurements

Using a controlled-stress rheometer (Paar Physica rheometer, MCR 301, Anton Paar GmbH, Germany), which was fitted with a serrated parallel plate geometry (PP25-SN23755; $d = 25$ mm, and gap $= 1$ mm),

rheological characteristics of the whipped cream were performed in two modes, steady and dynamic states. To lessen damage to the foam structure, foam was first scooped with a spoon and deposited in the center of the plate. The upper plate was then gently lowered to the preset gap. The extra whipped cream was scraped from the plate rims to lessen the edge appearance. In addition, silicon oil was utilized to prevent evaporation. At 10 °C, the temperature at which the fat solidifies on the acrylic plate, the sample's temperature was accurately regulated by a Peltier device (Viscotherm VT2, PaarPhysica). The samples were equilibrated for at least 10 min to remove the unidentified stresses.

At 10 °C and shear rates ranging from 0.1 to 1000 s^{-1}, the steady shear tests were conducted. The flow curve was plotted as a function of shear stress (τ) and shear rate (γ), and the apparent shear viscosity (η_a) was calculated. By comparing the upward and downward curves and integrating the area from the initial to the end of shear rate, the thixotropic property of the whipped cream samples was estimated.

To identify the linear viscoelastic region (LVE), where storage (G') and loss moduli (G'') are independent of strain, strain sweep measurements were carried out from 0.01% to 100% strain, frequency 1 Hz, and temperature 10 °C [40]. The test enables us to determine the region of linear viscoelasticity. Within the LVE region, the measured complex modulus (G^*) and microstructure are deemed to be essentially unperturbed by the rheological measurement. Above some characteristic critical shear strain, the measured moduli are no longer independent of stress/strain. For a weak gel-like system, beyond some characteristic 'yield strain', the decrease in G* may be associated with breakage of internal bonds within the material, leading to fracture/flow behavior on the macroscopic scale. The G', G'', and loss-tangent (tan δ_{LVE}) in the LVE region of whipped cream as a function of fat content and hydrocolloid type were determined. The fracture strain was determined by plotting elastic stress, the product of the elastic modulus and strain ($G'\gamma$), as a function of increasing strain [41, 42].

Frequency sweep provides adequate knowledge about the network design. Then, a period of 0.1 to 100 Hz was used to examine the viscoelastic behavior of cream at 10 °C. Since the degree of the storage modulus' frequency dependence is thought to be a sign of a material's viscoelastic nature, the degree of frequency dependence of G' (Eq. 1) and G'' (Eq. 2) were assessed by a power-law model as follows [40]:

$$G\prime = k\prime\omega^{p} \tag{1}$$

$$G\prime\prime = k\prime\prime\omega^{q} \tag{2}$$

where p and q are the viscoelastic components of G' and G'', k' and k'' are intercepts, and is the oscillation frequency (Hz).

Textural properties

The hardness and adhesiveness of the samples were examined using a Brookfield texture analyzer (CT3, Brookfield Engineering, Middleboro, MA, USA) utilizing a 38 mm cylinder probe to evaluate the textural behavior of whipped creams. The probe had a penetration depth of 30 mm and a penetration rate of 1 mms^{-1} (both up and down). The probe now travels back to its starting site (most likely to be the maximal force). The tests were carried out at room temperature (25 °C) and the maximum force value was for hardness, while the negative area of the graphs was for adhesiveness [43].

Foaming properties

Overrun measurement

After 30 s of whipping, overrun is the quantity of air per 100 mL of cream. The Scurlock technique was used to determine the overrun (OR) [44]. After beating the cream for 30 s, it was filled to a predetermined volume (100 mL) in a graduated cylinder. The weight of the volume and density of the cream without whipping was then taken into consideration as the overrun, which can be computed using the following equation (Eq. 3)[28]:

$$OR = \frac{M1 - M2}{M2} \times 100 \tag{3}$$

where M_1 (g) and M_2 (g) are the weights of unwhipped and whipped cream with 100 mL volume, respectively.

Foam stability

One of the simplest ways to evaluate the stability of foam is by foam drainage [45]. The amount of drainage is a gauge of foam stability; the more drainage and cream syneresis, the less stable the foam is. Using 20 g of whipped cream installed on the Buchner funnel, foam stability (FS) was determined. After that, the funnel spent 3 h in the incubator at 25 °C. The serum was collected in a tarred beaker, and the syneresis was calculated using the following equation [29]:

$$FS = \frac{M_s}{M_w} \times 100 \tag{4}$$

where M_s and M_w are the weights of the serum collected and the initial weight of whipped cream, respectively.

Particle size distribution

Using a Malvern Mastersizer 2000, laser scattering technique was used to determine the particle size distribution and average diameter of the samples (Malvern Instruments Ltd, Worcestershire, UK). Prior to measuring the particle size distribution, the samples were dissolved in water, and the volume-weighted mean diameter of $d_{4,3}$ (μm) was utilized to track changes in the droplet-size distribution. The refractive indices for milk fat and water were 1.46 and 1.33, respectively (Long, Zhao, Zhao, Yang, & Liu, 2012). An average value was obtained from three sets of measurements that were done. The mean particle size $d_{4,3}$ (μm) was calculated using the following equation:

$$d_{4,3} = \sum n_i d_i^4 / \sum n_i d_i^3 \quad (5)$$

where n_i and d_i are the number of particles with the same diameter and particle size, respectively.

Microstructure

To get the right micrograph, whipped cream samples were dehydrated using various concentrations of graded acetone solutions. Afterward, they were fixed for at least an hour in a solution of 2.5% glutaraldehyde in cacodylate buffer (pH 7.2). The samples were coated with gold and at least 5 regions of each sample were subjected to the SEM. The micrograph of the samples were obtained using scanning electron microscopy (SEM, model SC 7620, England) with an elevated voltage of 25 kV and a magnification of 3000 × and 5000×.

Statistical analysis

Triplicates of each rheological, textural, and physical investigation were performed. Analysis of variance (ANOVA) was used to examine the results with a 5% level of significance. Software from Jandel Scientific, Corte Madera, California, USA, called Sigmaplot (version 8.0) was used to assess rheological graphs, and Rheoplus (version 3.40 Anton Paar GmbH, Germany) was used to analyze rheological data.

Results and discussion

Flow behavior

The apparent viscosity (η_a) of dairy cream as a function of shear rate at different levels of fat and BSG, WPC and CGN are provided in Fig. 1. As it can be found, all the samples showed pseudoplastic behavior (non-Newtonian fluid) which is in agreement with previous works [46, 47]. The rupture of the fat globule structure under the shear stresses may be the cause of all the forward curves having higher η_a than the backward ones (Fig. 2). Higher shearing pressures were produced by the increase in shear rate, which favoured either the formation of amorphous aggregates or the breakup of aggregates. The structural disintegration of the fat clusters or aggregates that happened in the backward curves can be used to explain it [32, 48]. As a result, the η_a was decreased with increasing shear rate [46]. Indeed, the flow ability of cream was reduced while using a stabilizer (BSG/CGN) which can be related to the water binding of hydrocolloid molecules contributing to resistance in flow [49, 50]. It should be noted that the effect of CGN at fat content 35% was used as a control with the other hydrocolloids. In comparison, owing to the high intrinsic viscosity (3917 mL/g) of BSG, the viscosity of all cream containing BSG was greater than that of CGN (Fig. 1a), resulting in a high capacity to improve the viscosity of the cream emulsion [51]. In addition, it may be assumed that as more BSG (0.3%), CGN, or cream with a high fat content was utilized, the structural breakdown of the fat clusters or aggregates happened later. It should be emphasized that even at extremely low shear rates, the shear forces were powerful enough to break the secondary bonds holding the particles together, causing the cluster or aggregate to break or deform, and ultimately leading to a significant decrease in the value of η_a. According to a research, the creation of clusters or aggregation of droplets may be connected to the shear-thinning of the most oil-concentrated systems [52]. The effect on η_a diminished when shearing forces outweighed the attraction factors holding fat droplets/globules together. As shown in Fig. 1, the samples offered converging low viscosity at high shear rates.

Typical flow curves in forward and backward modes for WPC, BSG and CGN are given in Fig. 2. The energy per unit of time and per unit of volume needed to eliminate the influence of time on flow behavior is indicated by the integrated area between the forward and backward curves [53]. In fact, due to the complexity of the emulsion systems particularly the presence of foam, working with large deformation might induce destabilization of air bubbles (size, organization and etc.), and therefore, the foam at the beginning of the test might not be the same at the end [54, 55]. Dairy sweets and confectionery can take use of the dairy cream's less thixotropic behavior as a measure, since it relates to the capacity to reconstruct the broken structure more quickly following the removal of shear stresses. Therefore, the rheological instability increased as the area of the thixotropy hysteresis loop expanded. When the segments of the down curves attained shear stress values lower than those of the up curves at the identical values of shear rate, all the creams displayed thixotropic behavior across the shear rate range (0.1–200 s^{-1}). Increased shear rate causes aggregates to be disturbed

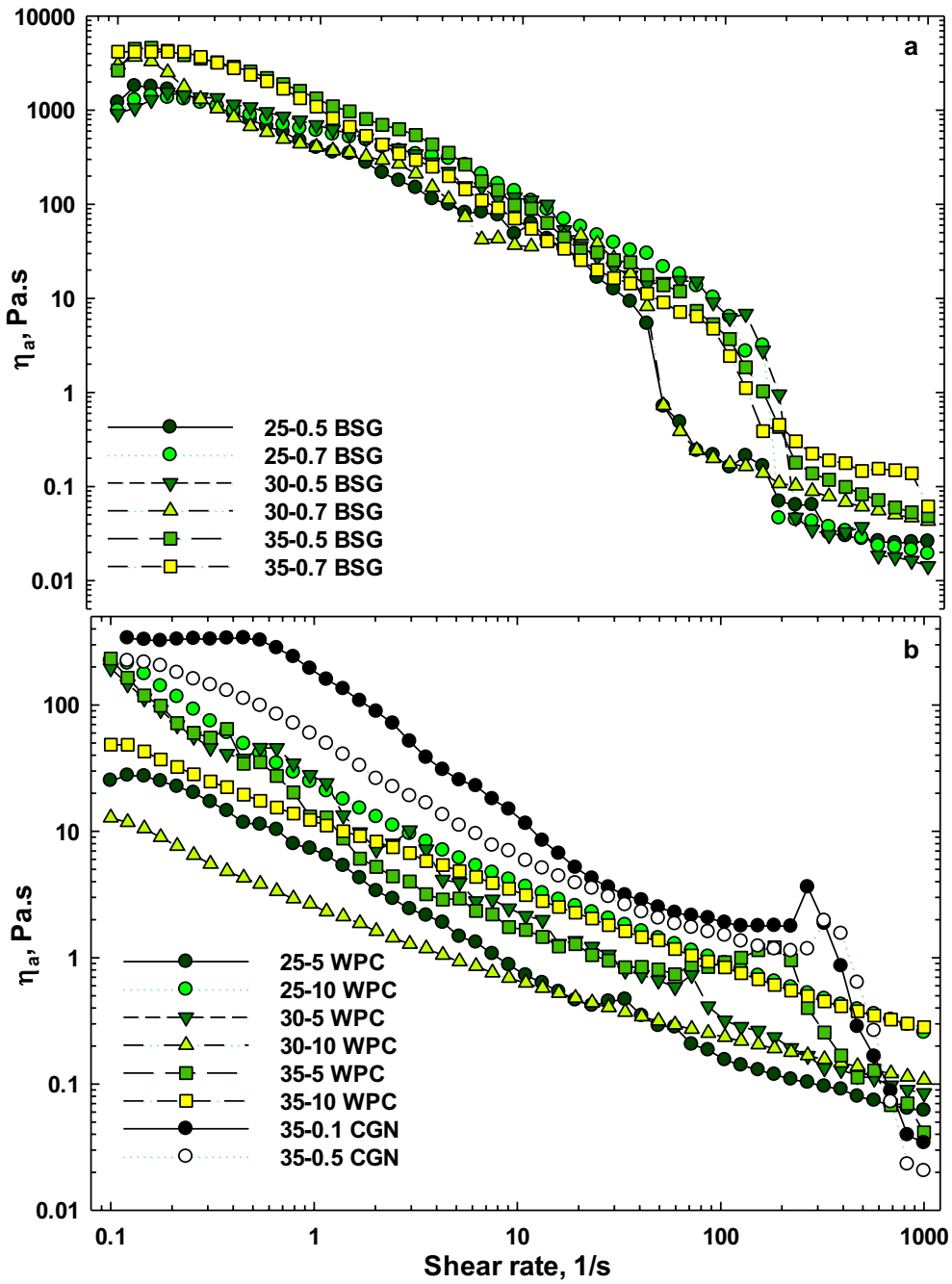

Fig. 1 Apparent viscosity (η_a) of whipped cream as a function of shear rate of (**a**) BSG, (**b**) WPC at 25%, 30% and 35% fat as well as CGN (35% fat)

and distorted by hydrodynamic forces, which reduces viscosity [56]. The hysteresis area grew with increasing BSG content, indicating the thixotropic nature of the gum solutions. It has been shown that even when a lower viscosity thixotropic fluid has a shorter structural disruption; it may nonetheless exhibit a bigger hysteresis region than a higher viscosity one [57]. However, thixotropic behavior increased higher for the creams with 30% and 35% fat than for the creams with 25% fat (Table 1). Data analysis revealed that there was no statistically significant variation in the hysteresis values of the samples containing 0.3% BSG for the creams with different fat concentrations ($P < 0.05$). The CGN samples showed the same patterns as well. The sample's

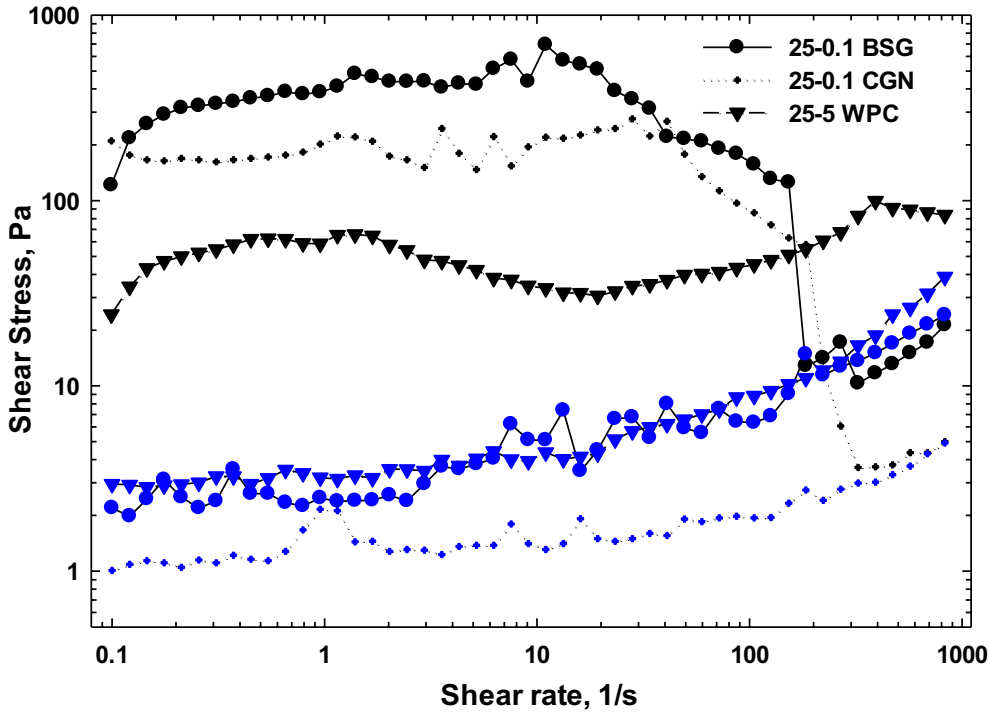

Fig. 2 Typical flow curves of stabilizers in forward (black) and backward mode (blue) at 10 °C

35–0.3% BSG and 25–5% WPC had the highest and lowest thixotropy properties, respectively (Table 1). The greater degree of thixotropy was observed in the samples with more hydrocolloids which is consistent with a gradual loss of product structure by increasing shear duration. The cream may be made at a very low dose of stabilizer without the addition of further stabilizer or thickening, as evidenced by the low value of thixotropy hysteresis loop (~ 579) that was obtained for the 35–0.1% CGN [58].

Large deformation rheology

Figure 3A depicts the influence of stabilizer and fat content on the G' of cream as a function of the applied strain amplitude, γ_0, at frequency 1 Hz and 10 °C. In the LVE region, G', G", complex shear modulus (G^*), and tan δ remained constant. For all samples, G' prevailed over G'' ($G' > G''$), and the values of G', G'' and tan in the LVE range was provided in Table 1. Despite the fact that dairy creams containing 35–0.1% and 0.3% CGN and 30–0.3% BSG had the highest G'_{LVE} and G''_{LVE} values, there was no discernible difference between the other creams ($P < 0.05$). Since G'_{LVE} discloses the structural integrity of the gels, it can be deduced that the creams with 35% fat together with CGN and 30–0.3% BSG had the greatest network structure.

When the slope of the plot deviates from unity, the strain and associated stress are nearly often referred to as the yield/fracture strain (γ_y) and yield/fracture stress (τ_y). In the plot of G as a function of stress, the yield point corresponds to the conclusion of the plateau. For this point, the applied strain has a significant impact on the sample's microscopic structure, the measured stress is no longer sinusoidal at strains greater than γ_y, and the material starts to flow. When $\gamma_{0<}\gamma_y$, $G' > G''$, the material's inherently elastic character is revealed. The weak network of linked globules that can withstand stress is what gives the material its elasticity. Both G' and G'' gradually decrease in the nonlinear area. Table 1 provides the yield stress (γ_y) and yield strain (τ_y).

The normalized G* as a function of the shear strain is shown in Fig. 3b to assist the reader have a better understanding of the massive deformation oscillatory rheology of the whipped cream. To calculate the normalized G^*, G^* was divided by G_0 in the absence of strain. Above the critical yield strain (γ_y), the measured moduli were no longer independent of stress or strain. The percentage strain at which there is a divergence of more than 5% from the constant value of G^* at limiting low strains in the LVE was identified as the yield or fracture strain. A drop in G^* may be caused by the sample's internal bonds breaking, which would cause macroscopic fracture/flow behavior. The stiff microstructure of whipped creams,

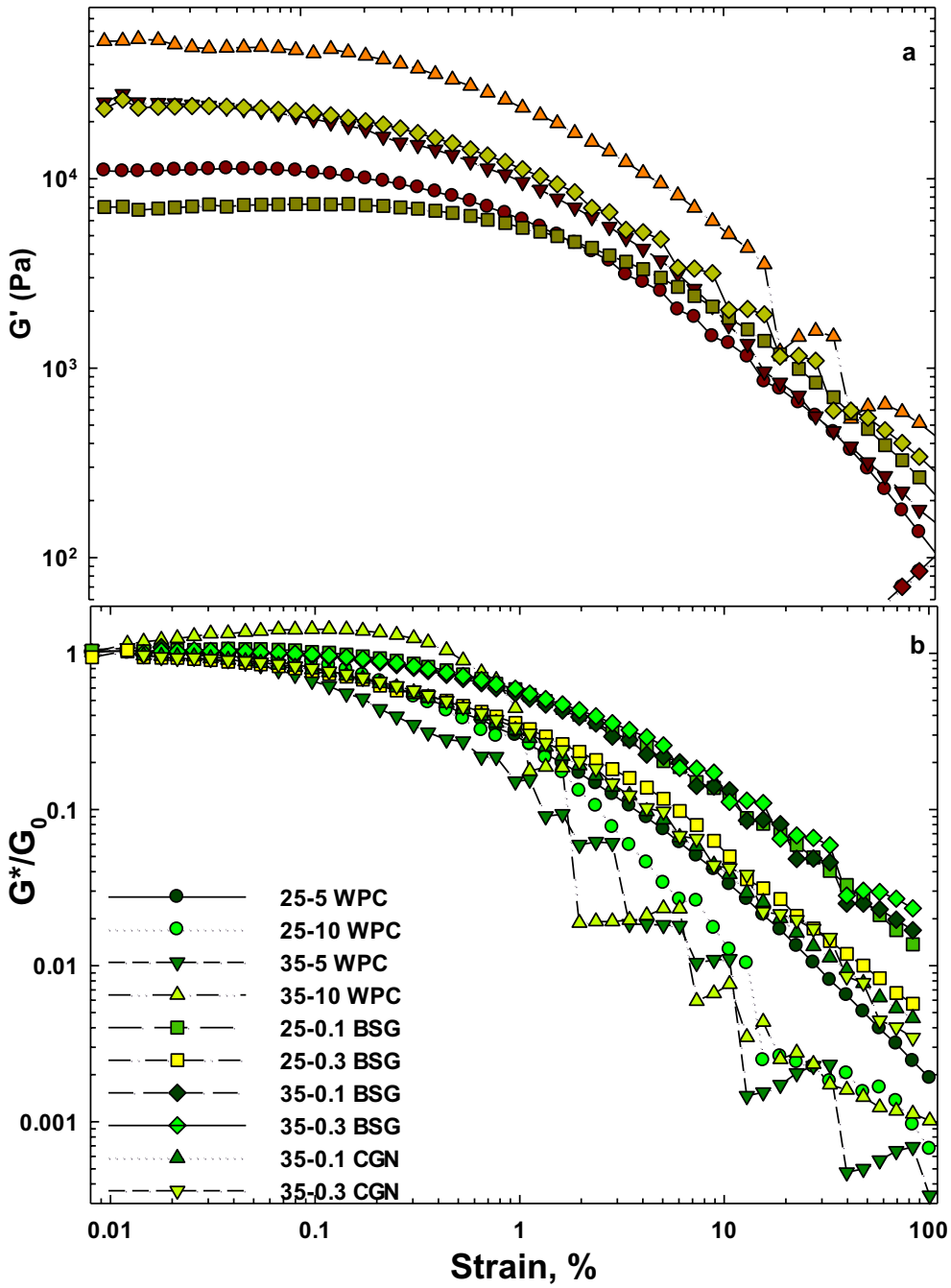

Fig. 3 Effect of fat and stabilizer on the G′ of dairy cream (**a**), and strain-dependent normalized complex modulus (G^*/G_0) (**b**) at frequency 1 Hz and 10 °C. The γ_y is defined here as the strain beyond which G^*/G^*_0 has fallen to 90% of the limiting low-strain value G^*_0

as shown in Fig. 3b, is shattered at extremely low strain levels of less than around 0.01 (< 1%), exposing a brittle network structure made of strong short-ranged connections that matches the behavior of a classical particle gel system [59]. The bonds are bridging between proteins like as whey proteins and polysaccharide in the stabilized emulsion foams. Numerous efforts have been made over the years to correlate and model the physical characteristics of aggregating suspensions, such as permeability, viscoelastic behavior, and compressive rheology, based on various factors, such as the primary particle size, the aggregate structure and strength, and the particle

Table 1 Hysteresis area, structural strength (G'_{LVE}), G''_{LVE}, loss-tangent (tan δ_{LVE}) in the LVE region, and yield stress and strain of the cream as a function of fat and hydrocolloid content

Fat-hydrocolloid (%)	Hysteresis area (Pa)	G'_{LVE} (Pa)	G''_{LVE} (Pa)	tan δ (−)	γ_y (%)	τ_y (Pa)
25–5 WPC	384 ± 65^{j}	5083 ± 90^{g}	654 ± 75^{h}	0.64 ± 0.02^{c}	0.76 ± 0.01^{c}	7084 ± 94^{f}
25–10 WPC	397 ± 34^{j}	8026 ± 85^{e}	764 ± 52^{h}	0.72 ± 0.02^{b}	0.74 ± 0.01^{c}	8214 ± 62^{f}
30–5 WPC	446 ± 54^{i}	7345 ± 64^{e}	945 ± 66^{g}	0.73 ± 0.02^{b}	0.63 ± 0.01^{d}	$40{,}974 \pm 66^{c}$
30–10 WPC	474 ± 89^{h}	9234 ± 86^{e}	1420 ± 56^{f}	0.86 ± 0.01^{a}	0.60 ± 0.01^{d}	$45{,}365 \pm 82^{c}$
35–5 WPC	465 ± 75^{h}	7776 ± 72^{e}	2567 ± 89^{e}	0.53 ± 0.01^{d}	0.51 ± 0.02^{e}	$58{,}761 \pm 57^{b}$
35–10 WPC	504 ± 67^{g}	$10{,}390 \pm 84^{d}$	3563 ± 93^{d}	0.89 ± 0.01^{a}	0.57 ± 0.02^{e}	$63{,}785 \pm 87^{b}$
25–0.1 BSG	2270 ± 74^{d}	7854 ± 90^{e}	2154 ± 52^{e}	0.32 ± 0.01^{e}	0.84 ± 0.03^{b}	2764 ± 93^{c}
25–0.3 BSG	2765 ± 88^{c}	$11{,}548 \pm 85^{d}$	4097 ± 69^{d}	0.36 ± 0.01^{e}	0.92 ± 0.01^{c}	2815 ± 58^{c}
30–0.1 BSG	2648 ± 57^{d}	$32{,}200 \pm 65^{c}$	5278 ± 47^{c}	0.28 ± 0.01^{f}	0.90 ± 0.02^{a}	$27{,}608 \pm 74^{e}$
30–0.3 BSG	3654 ± 73^{b}	$34{,}580 \pm 55^{c}$	5846 ± 35^{b}	0.29 ± 0.01^{f}	0.94 ± 0.04^{a}	$24{,}212 \pm 57^{e}$
35–0.1 BSG	2850 ± 44^{d}	$24{,}200 \pm 33^{d}$	4268 ± 38^{d}	0.29 ± 0.01^{f}	0.67 ± 0.01^{d}	$61{,}570 \pm 66^{a}$
35–0.3 BSG	3800 ± 80^{a}	$26{,}700 \pm 62^{d}$	5584 ± 54^{c}	0.30 ± 0.01^{f}	0.63 ± 0.03^{d}	$70{,}255 \pm 47^{a}$
35–0.1 CGN	579 ± 32^{f}	$46{,}725 \pm 90^{a}$	$11{,}225 \pm 50^{a}$	0.33 ± 0.01^{e}	0.92 ± 0.01^{a}	$29{,}450 \pm 78^{d}$
35–0.3 CGN	648 ± 93^{e}	$47{,}025 \pm 65^{a}$	$10{,}890 \pm 39^{a}$	0.34 ± 0.01^{e}	0.93 ± 0.01^{a}	$29{,}840 \pm 96^{d}$

* The statistical significant difference is shown in alphabetical order and significant difference among the samples ($P < 0.05$) were made by Duncan's test

concentration (de Kruif et al). At a specific critical particle concentration, ϕ_g, which corresponds to the creation of a space-filling particle network, the characteristics of the aggregating suspension alter dramatically for the majority of systems. The distinct clusters will settle more or less independently in diluted suspensions, since there is no yield stress $\phi < \phi_g$. A stress can be carried by the suspension above ϕ_g, and there may be substantial flexibility and little settling [59]. Between regular cream (~0.01%) and acidified caseinate stabilized emulsion foam, which behaves as a typical polymer gel beyond high γ_y (~10%) [60], there was an apparent fracture strain of the dairy cream with BSG or CGN.

Mechanical characteristics

Mechanical properties of dairy cream including different stabilizers, i.e., WPC, BSG and CGN at varying levels on the low fat (25%) and high fat (35%) creams were measured by F-sweep measurements at 0.5% strain and 10 °C (Fig. 4a, b). Over the frequency range, all creams showed low frequency dependency, and both moduli values were raised. Being $G' > G''$ for all samples, indicating a larger contribution of elastic characteristics, reveals an elastic solid-like nature with low transitional drive under shear stress due to the fat crystal complex. As it can be understood from Fig. 4, by increasing protein or polysaccharide as well as fat content, the G' value was increased. Table 2 lists the rheological characteristics of cream, including G', G'', η^*, and tan δ as functions of stabilizer and fat content. The sample that was submitted had more increase in G', G'', and η^* as well as a larger gap between G' and G'', which indicated a predisposition to form macromolecular networks. WPC and BSG scored higher on this metric than CGN did. The cream with the maximum elasticity was found to include 35–10% WPC (Fig. 3b), indicating that increasing the protein content enhanced the cream's elasticity and that it is possible to enhance the foam structure. Therefore, it can be seen that the addition of more protein had a higher effect than the addition of more fat on the improvement of the stiffness of the emulsion systems by producing a more solid-like structure ($G' > G''$). It has already been documented that stabilizers exhibit comparable characteristics when it comes to emulsion stability [34, 49, 60, 61]. According to Speroni and colleagues [62], these rheological analyses of whipped cream showed a weak gel system in which the protein segments of BSG or its polysaccharide fractions were adsorbed at the oil–water interface, G' was raised, and a pseudo-gel network was created, which in turn created a stronger molecular protein network.

Phase angles (δ) are widely employed to show the degree of viscoelasticity, since they vary from 0° for fully elastic solids to 90° for viscous materials [56]. A small value of phase angle, such as 20°, implies that the material has strong elastic (gel) properties (a high value of G' in compared to G''). Table 2 shows how whipped cream's phase angle values decrease as its hydrocolloid concentration rises. Since the tan δ values (0.45–0.67) were 0.1 to 1.0 suggests that the weak gel contains an elastic structure. Protein, polysaccharides, and fat droplets have been linked to similar rheological phenomena in dairy cream that are embarrassing [7, 63].

Table 3 displays the p and q indices, as well as the slope of whipped cream's complicated viscosity (η^*). All of the

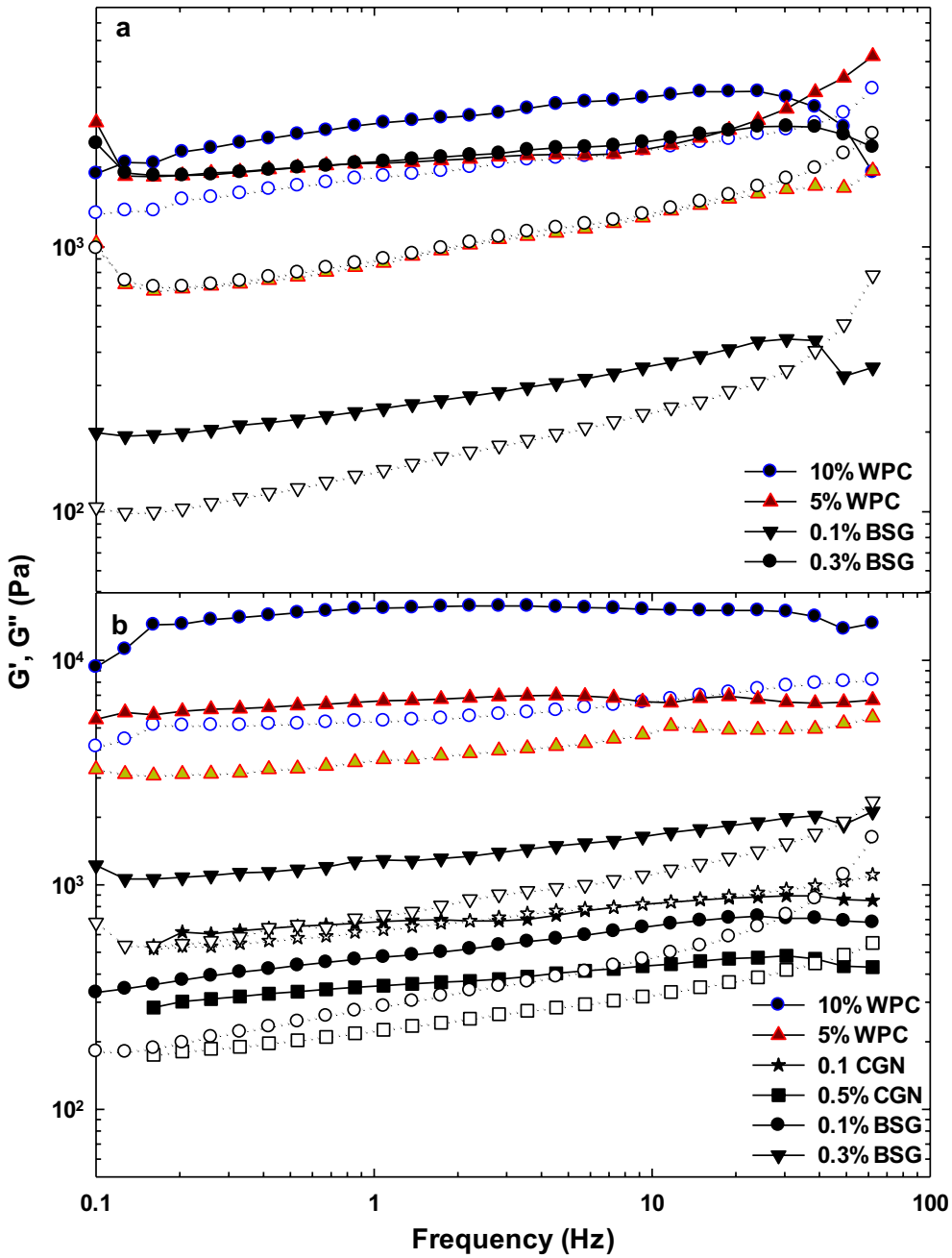

Fig. 4 Effect of stabilizers (WPC, BSG and CGN) on G' (filled symbols) and G'' (blank symbols) of the dairy cream at 25% fat (**a**) and 35% fat (**b**) (strain 0.5% and 10 °C)

samples' p (0.15) and q (0.23) values were very low, which is related to the low frequency dependence of G' and G'' and may be explained by the cream's more covalent gel structure [43]. The slope of log η^* was around − 0.82 to − 0.90 (Table 3), suggesting intermolecular biopolymer interactions. The complex viscosity (η^*), which defines the resistance to flow, similarly dropped linearly with frequency, demonstrating the shear thinning phenomena [36].

Particle size distribution

Particle size distribution, which indicates particle size and its volume percentage, can strongly influence the stability and property of whipped cream. The effect of stabilizer

Table 2 Dynamic rheological parameters of dairy cream at frequency 1 Hz as a function of fat and stabilizer content on the mechanical properties (strain 0.5% and 10 °C)*

Fat-hydrocolloid (%)	G' (kPa)	G'' (kPa)	η^* (kPa.s)	Tan δ
25–5 WPC	0.736 ± 0.054^{e}	0.216 ± 0.025^{g}	0.12 ± 0.05^{g}	0.34 ± 0.01^{e}
25–10 WPC	0.753 ± 0.043^{e}	0.253 ± 0.012^{g}	0.11 ± 0.01^{g}	0.48 ± 0.01^{d}
30–5 WPC	5.855 ± 0.035^{c}	2.411 ± 0.035^{c}	1.31 ± 0.07^{c}	0.32 ± 0.01^{e}
30–10 WPC	6.255 ± 0.710^{c}	2.583 ± 0.027^{c}	1.78 ± 0.04^{c}	0.28 ± 0.01^{e}
35–5 WPC	1710 ± 0.624^{a}	538.21 ± 1.78^{a}	263 ± 0.27^{a}	0.47 ± 0.01^{d}
35–10 WPC	102 ± 1.574^{b}	34.622 ± 0.682^{b}	15.92 ± 0.57^{b}	0.41 ± 0.02^{d}
25–0.1 BSG	0.650 ± 0.056^{e}	0.357 ± 0.025^{d}	0.10 ± 0.02^{d}	0.56 ± 0.03^{c}
25–0.3 BSG	2.765 ± 0.067^{d}	1.247 ± 0.364^{d}	0.43 ± 0.02^{d}	0.45 ± 0.02^{d}
30–0.1 BSG	0.794 ± 0.058^{e}	0.532 ± 0.233^{f}	0.13 ± 0.01^{f}	0.67 ± 0.03^{b}
30–0.3 BSG	0.930 ± 0.597^{d}	0.564 ± 0.126^{f}	0.15 ± 0.05^{f}	0.61 ± 0.01^{c}
35–0.1 BSG	0.495 ± 0.066^{f}	0.267 ± 0.241^{g}	0.22 ± 0.03^{g}	0.62 ± 0.03^{c}
35–0.3 BSG	1.108 ± 0.080^{d}	0.678 ± 0.897^{e}	0.20 ± 0.02^{e}	0.58 ± 0.01^{c}
35–0.1 CGN	0.700 ± 0.067^{e}	0.675 ± 0.055^{e}	0.18 ± 0.05^{e}	0.77 ± 0.01^{a}
35–0.3 CGN	0.257 ± 0.087^{g}	0.144 ± 0.008^{h}	0.04 ± 0.02^{h}	0.75 ± 0.07^{a}

* The statistical significant difference is shown in alphabetical order

levels on the particle size distribution of whipped cream after 20 min whipping are provided in Table 4. The particle size distribution curve showed two distinguishable peaks at approximately 5 and 80 µm for all stabilizers. The distribution curves for whipped cream 35% fat along with BSG and CGN at 0.1% and 0.3% were provided in the (see Additional file 1: data S1). Furthermore, the average particle size of dairy cream increased with increasing stabilizer levels (Table 4). BSG concentrations significantly impacted the typical dairy milk particle size ($P < 0.05$). In addition, whipped cream had an average particle size $d_{4,3}$ that was substantially larger than that of CGN and WPC ($P < 0.05$). The BSG can help create a network of partly coalesced droplets in whipped cream by linking the fat clumps in the bulk and causing the droplets to stick to the surface of the air bubbles. This gives the foam structural stability and raises $d_{4,3}$. In addition, the interaction of BSG with air bubbles during aeration may also result in a rise in $d_{4,3}$ [60]. When 0.3% BSG was introduced, the largest average particle size $d_{4,3}$ of 7.20 µm was produced, whereas 0.1% BSG produced a lower $d_{4,3}$ of 3.70 µm. (Table 4). Zhao et al. (2009) stated that high concentrations of sodium caseinate or whey protein lowered the average particle size of cream, despite the fact that the impact of BSG levels on the average particle size $d_{4,3}$ of cream has not yet been researched. Similar findings were also found in our work in which by applying high amount of WPC, the particle size reduced (Table 4). The molecules may be competitively adsorbed onto the surface of fat droplets when BSG/CGN levels rise, altering the surface tension and shrinking the particle size. On the other hand, a rise in stabilizer levels may result in an increase in emulsion capacity, which may prevent the average particle size $d_{4,3}$ from increasing. The possibility exists that the particle size will grow as a result of the interplay between mechanical shear and air inclusion during whipping. It is interesting to observe that dairy cream, which contains 35% fat and 0.1% stabilizer, produced particles of a comparable size when BSG or CGN were added in equal amounts. Moreover, the addition of BSG/CGN may cause the protein-covered fat droplets to develop into aggregated network, which can entrap air and increase structural integrity of foam, thus resulting in further increase of particle size [30, 64]. The dispersion of liquid fat at the air/water interface should be restricted, though since it might result in the production of thin lamellae between bubbles, which could ultimately weaken the film and rupture the air bubble [8].

Textural properties

To achieve the correct consistency of the foamed dairy emulsion, texture is a crucial aim.[27, 65]. Table 4 provides the hardness and adhesiveness of whipped cream at various fat contents and stabilizer levels. However, increasing BSG, WPC, and fat resulted in a substantial increase in hardness, but increasing CGN resulted in a decrease in hardness ($P < 0.05$). This beneficial impact, which has previously been seen for xanthan gum, can be interpreted by the high thickening capability of BSG [27]. The late crystallization of fat in whipped cream can be used to explain the fat concentration. Through crystallization, the fat globules in the emulsion partially coalesced, merging to form bigger granules that helped

Table 3 Effect of fat and stabilizer level on the frequency dependencies of G' and G'' by a power law model*

Fat-hydrocolloid (%)	p	R^2	q	R^2	Slope of η^*	R^2
25–10 WPC	0.046 ± 0.001^{e}	0.98	0.019 ± 0.003^{f}	0.99	-0.83 ± 0.02^{c}	0.99
30–5 WPC	0.038 ± 0.003^{f}	0.99	0.017 ± 0.002^{f}	0.99	-0.82 ± 0.03^{c}	0.99
30–10 WPC	0.037 ± 0.002^{f}	0.99	0.025 ± 0.004^{e}	0.98	-0.87 ± 0.01^{b}	0.99
35–5 WPC	0.047 ± 0.003^{e}	0.98	0.033 ± 0.002^{e}	0.99	-0.84 ± 0.02^{c}	0.99
35–10 WPC	0.054 ± 0.002^{e}	0.98	0.027 ± 0.001^{e}	0.99	-0.80 ± 0.01^{d}	0.99
25–0.1 BSG	0.150 ± 0.003^{a}	0.99	0.221 ± 0.004^{b}	0.99	-0.84 ± 0.01^{c}	0.99
25–0.3 BSG	0.100 ± 0.026^{c}	0.98	0.190 ± 0.017^{d}	0.99	-0.90 ± 0.03^{a}	0.99
30–0.1 BSG	0.090 ± 0.013^{c}	0.99	0.186 ± 0.009^{d}	0.99	-0.87 ± 0.07^{b}	0.99
30–0.3 BSG	0.112 ± 0.022^{c}	0.99	0.210 ± 0.022^{c}	0.98	-0.83 ± 0.07^{a}	0.99
35–0.1 BSG	0.128 ± 0.003^{b}	0.98	0.233 ± 0.015^{a}	0.99	-0.83 ± 0.01^{b}	0.99
35–0.3 BSG	0.131 ± 0.002^{b}	0.98	0.212 ± 0.013^{c}	0.99	-0.84 ± 0.03^{c}	0.99
35–0.1 CGN	0.012 ± 0.002^{d}	0.95	0.075 ± 0.076^{e}	0.99	-0.84 ± 0.05^{c}	0.99
35–0.3 CGN	0.010 ± 0.001^{d}	0.99	0.190 ± 0.028^{d}	0.99	-0.86 ± 0.02^{c}	0.99

* The statistical significant difference is shown in alphabetical order

Table 4 Textural attributes, foaming parameters and the average diameter ($d_{4,3}$, μm) of dairy cream creams subjected to different stabilizers at 25 °C

Fat-hydrocolloid (%)	$d_{4,3}$, B_w (μm)♣	$d_{4,3}$, A_w (μm)♣	Hardness (*N*)	Adhesiveness (*J*)	Overrun (%)
25–5 WPC	2.085 ± 0.007^{i}	1.705 ± 0.005^{h}	2.28 ± 0.34^{c}	26.27 ± 1.37^{d}	87 ± 1.05^{e}
25–10 WPC	2.847 ± 0.004^{h}	1.656 ± 0.003^{g}	2.37 ± 0.53^{c}	37.34 ± 1.02^{b}	94 ± 1.06^{e}
35–5 WPC	5.086 ± 0.002^{e}	3.474 ± 0.008^{f}	4.17 ± 0.60^{a}	39.08 ± 1.65^{b}	78 ± 0.98^{f}
35–10 WPC	6.693 ± 0.003^{c}	4.552 ± 0.006^{c}	4.52 ± 0.84^{a}	42.37 ± 1.27^{a}	85 ± 1.14^{e}
25–0.1 BSG	5.844 ± 0.006^{g}	3.703 ± 0.003^{e}	1.14 ± 0.62^{e}	24.15 ± 1.67^{d}	86 ± 1.23^{e}
25–0.3 BSG	7.243 ± 0.005^{a}	6.415 ± 0.003^{a}	1.84 ± 0.55^{e}	31.26 ± 1.82^{d}	120 ± 1.13^{c}
35–0.1 BSG	4.897 ± 0.002^{f}	4.086 ± 0.004^{d}	3.00 ± 0.75^{b}	36.96 ± 1.85^{b}	106 ± 1.15^{d}
35–0.3 BSG	7.142 ± 0.003^{b}	6.058 ± 0.006^{b}	3.82 ± 0.50^{b}	43.23 ± 1.63^{a}	108 ± 1.12^{d}
35–0.1 CGN	4.878 ± 0.003^{f}	4.115 ± 0.002^{d}	2.23 ± 0.22^{d}	34.26 ± 1.83^{c}	134 ± 1.22^{b}
35–0.3 CGN	5.146 ± 0.005^{d}	3.876 ± 0.007^{e}	2.83 ± 0.11^{e}	33.66 ± 1.80^{e}	139 ± 1.11^{a}

* The statistical significant difference is shown in alphabetical order and Significant difference among the samples ($P < 0.05$) were made by Duncan's test

♣ Average diameter of foams before whipping (B_w) and after whipping (A_w)

to release the serum and change the structure of the whipped cream. In comparison among various stabilizers, hardness of WPC and BSG was 2.28–452 N and 1.82–3.82 N, respectively, xanthan gum (4.32–7.67 N) and HPMC (3.47–6.55 N) [27], whey protein (1.5–3.0 N) and sodium caseinate (1.6–3.7 N) [24], MFGMP (3.92–9.8 N) [30]. The impact of BSG was smaller than that of commercial gums at the same concentration, which may be related to differences in their formulation and processing. Hardness was enhanced, however, by adding polysaccharides in the whipped cream. BSG does in fact absorb water and serve as a thickening agent due to its high hydrophilicity. To adsorb more water and function in the interfacial layer, BSG and caseinate competed with one another at both the fat/water and air/water interfaces. As a result, they were added to whipped cream to provide a more desired physical structure of the finished product [66].

The potential for flow or liquid condition of items is characterized by their adhesiveness. Adhesiveness, on the other hand, provides another illustration of how the microstructure affects the macroscopic features. It is the effort necessary to resist the forces of attraction between the surface of the meal and the other components that come into touch with one another [27]. The trend for adhesiveness was comparable to that for hardness with increasing WPC, BSG, CGN, and fat content, as shown in Table 4. Whipping cream 35–0.3% BSG had the highest adhesiveness. According to the relationship between BSG level and cohesiveness, whipped cream with a greater BSG level was less crumbly and less likely to distort.

Foaming properties

One of the most useful criteria for textural characteristics and foam stability is overrun, which measures gas hold-up or the proportion of gas in whipped cream. Therefore, the maximum overrun determines the stiffness and stability of ideal foam [7, 46]. Two important factors affecting the texture of whipped cream are the quantity of air inclusion and their size. The impact of fat content and BSG or CGN on the overrun of whipped cream is assessed, since proteins, lipids, and hydrocolloids are key components for air incorporation and regulation of the thermodynamically unstable air cells [67]. The findings demonstrated that stabilizer had a beneficial impact, while fat had a negative impact on overrun (Table 4). By lowering fat or introducing stabilizer, all samples demonstrated a statistically significant increase in overrun ($P < 0.05$). Conversely, whipped cream with higher polysaccharide content has better air entrapment during whipping, which has increased overrun. The stability of the foam may be inferred that gum rising is a significant factor. The aqueous phase's viscosity was further raised by increasing the gum content in the whipped cream, making the foam more stable and encouraging the creation of a network structure in the bulk phase that would prevent the interfacial wall from simply splitting. There were no appreciable variations in foam stability at lower BSG/CGN ratios (0.3%). At 35–0.3% BSG, the low stability value was attained. In addition, lipids hinder the ability of proteins or polysaccharides to foam, hence by increasing the fat content, the overflow was reduced [68]. Protein or polysaccharides competed for binding sites in the interfacial layer with lipids, which caused foam rupture in the foam lamella due to greater surface activity. Because of this, cream with a moderate BSG level may have more opportunities for air to incorporate, strengthening the stability of the incorporated air [60]. Surface tension, bubble size distribution, interface permeability, and interface thickness all have an impact on foam stability [45].

Microstructure of dairy cream

SEM images of high-fat cream (35%) at different amounts of stabilizers including WPC, CGN and BSG are given in Fig. 5 to provide quantitative information on the formation and structure of the cream. Low-fat dairy cream had smaller globular aggregates in its microstructure than high-fat dairy cream, allowing the high-fat samples to retain more water (Fig. 5a–d). Therefore, by increasing fat, the aggregates were decreased and more water retained in the cream. Thus, it can be inferred that the cream displayed more overrun and stability at high-fat content. The dairy cream containing CGN displayed smaller aggregates and increased water retention in contrast to BSG and CGN. Cream has allegedly established a continuous structure, too. Furthermore, the non-adsorbed polysaccharides or proteins may be the cause of the dairy cream containing CGN's mild flocculation (Fig. 5e, f). Conversely, it has been shown that BSG has a globular and cotton-like structure [37], which may be seen with reduced flocculation (Fig. 5g, h). In addition, dairy cream containing BSG showed more voids and holes that improved the foam's structure, and a sizable number of fat aggregates are also apparent in Fig. 5g, h. It was demonstrated that the amorphous shape of BSG fibrillar aggregates was impacted by the BSG's improved stability and overflow. Similar structures have also been seen in other mixed systems, including those including whey protein isolate–κ-carrageenan and BSG–β-lactoglobulin [37, 69]. It should be noted that by adding BSG to whipped cream, it can operate as a continuous gel in the dairy foam and protect from syneresis due to its emulsifying and surface active qualities. Despite the explanation that gels with a fibril structure had a poorer water holding capacity [70], BSG introduces a cotton-like structure into the system, increasing the bulk system's viscosity and preventing serum escape. Synergistic interactions between proteins and polysaccharides (WPC, BSG, or CGN) may, therefore, encourage the formation of cross-linked networks and improve emulsifying capabilities [70, 71]. Similar findings on the emulsion stability have been observed for guar and xanthan gum [71, 72]. As a result, homogenization lowered interfacial tension, allowed proteins and polysaccharides to adsorb to the surface of droplets, and prevented droplets from aggregating by creating a barrier surrounding them.

Conclusions

The structure–rheology relationships of dairy cream as affected by WPC, BSG and κ-carrageenan on low- and high-fat cream were investigated. The behavior of all the samples was pseudo-plastic. The rupture of the fat globule structure under the shear stresses may be the cause of all forward curves having greater η_a than the backward ones. Using a stabilizer (BSG/CGN) decreased the cream's capacity to flow, which may be connected to the hydrocolloid molecules' ability to attach to water, which adds to flow resistance. Higher degree of thixotropy for the samples with more hydrocolloids is consistent with a gradual loss of the product's structural integrity. The increase in BSG content had a bigger influence on the stiffness of the emulsion than on the application of high fat, according to rheological data that also revealed that increasing BSG enhanced the elasticity of the cream. Furthermore, beyond high γ_y (~ 10%), the fracture strain of BSG or CGN cream behaves like a conventional polymer gel. Overall, the

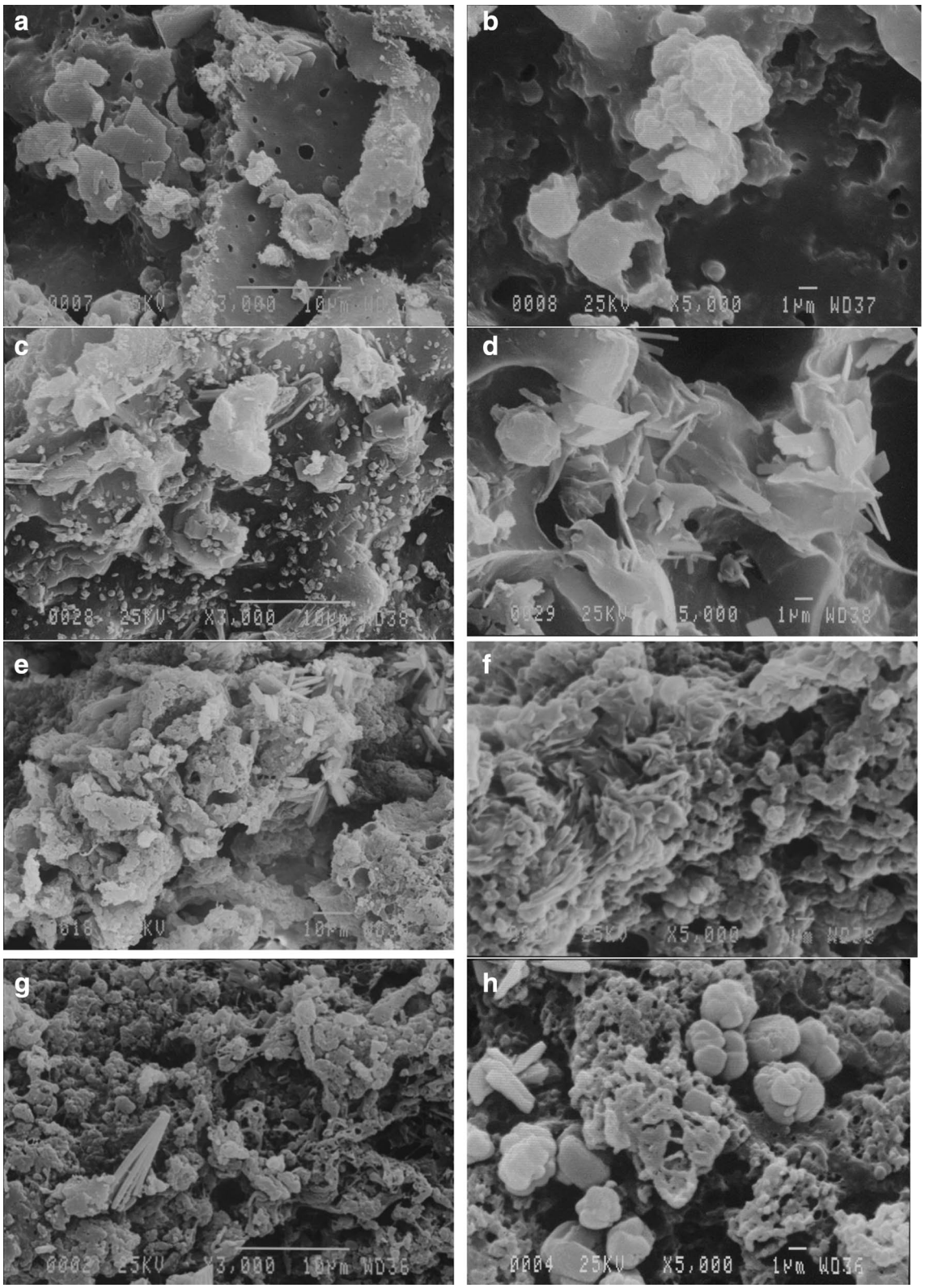

Fig. 5 SEM micrograph of whipped cream at 25 kV (**a**, **b**) 25–10% WPC (**c**, **d**) 35–10% WPC (**e**, **f**) 35–0.5% CGN (**g**, **h**) 35–0.5% BSG (left to right 3000 and 5000×)

rheological behavior pointed to weak gel systems, in which BSG protein segments or its polysaccharide portions were adsorbed at the oil–water interface, resulting in the development of a pseudo-gel network that in turn results in a stronger molecular protein network. The particle size distribution curve showed two distinguishable peaks 5 and 80 μm for all stabilizers. By increasing the BSG/CGN levels, the molecules may be competitively adsorbed onto the surface of fat droplets, thereby changing its surface tension and decreasing its particle size. The positive effect of the stabilizer and the negative effect of the fat on the overrun and foaming stability were found to be in proper connection with each other. The globular aggregates in the microstructure of high-fat dairy cream were smaller than those in low-fat dairy cream, allowing the high-fat samples to retain more water. The non-adsorbed polysaccharides or proteins may have contributed to the dairy milk containing CGN's mild flocculation. Synergistic interactions between polysaccharides and proteins may thereby encourage the formation of cross-linked networks and improve emulsifying characteristics. Even though the relationship between cream's rheology, texture, and microstructure was assessed, more research is necessary to understand how BSG adsorbed at the oil–water interface works.

Abbreviations

BSG: Basil seed gum; CGN: κ-Carrageenan; HPMC: Hydroxypropyl methylcellulose; LVE: Linear viscoelastic region; MFGMP: Milk fat globule membrane protein; OR: Overrun; WPC: Whey protein concentrate; G′: Storage modulus; G″: Loss modulus; G*: Complex modulus; φ_g: Critical particle concentration; τ_y: Yield strain; γ_y: Yield stress.

Supplementary Information

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Additional file 1: Data S1. Typical particle size distribution curves of whipped cream 35% fat along with BSG and CGN at 0.1% and 0.3%, (**a**) prior to whipping and (**b**) after whipping.

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Author contributions

NB: data curation; investigation; methodology; writing—original draft. SAS: conceptualization; supervision; validation; writing—review and editing, AR: conceptualization; supervision; validation; visualization; writing—review and editing, JML: writing—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials

All data are presented in the manuscript.

Declarations

Ethics approval and consent to participate

The authors will follow the Ethical Responsibilities of Authors and COPE rules. On behalf of all co-authors, I believe the participants are giving informed consent to participate in this study.

Consent for publication

All the authors give their consent for the submitted manuscript to be published in the Chemical and Biological Technologies in Agriculture.

Competing interests

The authors declare that they have no competing interests. The study does not involve any human or animal testing, the authors declare, and they do not have any conflicts of interest.

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