



Physicochemical, rheological, textural, tribological, and sensory insights into the role of citrus fiber in quark cheese spreads with varying fat content

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ABSTRACT

The objective of this study was to evaluate the effect of citrus fiber (1% wt/wt) on the physicochemical, rheological, textural, tribological, and sensory properties of quark cheese spreads with different fat content (10%, 15%, and 20% wt/wt). Physicochemical properties, including pH, DM, and water activity, were not affected by citrus fiber addition. Furthermore, rheological and textural analyses showed that citrus fiber increased samples' hardness and viscoelastic moduli, probably by reinforcing the protein-polysaccharide matrix, especially in low-fat variants. Tribological measurements indicated that higher fat improved lubrication, whereas fiber-containing quark cheese spread samples exhibited slightly higher coefficients of friction due to increased structural rigidity. Additionally, color analysis revealed minor shifts toward darker and more yellow tones when citrus fiber was used. Moreover, sensory evaluation confirmed that citrus fiber addition did not affect most of the tested organoleptic attributes, with slight improvement in flavor. The findings indicate that incorporating citrus fiber into quark cheese spreads can improve their functional properties, facilitate fat reduction, and promote the sustainable utilization of byproducts in dairy products.

Key words: quark cheese spread, citrus fiber, viscoelastic properties, textural properties, tribological properties

INTRODUCTION

Dairy products (including milk, cheese, dairy beverages, and dairy desserts) represent fundamental components of the human diet, as they provide a wide range of essential nutrients. Historically, milk and dairy products have played a crucial role in human nutrition, serving as rich sources of both energy and bioavailable nutrients. From a nutritional perspective, milk is considered one of the most valuable natural foods, as it contains nearly all the

essential substances required for growth, development, and the proper functioning of the human body. These include high-quality proteins, calcium, lactose, milk fat, vitamins, and other bioactive components. Moreover, the nutritional value of dairy products may vary from that of raw milk due to compositional and physicochemical changes that occur during processing and manufacturing (Huth et al., 2006; Siddiqui et al., 2024; Sanjulián et al., 2025). In addition, dairy products are recognized not only for their macronutrient content but also for their physiological benefits, as they often serve as carriers of beneficial microorganisms, commonly referred to as probiotics, which contribute positively to gut health (Dimitrellou et al., 2019; Aljutaily et al., 2020; Siddiqui et al., 2024).

Fat constitutes a crucial component of milk and, from a nutritional perspective, serves as the primary energy source in milk and significantly contributes to numerous physical properties, manufacturing characteristics, and sensory attributes of dairy products. Moreover, from an economic standpoint, fat plays a vital role in determining the value of milk, as it directly affects the yield of various dairy products (Bauman et al., 2011). Milk fat also carries naturally occurring fat-soluble vitamins (A, D, E, and K), as well as β -carotene, a provitamin A carotenoid. The main lipids in milk fat are triacylglycerides, which make up more than 98% of the total fat, whereas the remaining 2% are diacylglycerides, monoacylglycerides, free fatty acids, phospholipids, sterols, and hydrocarbons (Gómez-Cortés et al., 2018). Furthermore, the reduction of low-density cholesterol and the regulation of blood pressure are among the primary objectives in the prevention and treatment of cardiovascular diseases. In addition, poor dietary habits and a sedentary lifestyle are considered significant risk factors. Consequently, nutritional guidelines frequently emphasize the importance of limiting the intake of SFA, as these are known to elevate cholesterol levels. For this reason, the consumption of low-fat dairy products is generally suggested over regular or full-fat alternatives (Drouin-Chartier et al., 2016).

Consumers often perceive milk fat as a risk factor for cardiovascular diseases and obesity, which is reflected in

Received October 26, 2025.

Accepted December 28, 2025.

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The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-26. Nonstandard abbreviations are available in the Notes.

the growing interest in low-fat dairy products (Gómez-Cortés et al., 2018). Although some recent studies have challenged earlier negative evaluations and suggest that milk fat consumption may have neutral or even beneficial effects (Hirahatake et al., 2020; O'Sullivan et al., 2020), scientific evidence remains inconclusive. Given the limited proof that low-fat dairy products are indeed healthier, alongside emerging research indicating potential benefits of full-fat alternatives, the choice between the 2 should be left to individual discretion (Mozaffarian, 2019). Considering this ongoing controversy and the continued scientific debate regarding the health implications of milk fat, exploring strategies for its replacement appears to be a relevant approach. The objective is to reduce the content of potentially risky components in the product while maintaining its sensory and nutritional quality.

Recent research increasingly focused on the replacement of milk fat in dairy products to improve their health and functional properties. One promising approach involves the application of hydrocolloids within dairy matrices. Zhao et al. (2023) highlighted the potential of hydrocolloids in such systems, emphasizing not only their technological significance but also their considerable nutritional benefits. In line with modern lifestyles and the growing awareness of the effect of diet on human health, there is a rising demand for foods with higher fiber content and reduced fat levels. In this context, hydrocolloids (particularly certain polysaccharides) play an important role as ingredients with potential applications in functional foods. They may serve as fat or sugar replacers or as carriers of bioactive compounds. These properties support the development of contemporary functional foods that are richer in fiber and lower in energy-dense components. Notably, Pirsá and Hafezi (2023) reported the possibility of complete or partial fat replacement using specific hydrocolloids such as inulin, pectin, guar gum, tragacanth, xanthan gum, carrageenan, sodium alginate, and locust bean gum.

Dairy products (including cheese) inherently lack dietary fiber, as fiber is exclusively present in plant-derived materials. Hence, this nutritional limitation provides an opportunity to enhance dairy formulations through fiber incorporation (Szafránska and Sołowiej, 2020). Citrus fiber (CF) plays a similarly important role in the development of functional dairy products. Due to its content of both soluble and insoluble dietary fibers (primarily pectin, cellulose, hemicellulose, and lignin), it serves as a suitable additive for a variety of applications aimed at improving food texture and stability, and it is classified as a food hydrocolloid (Huang et al., 2021). The CF is a natural food ingredient derived from the extraction of citrus peels and byproducts generated during the processing or preservation of citrus fruits, and it has been identified as a particularly promising source of dietary fiber (Kour

et al., 2014; Wu et al., 2025). In fact, citrus peel residues contain significantly higher fiber concentrations than the fruit itself, with levels potentially exceeding those in the fruit by up to 50% (Wu et al., 2025). Owing to its numerous health benefits, the methods of extraction and modification of CF are receiving increasing attention not only from researchers but also within the food and pharmaceutical industries. In addition to its positive impact on health, the use of CF in the food sector contributes to waste reduction and promotes environmental sustainability (Liu et al., 2024; Wu et al., 2025). The technological properties of products incorporating CF are strongly influenced by its water-binding capacity, lower bulk density, and higher viscosity, which further enhance its functional applications (Su et al., 2019). As a result, it has become an increasingly studied raw material. A study by Lundberg et al. (2014) demonstrated its significant potential for applications in the food industry, highlighting its ability to improve texture, stability, and nutritional value in various food products. Furthermore, previous research has demonstrated that the incorporation of CF into cheese and cheese analog formulations confers multiple functional advantages, including improved moisture retention, enhanced creaminess, reduced hardness (in low-fat variants), and increased structural stability, while simultaneously contributing to product overall nutritional profile (Szafránska and Sołowiej, 2020; Gurbuz et al., 2024; Nademi et al., 2025). Hence, the addition of CF in quark cheese spreads (QCS) could enhance not only the consistency of the final product but also its nutritional profile, due to its fiber content, which supports gut microbiota and overall consumer health. The QCS are products with a spreadable paste-like consistency and can be prepared using the blending technology (utilizing thermomixers for blending and heating simultaneously), applying quark cheese, cream, buttermilk, milk, water, and other optional powdered ingredients (Gryger et al., 2025).

In the scientific literature, information regarding the effect of CF addition on the techno-functional properties of QCS is rather limited. It was hypothesized that CF would improve texture, stability, and viscoelastic properties of QCS without compromising sensory quality. Therefore, this study aimed to evaluate the effect of CF addition on the physicochemical, textural, viscoelastic, and tribological properties of QCS with varying fat content (10%, 15%, and 20% wt/wt).

MATERIALS AND METHODS

Ingredients Used for the Manufacture of the Quark Cheese Spread Samples

The QCS formulation was based on the following ingredients: quark cheese (Choceňská mlékárna s.r.o.,

Table 1. Ingredient formulation of the model quark cheese spread (QCS) samples manufactured without and with citrus fiber addition

Ingredient	Ingredient composition ¹ (% wt/wt)					
	QCS 10	QCS 15	QCS 20	QCSCF 10	QCSCF 15	QCSCF 20
Quark cheese	72.5	56.5	26.0	72.5	51.5	21.0
Sour cream	26.5	38.5	54.0	25.5	39.0	54.5
Water	0.0	4.0	19.0	0	7.5	22.5
NaCl	1.0	1.0	1.0	1.0	1.0	1.0
Citrus fiber	—	—	—	1.0	1.0	1.0
DM content	30.0	30.0	30.0	30.0	30.0	30.0
Fat content ²	10.0	15.0	20.0	10.0	15.0	20.0
Fat in DM content ²	33.0	50.0	66.0	33.0	50.0	66.6

¹QCS 10, 15, and 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10, QCSCF 15, and QCSCF 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt) and citrus fiber addition, respectively.

²Target values of the QCS samples.

Chocení, Czech Republic) with a DM content of 27% (wt/wt) and fat in DM (FDM) of 11% (wt/wt), declaration from the packaging; sour cream (Bohemilk, a.s., Opočno, Czech Republic), containing 36% (wt/wt; DM) and 40% (wt/wt; FDM) content, declaration from the packaging; water; sodium chloride (NaCl). Citrus fiber (Herbacel AQ Plus Citrus – N, derived from citrus fruit pomace) was obtained from Herbafood Ingredients GmbH (Werder, Germany) in food grade. The CF used in this study contained 71.6 ± 2.9 (wt/wt) on DM insoluble dietary fiber, 16.3 ± 3.2 (wt/wt) on DM soluble dietary fiber, 5.8 ± 0.1 (wt/wt) on DM protein, and 1.3 ± 0.2 (wt/wt) on DM ash (Miehle et al., 2024).

Manufacture of the Quark Cheese Spread Samples

The ingredient composition (Table 1) of the model QCS samples was designed to achieve final products with a DM content of 30% (wt/wt) and a fat content of 10%, 15%, and 20% (wt/wt).

The manufacturing process was performed using the Vorwerk Thermomix TM6 (Vorwerk & Co. Thermomix GmbH, Wuppertal, Germany). Initially, the quark cheese was mechanically blended with sour cream in the Thermomix apparatus. In the next step, the remaining ingredients, including CF, were added, and the mixture was subjected to mechanical stirring at 3,000 rpm until reaching the temperature of $80^\circ\text{C} \pm 1^\circ\text{C}$, with a holding time of 10 ± 1 min. The total manufacturing time was 15 ± 1 min. Additionally, a control sample (CS) was manufactured without CF addition. The hot mass was then filled into 100 g laminated aluminum containers (conical shape; inner dimensions of 26.8 mm height, 81.1 mm diameter at the top, and 68.9 mm diameter at the bottom) and sealed with aluminum lids using the NovaSeal equipment (Nirosta Ltd., Chlumec nad Cidlinou, Czech Republic). The QCS sample weight in one packaging container was $\sim 87 \pm 5$ g. The QCS samples were left to cool ($25^\circ\text{C} \pm 2^\circ\text{C}$; approximately for 6 h) and then were stored at 6°C

$\pm 2^\circ\text{C}$ until analyses were performed. The QCS samples were analyzed after 7 d of storage (at $6^\circ\text{C} \pm 2^\circ\text{C}$). The experiment was carried out 3 times, and a total number of 6 QCS batches (6 QCS samples $\times$ 3 repetitions = 18; $n = 18$) were manufactured.

Basic Physicochemical Analysis of the Quark Cheese Spread Samples

The DM content of all QCS samples was determined according to the norm International Organization for Standardization (ISO) 5534:2004 (ISO, 2004). The pH of QCS samples was measured with a pH meter fitted with a glass-tipped electrode (Foodcare HI 99161, Hanna Instruments Czech s.r.o., Prague, Czech Republic) in the QCS samples at 3 randomly selected locations. The water activity (a_w) of QCS samples was determined with the AquaLab 4TE apparatus (Qi Analytical, s.r.o., Prague, Czech Republic, Decagon) at $25.0^\circ\text{C} \pm 0.1^\circ\text{C}$. The water activity meter was calibrated using a standardized solution with the a_w of 0.92 ($a_w = 0.92$ NaCl 2.33 molar in H_2O ; Qi Analytical, s.r.o., Prague, Czech Republic). The analyses were conducted at least 9 times (3 production batches with 3 repetitions; $n = 9$).

Determination of Quark Cheese Spread Samples' Viscoelastic Properties

The viscoelastic properties of the QCS samples were analyzed using a Kinexus Pro+ rheometer (Malvern Panalytical Ltd., Malvern, UK), equipped with a parallel plate geometry (35 mm diameter) and a fixed gap of 1 mm. To ensure measurement accuracy, all tests were conducted within the linear viscoelastic region, using a shear stress amplitude of 5 Pa during frequency sweep measurements ranging from 0.1 to 100.0 Hz. Each model sample was evaluated in triplicate ($n = 3$) to guarantee reproducibility and statistical reliability. Throughout the measurements, the storage modulus (G' ; Pa) and the

loss modulus (G'' ; Pa) were recorded to characterize the elastic and viscous behavior of the samples, respectively. Furthermore, the complex modulus (G^* ; Pa), reflecting the overall resistance of the material to deformation, was calculated according to Equation [1]. Moreover, the tangent of the phase angle ($\tan \delta$) was calculated (Equation [2]) to further characterize the viscoelastic behavior of the material, providing complementary insight into the balance between its elastic and viscous responses (Tammime et al., 2011; Černíková et al., 2017):

$$G^* = \sqrt{(G')^2 + (G'')^2}, \quad [1]$$

$$\tan \delta = \frac{G''}{G'}. \quad [2]$$

The Winter's critical gel theory was implemented for a more accurate evaluation of the viscoelastic properties in the developed QCS samples. Hence, the G^* was expressed according to the following Equation [3]:

$$G^*(f) = A_F f^{1/q}, \quad [3]$$

where A_F ($\text{Pa} \cdot \text{s}^{1/q}$) is the gel strength, f represents the frequency (Hz), and q corresponds to the interaction factor, which is defined as the number of structural units interacting in a 3-dimensional network (Vincová et al., 2023).

Penetration and Spreadability Tests of the Quark Cheese Spread Samples

Food texture constitutes a key parameter for evaluating both the stability of product properties during storage and their resistance to mechanical stress during simulated mastication (Salek et al., 2020). Penetration test was conducted using a TA.XT plus texture analyzer (Stable Micro Systems Ltd., Godalming, UK). The analysis was performed by means of a compression test (2 sequential penetration events) using a cylindrical probe with a diameter of 20 mm, applied directly into the container containing the sample. The probe penetrated to a depth of 10 mm, with a return speed of $2 \text{ mm} \cdot \text{s}^{-1}$, a trigger force of 5 g, a total deformation of 20%, and the time between the 2 cycles was set at 5 s. During the tests, force-deformation curves were recorded. In particular, the attributes of hardness, relative adhesiveness, elasticity, cohesiveness, chewiness, and gumminess were evaluated.

The evaluation of spreadability was conducted using a 90° cone-shaped main probe (male) along with Plexiglas cone-shaped analyte holders (female). The QCS samples were evenly distributed onto the lower cone (female),

with any excess carefully removed to ensure uniformity. The upper cone then penetrated the sample at a 45° angle, with a penetration speed of $1.0 \text{ mm} \cdot \text{s}^{-1}$ and a depth of 2.0 mm. Throughout the measurement process, the sample naturally flowed outward at the same angle, with its spreadability determined by the ease of flow. In both texture profile analysis and spreadability determination, for each attribute examined, the average of a minimum of 3 samples of QCS was used for the statistical analysis (3 manufactured batches $\times$ 3 repetitions; $n = 9$).

Tribological Analysis of the Quark Cheese Spread Samples

To gain a more comprehensive understanding of the sensory-relevant characteristics of QCS, particularly attributes such as slipperiness and adhesiveness perceived during oral processing, tribological analysis was employed. This method provides critical information on the mechanical interactions of food products under conditions that simulate oral consumption. Fundamentally, tribology examines the principles of friction, wear, and lubrication between interacting surfaces in relative motion. In this context, these interactions are used to model the contact between QCS and the human tongue (Habig and Woydt, 2020).

Tribological measurements were conducted using a rheometer Kinexus Pro+ (Malvern Panalytical Ltd., Malvern, UK) with 3 balls on plate geometry on a coarse plastic surface 3M Transpore Surgical Tape 1527 (3M Company, St. Paul, MN). According to Nguyen et al. (2016), the material exhibits characteristics comparable to those of the human tongue, particularly in terms of wetting properties and surface roughness. To ensure consistency, the tape was precisely trimmed into a square shape ($50 \text{ mm} \times 50 \text{ mm}$) and firmly secured onto the base plate of the tribological setup. Subsequently, the sample ($\sim 2 \text{ g}$) was evenly distributed over the tape, forming a uniform layer with an approximate thickness of 2 mm. These measurements were conducted using a predefined axial force of 1 N over a total distance of 27.17 m across 100 cycles. Notably, the speed was progressively increased from 0.015 to $1,463.85 \text{ mm} \cdot \text{s}^{-1}$ (equivalent to 0.001 to $97.59 \text{ rad} \cdot \text{s}^{-1}$) based on the tribological geometry radius of 15 mm.

Furthermore, the frictional (or lubrication) properties of the QCS samples were evaluated using the coefficient of friction (CoF), which represents the ratio of frictional stress to normal stress. This relationship is expressed as Equation [4]:

$$\mu = \frac{F}{N}, \quad [4]$$

where F represents the torque (Nm) and N is equivalent to 1 N (Šantová et al., 2024).

The resulting friction curves were generated by plotting CoF against the sliding velocity. Based on this analysis, the minimum coefficient of friction ($\text{CoF}_{\min}$) and the maximum coefficient of friction ($\text{CoF}_{\max}$) were extracted from the graph, providing valuable insights into the lubrication behavior of the samples. All measurements were performed at least 6 times ($n = 6$).

Viscosity Measurement During In Situ Preparation of Quark Cheese Spreads

Viscosity measurements were performed using a coaxial cylinder (cup-and-bob) geometry integrated in a temperature-controlled cartridge (Peltier system) of the Kinexus Pro+ rheometer (Malvern Panalytical, UK), which allowed the in situ monitoring of viscosity changes during sample processing. A 35-g portion of the ingredients (formulated according to the proportions detailed in Table 1) was placed into the geometry and was tempered to a temperature of 40°C while being stirred at a rate of 100 rpm for 10 min. Subsequently, the temperature was gradually increased to 80°C for a period of 8 min, while the shear rate was raised to 500 rpm. During this heating phase, apparent viscosity was recorded at 5 s intervals. After reaching the target temperature, shear loading continued for 10 min, followed by a controlled cooling phase to 40°C, also lasting 8 min. Viscosity data were continuously recorded throughout the entire measurement.

The obtained data were then processed to express the dependence of viscosity on the sample's internal temperature. This approach could allow a detailed assessment of the rheological behavior of the model formulation during the simulated manufacturing process and could contribute to a deeper understanding of the influence of CF on the consistency of QCS.

Instrumental Determination of the Color of the Quark Cheese Spread Samples

The colorimetric characteristics of the QCS samples were assessed utilizing an UltraScan PRO spectrophotometer (Hunter Associates Laboratory, Inc., Reston, VA). Specifically, the analysis was conducted following the CIELAB color scale (L^* , a^* , b^*) in reflectance mode while excluding specular reflection. Moreover, the measurements were performed under illuminant D65, simulating average daylight, with a 10° standard observer angle. In addition, the L^* parameter, which represents lightness, was recorded on a scale ranging from 0 to 100, where $L^* = 0$ corresponds to black and $L^* = 100$ to white (Wang and Sun, 2003). The coordinate values of each sample were determined by adjusting the intensity

of the transmitted rays. Within the scope of this study, all QCS samples underwent 3 rounds of analysis, and the recorded values were subsequently evaluated based on the CIE $L^*a^*b^*$ color scale. Additionally, hue and chroma (C^*) were calculated. All QCS samples were measured at least 9 times (3 manufactured batches $\times$ 3 repetitions; $n = 9$).

The hue angle (h°) represents the dominant spectral component of a color, ranging from 0° to 360°. More specifically, a hue angle of 0° or 360° corresponds to red, whereas angles of 90°, 180°, and 270° indicate yellow, green, and blue, respectively (Dimitrellou et al., 2020). In general, the combination of a^* , b^* , and h° (hue angle) offers a more comprehensive characterization of color and is calculated using the following Equation [5]:

$$h^\circ = \tan^{-1}(a^*/b^*). \quad [5]$$

The C^* parameter represents the intensity or saturation of a color and was calculated according to Equation [6]:

$$C^* = (a^{*2} + b^{*2})^{0.5}. \quad [6]$$

The total color difference (ΔE_{12}^*) was used to evaluate the color changes, indicating the magnitude of color difference between any 2 samples according to the following Equation [7]:

$$\Delta E_{12}^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{0.5}. \quad [7]$$

For each tested group, the corresponding QCS sample served as the control. In particular, QCS 10 was used as the control for QCSCF 10, QCS 15 for QCSCF 15, and QCS 20 for QCSCF 20, respectively. This approach ensured that comparisons were made between samples with identical base formulations, differing only in the presence or absence of the added CF.

Sensory Analysis

Sensory analysis of QCS was concluded in order with ISO 8586 (ISO, 2012) at the Department of Food Technology, Faculty of Technology, Tomas Bata University in Zlín (Czech Republic). Table 2 presents the characteristics of the sensory assessors. The assessors evaluated the sensorial properties of the QCS samples, which were labeled with 4-digit codes and presented in a random order on white plates. To minimize carry-over effects, water and crackers were provided as a palate cleanser between the testing and evaluation of the QCS samples. In accordance with ISO 8589 (ISO, 2007), the sensory analysis was conducted in sensory booths at a controlled

Table 2. Characteristics of participants at sensory analysis of quark cheese spread samples; values are expressed as mean $\pm$ SD

Experiment	Panelist	n	Gender (%)		Age (yr)		
			Female	Male	Total	Female	Male
QCS samples	Experienced	14	40	60	55.75 $\pm$ 3.38	51.50 $\pm$ 0.41	60.00 $\pm$ 6.34
	Trained	6	65	35	35.67 $\pm$ 3.89	25.33 $\pm$ 2.45	46.00 $\pm$ 5.23

temperature of 22°C $\pm$ 2°C, with standard lighting provided by daylight-type bulbs. Furthermore, the assessors were asked to evaluate the QCS samples based on appearance, consistency, hardness, spreadability, flavor, and off-flavor attributes. The evaluation used a 5-point hedonic scale (1: excellent, 3: less good, 5: unacceptable) for appearance, spreadability, hardness, and flavor and (1: negligible, 3: medium, and 5: excessive) for off-flavors. Terms for intensity scales were used to describe each point of the used 5-point scales. Tomas Bata University in Zlín, which does not have a formal institutional ethical committee for sensory analysis. However, all research was performed in accordance with the ethical principles outlined in the Declaration of Helsinki. Furthermore, all participants were informed about the purpose of the study and any potential risks, and they provided written consent before participation. All participants were fully aware they could withdraw from the study at any time without penalty. Participant anonymity and data confidentiality were maintained throughout the study, and no personally identifiable information was published. The study posed minimal risk to participants, and the anticipated benefits were considered to outweigh any potential harm.

Statistical Analysis

To assess the normality of the data distribution, the Shapiro–Wilk test was employed using Minitab 16 software (Minitab Ltd., Coventry, UK) at a significance level of 0.05. This test is recommended by the ISO 5479 standard (ISO, 1997) as a suitable method for analyzing small datasets. Because most of the obtained data did not meet the criterion of normality ($P < 0.05$), the use of parametric tests was deemed inappropriate. Therefore, nonparametric statistical analyses were subsequently applied to evaluate differences between groups, specifically the Kruskal–Wallis and Wilcoxon tests, while maintaining the significance level at 0.05.

RESULTS AND DISCUSSION

Visual Examination of Model QCS Samples with Varying Fat Content and Citrus Fiber Addition

The samples were initially visually inspected immediately after manufacturing (data not shown) to confirm

that no significant defects had occurred, which could have compromised their suitability for subsequent analyses. Furthermore, after 7 d of storage, the samples were photographed using a digital camera (Coolpix P6000, 13.5 Mpx; Nikon, Tokyo, Japan) mounted on a tripod, and the corresponding images are presented in Figure 1.

Basic Physicochemical Analysis and Water Activity of the Quark Cheese Spread Samples

The physicochemical analysis results are summarized in Table 3. Dry matter content ranged from 30.62 to 31.89% (wt/wt; corresponding to the target DM content of 30% wt/wt), indicating similar levels across QCS samples, with no significant effect of CF addition ($P > 0.05$). Similarity in DM values is essential, as it may influence sample textural and rheological properties (Weiserová et al., 2011; Gryger et al., 2025).

The pH values obtained in this study (4.28–4.34; $P > 0.05$) are in accordance with that generally reported for quark cheese, which typically exhibits values close to casein isoelectric point (~ 4.6). The slightly lower pH observed in our samples is most likely due to the combined use of quark and sour cream, both of which are characterized by an inherently high acidity. As the incorporation of CF did not affect samples' pH, it can be inferred that QCS acidity was primarily determined by the composition of the remaining raw ingredients. This finding is consistent with previous reports indicating that quark cheese acidity is largely governed by fermentation processes and starter culture activity. Importantly, the pH values obtained fall within the expected range for fresh acid-curd cheeses, thereby ensuring both sensory acceptability and microbiological safety (Schulz-Collins and Senge, 2004; Gryger et al., 2025).

The a_w ranged from 0.983 to 0.990 ($P > 0.05$), again reporting no significant effect of CF addition. These values align with previous findings (Møller et al., 2012). According to US Food and Drug Administration (FDA) recommendations, food products with an a_w below 0.85 and a pH above 4.6 are considered shelf-stable at room temperature. In contrast, the tested QCS samples exhibited a_w values, which are far above the FDA threshold. At such high a_w , most pathogenic and spoilage microorganisms can proliferate unless additional hurdles (NaCl

Table 3. Values of DM content, fat content, fat in DM content, pH, and water activity (a_w) of the model quark cheese spread (QCS) samples ($n = 6$)¹

Parameter	Samples ²					
	QCS 10	QCS 15	QCS 20	QCSCF 10	QCSCF 15	QCSCF 20
DM content (% wt/wt)	30.62 ± 0.27 ^a	31.89 ± 1.01 ^a	31.66 ± 0.61 ^a	31.40 ± 0.47 ^a	31.67 ± 0.24 ^a	31.15 ± 0.51 ^a
Fat content (% wt/wt)	10.16 ± 0.17 ^a	15.34 ± 0.27 ^b	20.02 ± 0.28 ^c	10.32 ± 0.37 ^a	15.12 ± 0.14 ^b	20.47 ± 0.39 ^c
Fat in DM content (% wt/wt; calculated)	33.18 ^a	48.10 ^b	63.23 ^c	32.86 ^a	47.74 ^b	65.71 ^c
pH	4.32 ± 0.02 ^a	4.34 ± 0.03 ^a	4.28 ± 0.07 ^a	4.34 ± 0.03 ^a	4.34 ± 0.01 ^a	4.33 ± 0.03 ^a
a_w	0.983 ± 0.01 ^a	0.984 ± 0.01 ^a	0.988 ± 0.01 ^a	0.988 ± 0.01 ^a	0.990 ± 0.01 ^a	0.987 ± 0.02 ^a

^{a-c}Mean values within a row followed by different superscripts statistically differ ($P < 0.05$).

¹Values are presented as the mean ± SD.

²QCS 10, QCS 15, and QCS 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10, QCSCF 15, and QCSCF 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt) and citrus fiber addition, respectively.

addition, refrigeration, and hygienic processing) are applied. Overall, the physicochemical characteristics, combined with the manufacturing process and proper storage at refrigeration temperatures, could indicate that QCS can be regarded as a safe food product (Sołowiej et al., 2023).

Viscoelastic Properties of the Quark Cheese Spread Samples

To assess the viscoelastic properties of the QCS, rheological analysis was therefore employed under small shear deformation. Whereas texture profile analysis

(TPA) provides valuable textural information, rheometry offers greater precision. and, importantly, both methods have been shown to correlate (Salek et al., 2020). Furthermore, unlike static texture measurements, dynamic oscillatory rheometry allows sample characterization within the linear viscoelastic region, where deformations are minor and fully reversible. Consequently, the rheological data not only complement the TPA results but also provide additional insights into the subtle textural differences observed between the samples (Norton et al., 2010). Figure 2 illustrates the frequency-dependent development of the elastic modulus (G'), viscous modulus (G''), complex modulus (G^*), and loss tangent (also

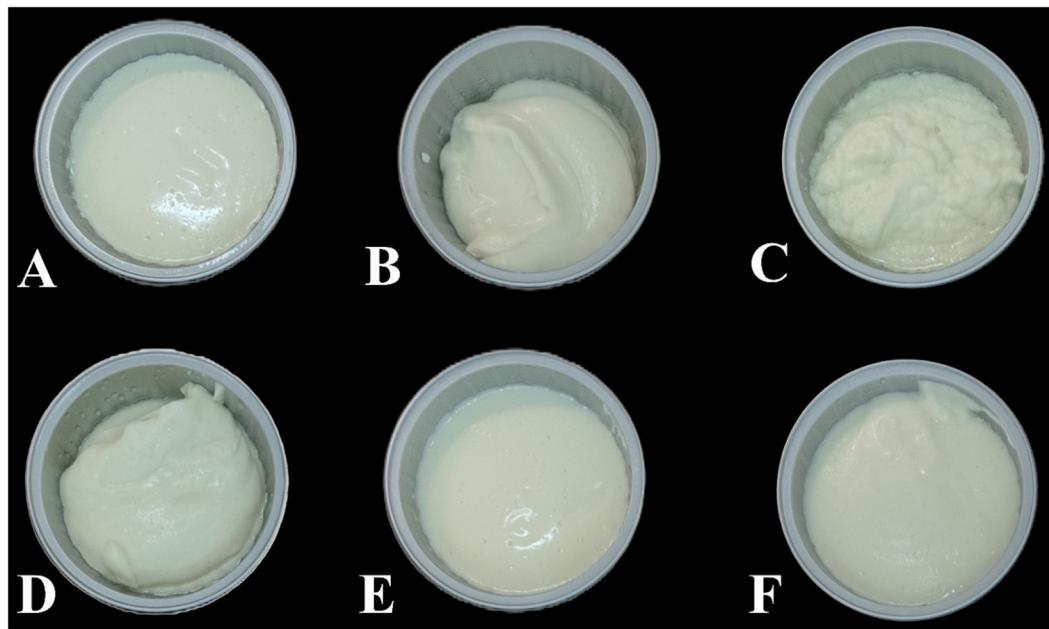


Figure 1. Images of the developed model quark cheese spread samples manufactured without and with citrus fiber addition, after 7 d of storage ($6^\circ\text{C} \pm 2^\circ\text{C}$). The QCS 10 (part A), QCS 15 (part B), and QCS 20 (part C) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10 (part D), QCSCF 15 (part E), and QCSCF 20 (part F) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively, and citrus fiber addition. The computer vision system used included a digital camera (Coolpix P6000, Nikon, Tokyo, Japan) supported by a copy stand, monitor, and computer.

called phase angle, $\tan \delta$) of QCS samples with different fat contents and with or without CF addition after 7 d of storage ($6^\circ\text{C} \pm 2^\circ\text{C}$). Overall, both viscoelastic moduli (G' and G'') values increased with frequency, and the elastic component consistently dominated over the viscous component ($G' > G''$), confirming the predominantly solid-like behavior of all samples. Moreover, the incorporation of CF resulted in higher values of viscoelastic moduli compared with the corresponding samples without CF addition, indicating a strengthening of the gel network structure ($P < 0.05$). Additionally, fat content influenced the absolute values of the moduli, with lower-fat samples generally exhibiting higher G' and G'' values. The $\tan \delta$ further demonstrated that CF reduced the relative contribution of viscous behavior, thereby enhancing the structural stability of the QCS matrices. Moreover, the incorporation of CF markedly enhanced both G' and G'' compared with their corresponding controls (samples without CF addition), suggesting a reinforcement of the protein-polysaccharide matrix ($P < 0.05$). The reduction in $\tan \delta$ further confirmed that CF addition shifted the balance toward a more elastic and structurally probably more stable system. These effects can be explained by the high water-binding capacity and viscosity-building potential of CF, which are attributed to its high content of pectin, cellulose, hemicellulose, and lignin (Su et al., 2019). Through its ability to retain water and strengthen the protein network, CF counteracts the weakening effect of fat reduction. These findings align with previous reports highlighting that CF can serve as a fat replacer in dairy systems without adversely affecting sensory properties (Szafrńska and Sołowiej, 2020). Consequently, CF not only improved rheological performance but also demonstrated potential for developing QCS with reduced fat content.

In Table 4, the values of G' , G'' , G^* , $\tan \delta$ (1 Hz was used as the reference frequency), A_F , and q are presented. Fat content significantly influenced these parameters, with higher levels (15–20% wt/wt) leading to increased values of G' , G'' , and G^* compared with the low-fat variants (10% wt/wt). However, the most pronounced effects were observed upon the addition of CF, which markedly enhanced G' , G'' , and G^* values ($P < 0.05$), particularly in QCSCF 10 and QCSCF 15 samples. This improvement was reflected in a 3-fold increase in A_F and an elevated interaction factor (q), indicating stronger protein-polysaccharide interactions and a more interconnected gel network. The reinforcing effect of CF can be attributed to its water-binding capacity and interactions with casein micelles, which stabilize the 3-dimensional network and prevent structural collapse under reduced fat conditions. Notably, similar trends have been reported in other studies investigating the addition of hydrocolloids, including κ - and ι -carrageenan and pectin (Míšková et al., 2021;

Gryger et al., 2025). In particular, the increasing polysaccharide concentrations also enhanced viscoelastic moduli and gel strength through the formation of denser network structures (Langendorff et al., 1999; Kůrová et al., 2022). These mechanisms parallel those observed with other polysaccharide-protein systems, in which water entrapment and network interactions improved sample rigidity and mechanical stability (Su et al., 2019; Szafrńska and Sołowiej, 2020).

Murata (2012) defined $\tan \delta$ as the phase angle between the viscous and elastic components of a material's behavior. Similarly, Piska et al. (2002) reported that a material with $\tan \delta = 1$ exhibits both solid- and liquid-like behavior to an equal extent. When $\tan \delta < 1$, the material displays more elastic characteristics, whereas $\tan \delta > 1$ indicates a predominantly viscous nature. The measured $\tan \delta$ values for all samples were below 1, indicating predominantly elastic behavior of the systems. This finding is consistent with previous reports for hydrocolloid-stabilized dairy gels, in which low $\tan \delta$ values reflect the elastic character of the curd network (Piska et al., 2002). Furthermore, the addition of CF slightly decreased the $\tan \delta$ values, suggesting an enhancement of the elastic properties and a shift toward more ideally elastic behavior, in agreement with observations for dairy matrix. This finding agrees with previous reports on hydrocolloid-stabilized dairy gels and with the results of Szafrńska et al. (2021), who similarly observed that dairy products enriched with CF, anhydrous milk fat, or pectin generally show lower $\tan \delta$ values, indicative of enhanced elastic properties.

Penetration and Spreadability Tests of the Quark Cheese Spread Samples

Penetration test was conducted to evaluate hardness, elasticity, cohesiveness, relative adhesiveness, chewiness, and gumminess, and the results are presented in Figure 3 and Table 5. Figure 3A illustrates the effect of CF addition on the hardness development of the QCS samples. The results indicate that CF significantly increased hardness regardless of the fat content ($P < 0.05$). All samples exhibited a pronounced rise in hardness, with the highest value observed for the QCS sample containing 10% (wt/wt) fat ($P < 0.05$). This increase in hardness is primarily attributed to hydrophobic interactions through hydrogen bonding and the reinforcement of the CF structure, which mainly consists of pectin, cellulose, and hemicellulose (Lundberg et al., 2014). Conversely, an increase in fat content was associated with a reduction in hardness among all QCS samples with CF, with the lowest value recorded for the sample containing 20% (wt/wt) fat. This observation aligns with previous findings, indicating that samples with higher fat content exhibit softer textures due to the dispersion of fat globules within the

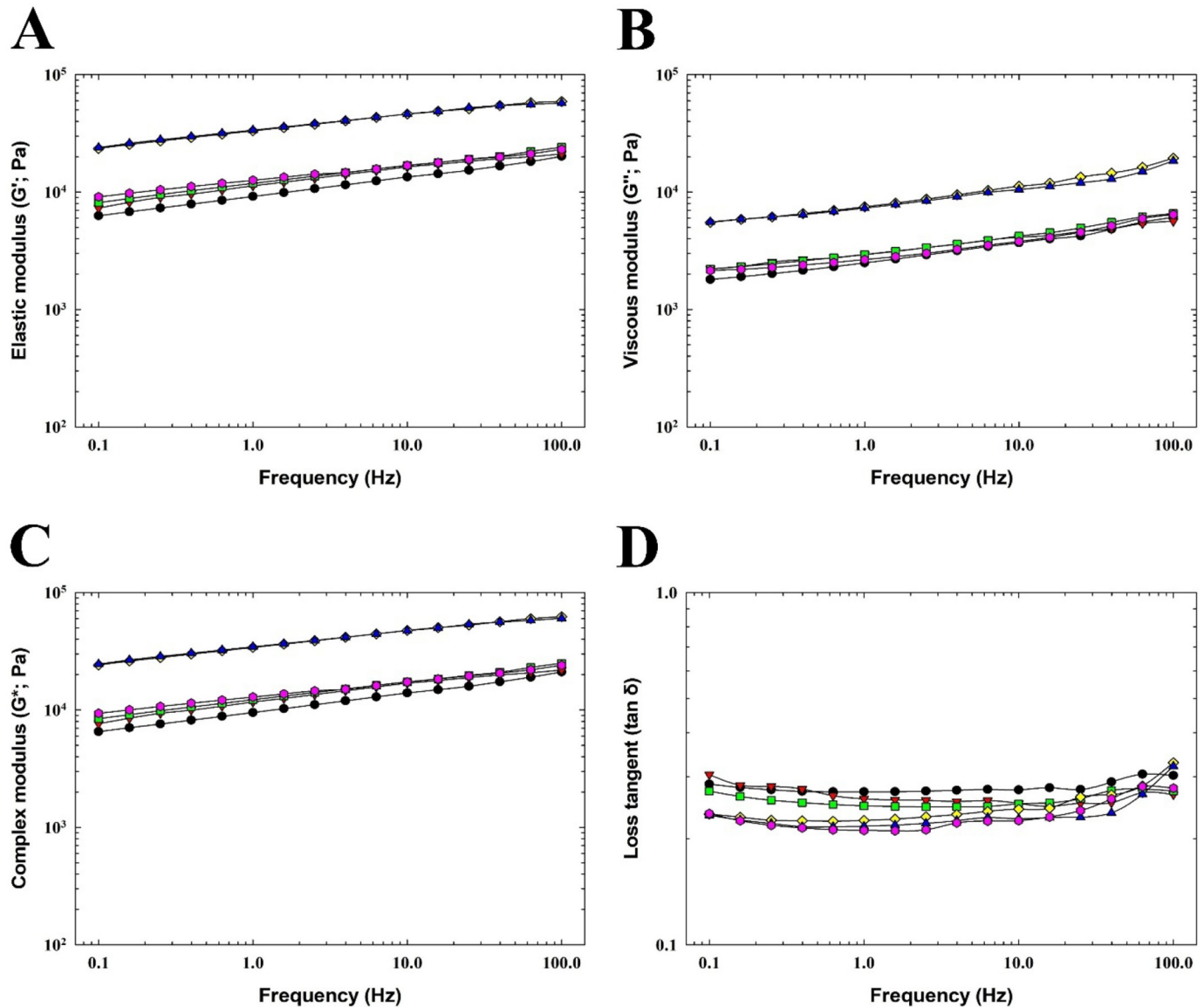


Figure 2. Effect of fat content and citrus fiber addition on the elastic modulus (G' ; Pa; A), viscous modulus (G'' ; Pa; B), complex modulus (G^* ; Pa; C), and tangent delta ($\tan \delta$; D) values development of the model quark cheese spread samples manufactured after 7 d of storage ($6^\circ\text{C} \pm 2^\circ\text{C}$; $n = 6$). The QCS 10 (black circle), QCS 15 (red triangle), and QCS 20 (green square) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10 (yellow rhombus), QCSCF 15 (blue triangle), and QCSCF 20 (purple hexagon) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively, and citrus fiber addition.

protein network (Ningtyas et al., 2017). Differences in the chemical structure of fats can also influence interactions with fiber and cheese proteins, leading to textural variations (Szafrńska et al., 2025). Similar results were reported by Szafrńska et al. (2025), who found that the addition of carrot fiber increased the hardness of processed cheese sauces. These findings confirm that the type of dietary fiber significantly influences the textural properties of processed cheese products. A comparable trend was observed in our study, where CF addition also led to increased hardness of the QCS samples, suggest-

ing a generally reinforcing effect of dietary fibers on the protein matrix. This effect can be explained by the ability of dietary fibers to bind water and form a spatial network within the product, which contributes to increased firmness and overall structural integrity. Overall, these findings highlight that both the type of dietary fiber and the composition of the fat phase significantly influence the texture of QCS, mainly through their effects on the microstructure and interactions within the protein matrix.

The CF addition also increased elasticity ($P < 0.05$), which is defined as the rate at which the deformed ma-

Table 4. Values of the elastic modulus G' (at the reference frequency of 1 Hz), viscous modulus G'' (at the reference frequency of 1 Hz), complex modulus G^* (at the reference frequency of 1 Hz), and $\tan \delta$ (at the reference frequency of 1 Hz), gel strength A_F , and interaction factor q of the model quark cheese spread (QCS) samples ($n = 6$)¹

Parameter	Samples ²					
	QCS 10	QCS 15	QCS 20	QCSCF 10	QCSCF 15	QCSCF 20
G' (kPa)	91.9 ± 1.8 ^a	113.2 ± 5.4 ^b	118.8 ± 7.5 ^b	332.7 ± 10.5 ^c	337.2 ± 15.7 ^c	126.2 ± 10.2 ^b
G'' (kPa)	24.9 ± 1.1 ^a	29.4 ± 2.3 ^a	29.5 ± 0.2 ^a	75.1 ± 1.7 ^b	73.2 ± 1.8 ^b	26.6 ± 3.3 ^a
G^* (kPa)	95.2 ± 2.5 ^a	116.9 ± 8.7 ^b	122.4 ± 10.5 ^b	341.1 ± 14.8 ^c	345.1 ± 13.2 ^c	128.9 ± 11.7 ^b
$\tan \delta$	0.3 ± 0.1 ^a	0.3 ± 0.1 ^a	0.3 ± 0.1 ^a	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a
A_F	9,463.1 ± 157.7 ^a	11,661.8 ± 124.8 ^b	12,172.1 ± 147.5 ^c	34,146.5 ± 257.7 ^d	34,572.9 ± 357.8 ^d	12,779.4 ± 128.1 ^c
q	6.1 ± 0.1 ^a	6.9 ± 0.2 ^b	6.8 ± 0.2 ^b	7.4 ± 0.2 ^c	7.8 ± 0.1 ^d	7.5 ± 0.1 ^c

^{a-d}Mean values within a row followed by different superscripts statistically differ ($P < 0.05$).

¹Values are presented as the mean ± SD.

²QCS 10, QCS 15, and QCS 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10, QCSCF 15, and QCSCF 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt) and citrus fiber addition, respectively.

terial returns to its original shape (Khule et al., 2024). Cohesiveness, representing the strength of internal bonds within the QCS samples, was not significantly affected ($P < 0.05$) by either fat content or CF addition (Khule et al., 2024). Relative adhesiveness, that is, the force required to detach the adhering substance from the material, varied depending on both CF and fat content; the QCSCF 10 sample exhibited the lowest relative adhesiveness, whereas QCS 10 and QCSCF 20 showed relatively higher values ($P < 0.05$), indicating a possible complex interaction between CF and fat (Lee and Klostermeyer, 2001;

Khule et al., 2024). The CF also significantly increased chewiness and gumminess, particularly at lower-fat contents ($P < 0.05$; QCSCF 10 and QCSCF 15), whereas higher fat content reduced the above-mentioned parameters (QCSCF 20), consistent with the trends observed for hardness (Khule et al., 2024). Overall, these results indicate that CF plays a dominant role in enhancing elasticity, chewiness, and gumminess, whereas fat content primarily modulates hardness, chewiness, gumminess, and, to a lesser extent, relative adhesiveness (Lee and Klostermeyer, 2001; Khule et al., 2024).

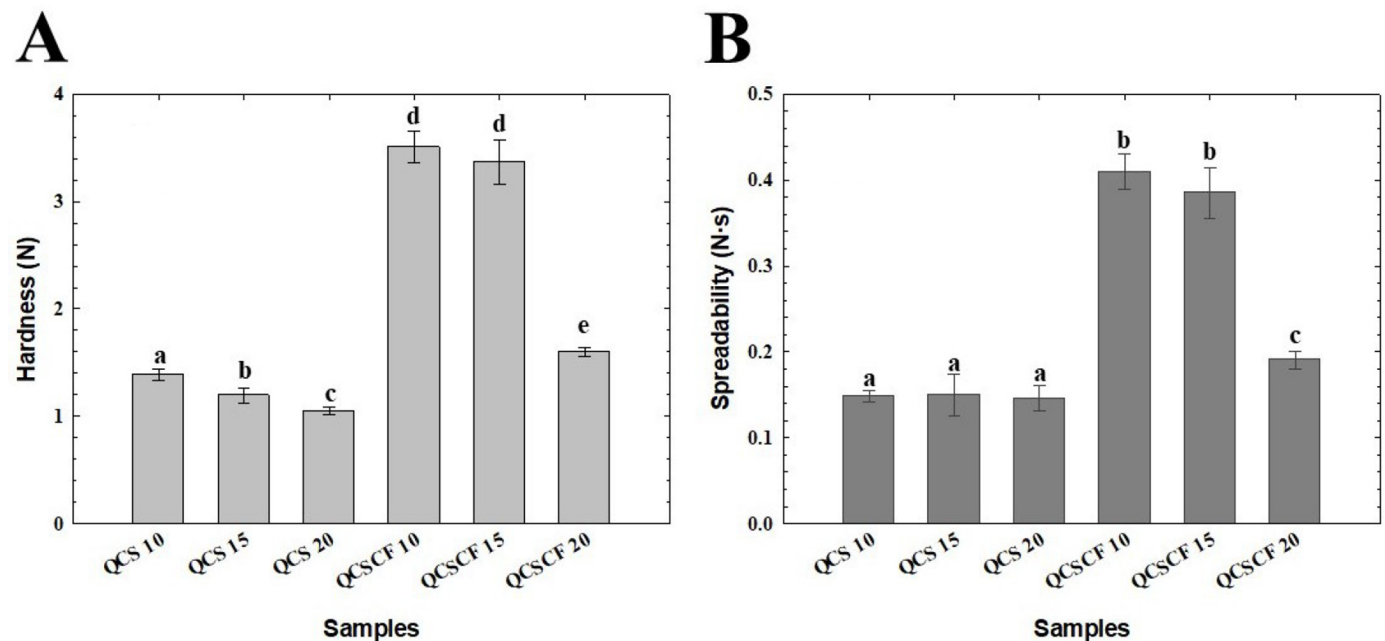


Figure 3. Effect of fat content on the development of the hardness (data obtained from penetration test; N; A) and spreadability (data obtained from spreadability test; N·s; B) values of the model quark cheese spread samples manufactured without and with citrus fiber addition after 7 d of storage ($6^\circ\text{C} \pm 2^\circ\text{C}$; $n = 6$). The QCS 10, QCS 15, and QCS 20 = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10, QCSCF 15, and QCSCF 20 = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively, and citrus fiber addition. Different letters (a–e) indicate significant differences at $P < 0.05$; error bars represent the SD.

Table 5. Values of elasticity, cohesiveness, relative adhesiveness, chewiness, gumminess, and of the model quark cheese spread (QCS) samples ($n = 6$)¹

Parameter	Samples ²					
	QCS 10	QCS 15	QCS 20	QCSCF 10	QCSCF 15	QCSCF 20
Elasticity (-)	4.35 ± 0.49 ^a	4.10 ± 0.08 ^a	4.00 ± 0.01 ^a	5.28 ± 0.18 ^b	5.82 ± 0.26 ^b	5.33 ± 0.21 ^b
Cohesiveness (-)	0.45 ± 0.03 ^a	0.51 ± 0.05 ^a	0.54 ± 0.01 ^a	0.50 ± 0.06 ^a	0.50 ± 0.03 ^a	0.49 ± 0.02 ^a
Relative adhesiveness (N·s)	0.20 ± 0.03 ^a	0.13 ± 0.02 ^b	0.10 ± 0.01 ^b	0.09 ± 0.03 ^b	0.05 ± 0.02 ^b	0.19 ± 0.02 ^a
Chewiness (N·s)	2.73 ± 0.37 ^a	2.49 ± 0.41 ^a	2.27 ± 0.06 ^a	9.09 ± 0.22 ^b	9.90 ± 1.05 ^b	4.17 ± 0.10 ^c
Gumminess (N)	0.63 ± 0.06 ^a	0.61 ± 0.09 ^a	0.57 ± 0.02 ^a	1.77 ± 0.27 ^b	1.70 ± 0.11 ^b	0.78 ± 0.03 ^a

^{a-c}Mean values within a row followed by different superscripts statistically differ ($P < 0.05$).

¹Values are presented as the mean ± SD.

²QCS 10, QCS 15, and QCS 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10, QCSCF 15, and QCSCF 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt) and citrus fiber addition, respectively.

Spreadability represents the total force required to perform the shear process and is considered a dynamic textural attribute that, unlike hardness, is influenced not only by the force needed to achieve deformation but also by the softening of the sample during measurement (Lee and Klostermeyer, 2001; Vincová et al., 2023). In the present study, spreadability of QCS samples exhibited trends similar to that observed for hardness (Figure 3B). An increase in fat content reduced both the force and the time required for sample spreading ($P < 0.05$), indicating improved spreadability. Conversely, the addition of CF led to higher force and prolonged spreading time, reflecting a decrease in spreadability ($P < 0.05$). Notably, at higher fat contents, the effect of CF on spreadability was diminished ($P < 0.05$), suggesting that fat may counteract the structuring influence of CF. These observations are consistent with previous studies on cheese-type spreads, which reported a negative correlation between fat content and spreadability, whereas hydrocolloid addition tended to increase this textural attribute (Vincová et al., 2023; Gryger et al., 2025).

Tribological Analysis of the Quark Cheese Spread Samples

The perception of fat content and creaminess is a key sensory attribute in QCS samples, which cannot be reliably predicted solely from rheological properties (Nguyen et al., 2016). In this context, tribology (the study of friction between 2 surfaces separated by a lubricating layer) has emerged as a valuable tool, as in foods it corresponds to the thin film formed during oral processing (Michel et al., 2022). In the present study, tribological friction curves (Stribeck curves) were obtained by plotting the CoF as a function of sliding speed, as shown in Figure 4. According to Ningtyas et al. (2017), these curves can be divided into 3 characteristic regimens: (1) a boundary regimen, where the friction is independent from the entrainment speed; (2) a mixed regimen, where

the fluid starts to form a thin lubricating film around the surfaces, reducing the friction; and (3) a hydrodynamic lubrication regimen with increasing friction as the bulk dominates.

At low sliding speeds, all samples exhibited relatively high friction coefficients ($P < 0.05$), which are characteristic of the boundary regimen, where direct contact occurs between protein and fat particles. With increasing sliding speed, the CoF decreased and reached a minimum, corresponding to the formation of a continuous lubricating film. At the highest speeds, a slight increase in CoF was observed, most likely due to shear thinning and partial disruption of the emulsion structure. The results clearly demonstrated the influence of fat content and CF

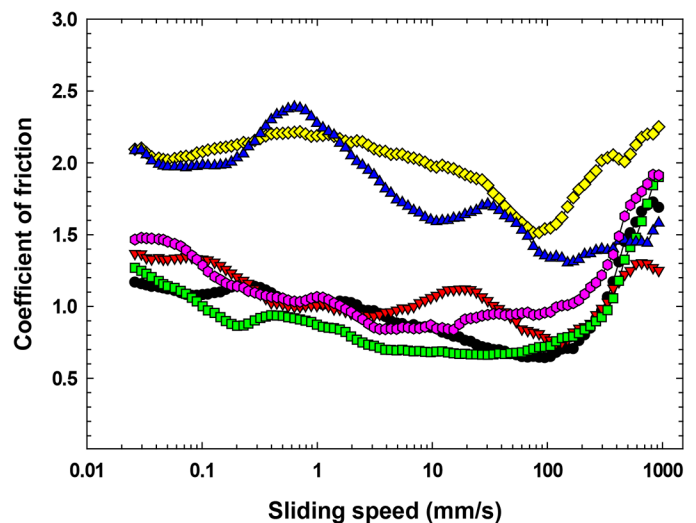


Figure 4. The dependence of coefficient of friction (CoF) on the sliding speed (mm/s; Stribeck curves) of the model quark cheese samples manufactured without and with citrus fiber addition after 7 d of storage ($6^{\circ}\text{C} \pm 2^{\circ}\text{C}$; $n = 3$). The QCS 10 (black circle), QCS 15 (red triangle), and QCS 20 (green square) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10 (yellow rhombus), QCSCF 15 (blue triangle), and QCSCF 20 (purple hexagon) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively, and citrus fiber addition.

addition on sample lubrication behavior. Samples with a higher fat content showed lower CoF values across the entire range of sliding speeds ($P < 0.05$), confirming the lubricating role of the fat phase, which forms a thin film that reduces friction between the interacting surfaces. In contrast, samples containing CF exhibited higher CoF values ($P < 0.05$), indicating a rougher and less lubricated surface, likely due to the increased water-binding capacity and greater structural rigidity of the continuous phase. However, it should be noted that CF, owing to their strong water-holding capacity (~ 15 g/g dry weight), can also contribute to the formation of an additional lubricating film between the oral surfaces. The highly viscous fiber layer may suppress turbulent flow within the contact zone, thereby reducing local friction (Garrec and Norton, 2012). Similarly, some polysaccharides used as thickening agents have been reported to lower friction and enhance the perception of creaminess (Selway and Stokes, 2013; Ruan et al., 2019). Chojnicka-Paszun and de Jongh (2014) also observed that pectin and xanthan gum can provide effective lubrication to compensate for surface roughness effects. Therefore, the higher friction values observed in the present study for CF-enriched samples may be attributed to the specific composition of the system and the interactions of CF with the protein-fat matrix. The presence of fibers likely increased the rigidity of the continuous phase and limited the formation of a homogeneous lubricating film, resulting in higher CoF values. These findings are consistent with previously published results. Ningtyas et al. (2017) reported that low-fat cream cheese (0.5% wt/wt of fat) exhibited significantly higher friction coefficients compared with medium-fat (5.5% wt/wt) and high-fat (11.6% wt/wt) samples. This behavior was attributed to the formation of an interfacial fat film acting as a spacer between the tribo-pairs (Nguyen et al., 2016). Similarly, Prakash et al. (2013) observed a decrease in friction with increasing fat levels, attributed to the coalescence of fat globules on the tongue and palate surfaces. These conclusions agree with other studies linking lower friction to higher fat content, as fat acts as an efficient lubricant, even under different tribological conditions and methodologies (Chojnicka-Paszun et al., 2012; Sonne et al., 2014). Conversely, the adhesion of protein particles to the contact surface can also influence lubrication performance, as larger protein aggregates may not fit into the surface asperities, resulting in increased friction (Sonne et al., 2014). This mechanism is consistent with the current findings, where samples with higher fat content exhibited superior lubrication properties, whereas samples containing CF and a higher protein fraction showed elevated friction levels. As shown in Figure 5, the $\text{CoF}_{\min}$ and $\text{CoF}_{\max}$ of friction of the QCS samples were clearly affected by fat content and CF addition. For the samples without CF, the $\text{CoF}_{\min}$

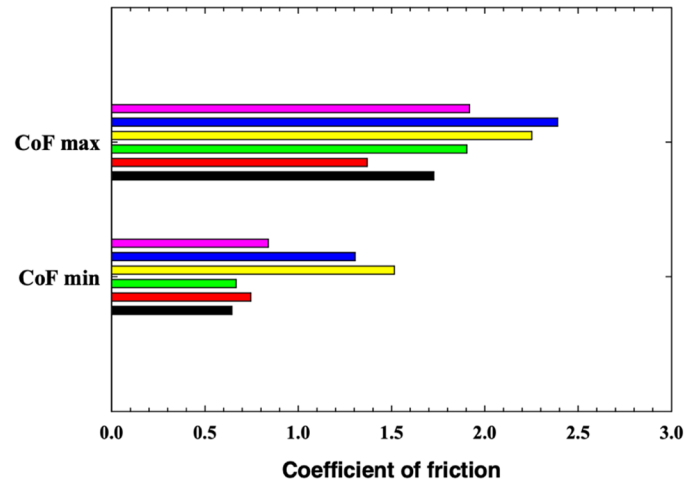


Figure 5. Effect of fat content on the development of the minimum coefficient of friction ($\text{CoF}_{\min}$) and maximum coefficient of friction ($\text{CoF}_{\max}$) values of the model quark cheese spread samples manufactured without and with citrus fiber addition after 7 d of storage ($6^\circ\text{C} \pm 2^\circ\text{C}$; $n = 3$). The QCS 10 (black column), QCS 15 (red column), and QCS 20 (green column) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10 (yellow column), QCSCF 15 (blue column), and QCSCF 20 (purple column) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively, and citrus fiber addition.

was slightly higher for QCS 15 compared with QCS 10 and QCS 20, which exhibited similar values. In contrast, the $\text{CoF}_{\max}$ was highest for QCS 20, followed by QCS 10, whereas QCS 15 showed the lowest $\text{CoF}_{\max}$. These results indicate that fat content affects the lubrication behavior. The addition of CF increased both $\text{CoF}_{\min}$ and $\text{CoF}_{\max}$ compared with the corresponding samples without fiber, suggesting that fiber increased resistance to sliding, likely due to interactions with the protein network and alterations in the continuous fat phase. Among the fiber-enriched samples, CoF values slightly decreased with increasing fat content, indicating that higher fat levels can partially mitigate the friction-enhancing effect of the fiber.

Overall, the tribological data complement the textural and rheological observations, as they provide a direct link between sample composition and sensory perception, particularly regarding the feeling of smoothness and lubrication during oral processing.

Viscosity Measurement During In Situ Preparation of Quark Cheese Spreads

Hydrocolloids are widely recognized for their ability to modify the mechanical and flow properties of complex food systems (Saha and Bhattacharya, 2010). In dairy-based matrices, these polysaccharides (or proteins) can interact with proteins, lipids, and water to modulate

viscosity, stability, and texture. Viscosity, a key rheological parameter, represents the resistance of a fluid to flow, whereas gelation involves the formation of a 3-dimensional molecular network capable of entrapping water and behaving as a solid-like structure (Wanders et al., 2014). The viscosity of hydrocolloid-containing systems depends strongly on the molecular weight and chain length of the polymers present. As molecular weight increases, so does the apparent viscosity of the solution, which explains why soluble fibers generally exhibit higher viscosities than insoluble ones (Fabek et al., 2014). Given that plant cell walls form the structural backbone of dietary fibers, they play a critical role in determining textural and rheological properties of foods (Lundberg et al., 2014). Among various hydrocolloids, CF has gained attention due to its high content of pectin and cellulose. The acidic nature of pectin components provides both thickening and gelling functionalities, making CF a valuable texture modifier in dairy systems (Willats et al., 2006; Lundberg et al., 2014). In addition, CF incorporation into QCS can therefore be expected to influence the rheological behavior during processing, particularly under heating and cooling conditions that can simulate real manufacturing steps.

During the in situ viscosity measurements, each formulation exhibited 2 distinct viscosity curves corresponding to the heating and subsequent cooling phases (Figure 6). As the temperature increased from 40°C to 80°C, the apparent viscosity of all samples decreased progressively, which is typical for protein-based systems undergoing thermal denaturation. Heat exposure induces partial unfolding of casein and whey proteins, leading to reduced structural resistance and a temporary thinning of the matrix. However, throughout the heating phase, formulations containing CF (QCSCF 10, 15, and 20) consistently displayed higher apparent viscosities ($P < 0.05$) compared with their respective controls (QCS 10, 15, and 20). This observation highlights the stabilizing and thickening effect of CF, attributed to the water-binding and network-forming capacity of pectin and cellulose. The difference between CF-enriched and samples without CF became particularly evident above 60°C, where apparent viscosity in QCSCF decreased less sharply, suggesting improved network integrity under thermal stress (Saha and Bhattacharya, 2010; Lundberg et al., 2014). After reaching 80°C, samples were maintained under shear for 10 min and then subjected to a controlled cooling phase back to 40°C. During cooling, all formulations exhibited a progressive increase in apparent viscosity, indicating structural reorganization and potential formation of protein-fiber-fat aggregates. The viscosity recovery was notably more pronounced in the CF-enriched samples, implying that fiber components facilitated the development of a more cohesive and elastic matrix upon cool-

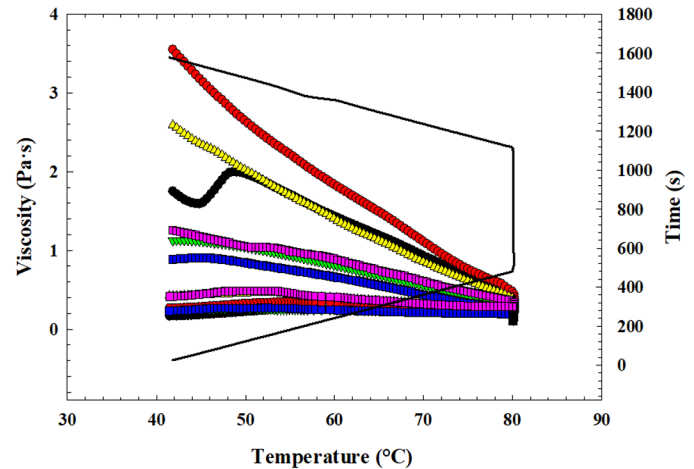


Figure 6. Viscosity (Pa·s) profiles obtained during in situ manufacture (triplicate manufacture of one of the pasteurized process cheese food treatments is indicated) of quark cheese spreads (QCS) manufactured without and with citrus fiber addition after 7 d of storage ($6^{\circ}\text{C} \pm 2^{\circ}\text{C}$; $n = 3$). The QCS 10 (black circle straight line), QCS 15 (green triangle dash line), and QCS 20 (blue square dash line) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10 (red circle dot line), QCSCF 15 (yellow triangle dash dot line), and QCSCF 20 (purple square dash dot line) = quark cheese spread samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively, and citrus fiber addition. The progress of temperature was presented as a black line without any symbols.

ing. This behavior is consistent with the reformation of hydrogen bonding and hydrophobic interactions as the temperature decreased, contributing to partial gelation and improved consistency (Wanders et al., 2014). Additionally, increasing fat content from 10% to 20% (wt/wt) resulted in higher apparent viscosity values across both thermal (heating and cooling) cycles. The increased viscosity at higher fat levels can be associated with increased dispersed phase volume and stronger interactions between fat globules and the protein-fiber network, resulting in a denser and more structured matrix. Such synergistic effects between fat and polysaccharides have been previously reported to improve the mouthfeel and spreadability of dairy emulsions (Fabek et al., 2014; Lundberg et al., 2014).

Overall, these results demonstrate that both fat content and CF addition can significantly affect the rheological behavior of QCS during thermal processing. The CF not only increases apparent viscosity but also mitigates thermal thinning and promotes structural recovery during cooling, leading to improved consistency and potential textural stability of the final product.

Instrumental Color Analysis of the Quark Cheese Spread Samples

Color analysis (Table 6) revealed that the addition of CF significantly affected the color parameters of QCS.

Table 6. Values of lightness (L^*), chromaticity on a green-to-red axis (a^*), chromaticity on a blue-to-yellow axis (b^*), chroma (C^*), hue angle (h°), whiteness index (WI), and total color difference ($\Delta E_{1,2}$) of the model quark cheese spread (QCS) samples ($n = 6$)¹

Parameter	Samples ²					
	QCS 10	QCS 15	QCS 20	QCSCF 10	QCSCF 15	QCSCF 20
L^*	92.70 $\pm$ 0.14 ^a	91.80 $\pm$ 0.07 ^a	92.28 $\pm$ 0.21 ^a	91.25 $\pm$ 0.18 ^a	91.52 $\pm$ 0.21 ^a	91.08 $\pm$ 0.19 ^a
a^*	-1.13 $\pm$ 0.05 ^a	-0.92 $\pm$ 0.09 ^b	-0.49 $\pm$ 0.06 ^c	-0.70 $\pm$ 0.02 ^d	-0.41 $\pm$ 0.02 ^c	-0.14 $\pm$ 0.02 ^c
b^*	13.98 $\pm$ 0.04 ^a	15.34 $\pm$ 0.08 ^b	15.49 $\pm$ 0.30 ^b	14.49 $\pm$ 0.01 ^c	14.44 $\pm$ 0.14 ^c	15.64 $\pm$ 0.24 ^b
h°	85.38 $\pm$ 0.18 ^a	86.56 $\pm$ 0.32 ^b	88.19 $\pm$ 0.19 ^c	87.25 $\pm$ 0.07 ^d	88.39 $\pm$ 0.05 ^c	89.49 $\pm$ 0.08 ^c
C^*	14.03 $\pm$ 0.04 ^a	15.36 $\pm$ 0.09 ^b	15.49 $\pm$ 0.31 ^c	14.50 $\pm$ 0.01 ^d	14.45 $\pm$ 0.14 ^d	15.46 $\pm$ 0.24 ^c
WI	84.19 $\pm$ 0.18 ^a	82.58 $\pm$ 0.09 ^b	82.69 $\pm$ 0.25 ^b	83.06 $\pm$ 0.23 ^c	83.25 $\pm$ 0.26 ^c	81.99 $\pm$ 0.24 ^d
$\Delta E_{1,2}$	—	—	—	1.60 $\pm$ 0.07 ^a	1.46 $\pm$ 0.15 ^b	2.53 $\pm$ 0.25 ^c

^{a-c}Mean values within a row followed by different superscripts statistically differ ($P < 0.05$).

¹Values are presented as the mean $\pm$ SD.

²QCS 10, QCS 15, and QCS 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10, QCSCF 15, and QCSCF 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt) and citrus fiber addition, respectively.

The lightness (L^*) values of CF-containing samples were lower compared with the CS, indicating a slightly darker appearance. This trend is consistent with the findings of García-Pérez et al. (2005) and Szafrńska et al. (2021). The addition of CF also affected chromatic coordinates. The a^* values shifted toward higher (less negative) values, suggesting a slight movement toward red tones. Furthermore, across the control formulations (QCS 10, QCS 15, and QCS 20), b^* values were positive and increased with fat level, indicating a progressive intensification of yellowness. The samples containing CF exhibit a nuanced pattern. In particular, at lower-fat levels (10% and 15% wt/wt), the tested samples presented similar b^* values to the corresponding controls, whereas at the highest fat level (20% wt/wt), the b^* were higher compared with the corresponding control sample (QCS 20). The observed trend could suggest that fat content exerts a concentration-dependent effect on yellowness, leading to reduced chromatic intensity at intermediate levels while amplifying it at higher concentrations, probably due to pigment interactions and modifications in light-scattering properties introduced by fiber particles. Similar findings were previously reported by Fernández-Ginés et al. (2003), who found that the enrichment of meat products with CF led to higher a^* and b^* values. Furthermore, a slight increase was noted in h° . The C^* values reported a similar trend to that of b^* values, reflecting the saturation of the yellow hue. The C^* values for the control samples increased with the increasing level of fat. In addition, the QCS samples containing CF showed lower C^* values at a fat level of 10 and 15% wt/wt compared with their controls. For the QCSCF 20 sample, the detected C^* value increased again, aligning closely with the C^* values observed for the samples without CF addition. The whiteness index (WI) exhibited a progressive decline with the increasing fat level in the control samples, reflecting a deviation from the

characteristic bright white appearance typically associated with dairy products. Moreover, the incorporation of CF further accentuated this reduction at corresponding fat levels, with the most substantial decrease observed in the QCSCF 20 sample. However, a deviation from this general trend occurred in the QCSCF 15 sample, where a slight increase in WI was recorded. Additionally, the above-mentioned trends in the color properties could be explained by the intrinsic color values of CF ($L^* = 82.29$, $a^* = 1.89$, $b^* = 17.65$), indicating a material with relatively high lightness values and a distinct yellow hue. Hence, the relatively high b^* value introduces significant yellowness into the cheese matrix, leading to reduced WI values (Szafrńska et al., 2021). The total color difference (ΔE) between control and fiber-enriched samples ranged from 1.46 to 2.53, corresponding to values perceptible to consumers according to Inami et al. (2015). Overall, these findings suggest that CF addition slightly modifies the color profile of QCS, although the observed changes remain within an acceptable range without negatively affecting sensory perception.

Sensory Analysis

The results of the sensory evaluation of QCS samples are presented in Table 7. Overall, the appearance of the samples was rated very good, with no pronounced differences among the variants. Sample QCSCF 10, however, received a significantly better score ($P < 0.05$), being evaluated as excellent, whereas the other samples scored slightly higher values, indicating slightly lower preference. Regarding spreadability, the control samples QCS were preferred over the formulations containing CF. Specifically, samples QCSCF 10 and QCSCF 15 received significantly higher scores ($P < 0.05$), reflecting lower sensory acceptance compared with the control. According to Gurbuz et al. (2024), the reduced spreadability

Table 7. Results of the sensory analysis¹ of the quark cheese spread (QCS) samples²

Parameter	Samples ³					
	QCS 10	QCS 15	QCS 20	QCSCF 10	QCSCF 15	QCSCF 20
Appearance	2 ^a	2 ^a	2 ^a	1 ^b	2 ^a	2 ^a
Spreadability	1 ^a	1 ^a	1 ^a	2 ^b	2 ^b	1 ^a
Hardness	4 ^a	3 ^b	4 ^a	3 ^b	3 ^b	4 ^a
Flavor	3 ^a	3 ^a	3 ^a	2 ^b	2 ^b	2 ^b
Off-flavor	1 ^a	1 ^a	1 ^a	2 ^a	2 ^a	1 ^a

^{a,b}Median values within a row followed by different superscripts statistically differ ($P < 0.05$).

¹Appearance, spreadability, hardness, and flavor: 1 = excellent; 3 = less good; 5 = unacceptable. Off-flavors: 1 = negligible, 3 = medium, 5 = excessive.

²The values are expressed as the median.

³QCS 10, QCS 15, and QCS 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt), respectively; QCSCF 10, QCSCF 15, and QCSCF 20 = samples with a fat content of 10%, 15%, and 20% (wt/wt) and citrus fiber addition, respectively.

observed in samples containing CF may be attributed to its enhanced water-binding capacity, which decreases the amount of free moisture available to ensure a smooth product consistency. Furthermore, fat crystallization, which is typical in cream and curd-based products with higher fat content, can also affect spreadability. Indeed, Brighenti et al. (2008) reported that high-fat cream cheeses exhibited lower spreadability compared with their low-fat counterparts. Hardness was clearly influenced by fat content: samples with 15% fat (QCS 15 and QCSCF 15) were perceived as softer than those with 10% and 20% fat ($P < 0.05$). In terms of flavor, spreads containing CF were rated more favorably than the control samples ($P < 0.05$), regardless of fat content. Notable differences were observed for flavor: the control samples QCS received higher scores, whereas all formulations with CF were rated more positively ($P < 0.05$), indicating a beneficial effect of CF addition on flavor acceptability. Finally, no significant differences ($P > 0.05$) were observed among the samples for off-flavors. All formulations scored low in this attribute, suggesting that CF addition did not contribute to undesirable taste notes. Furthermore, Szafrńska and Sołowiej (2020) reported that CF allows partial fat reduction without adversely affecting sensory characteristics, highlighting its potential as a promising additive for the development of modern functional QCS with improved health-related attributes. In the present study, these findings were confirmed, demonstrating that the incorporation of CF does not compromise sensory quality.

CONCLUSIONS

The findings presented in this study can contribute to expanding knowledge on the effects of CF on the functional properties of QCS. In particular, the CF addition did not significantly influence QCS sample pH,

DM content, and water activity values. In contrast, samples containing CF presented improved textural and viscoelastic properties, particularly in reduced fat formulations. Tribological analysis indicated that higher fat levels enhanced lubrication, whereas CF-containing QCS exhibited higher friction coefficients. Color analysis indicated slight shifts toward darker shades and increased yellowness following the incorporation of CF. Moreover, sensory analysis confirmed that CF addition had no adverse effect on most organoleptic attributes. Overall, CF demonstrates strong potential as a clean-label ingredient for developing healthier, lower-fat QCS. The CF application also supports sustainable utilization of citrus processing byproducts, contributing to waste reduction and more environmentally friendly production. These results highlight both the functional and economic benefits of CF, providing a foundation for further research on its role in improving the quality, consistency, and nutritional value of QCS.

NOTES

This research was financially supported by the Internal Grant Agency of Tomas Bata University in Zlín (Project No. IGA/FT/2025/007, Czech Republic). No human or animal subjects were used, so this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board. The authors have not stated any conflicts of interest.

Nonstandard abbreviations used: a_w = water activity; C^* = chroma; CF = citrus fiber; CoF = coefficient of friction; CoF_{max} = maximum coefficient of friction; CoF_{min} = minimum coefficient of friction; CS = control sample; FDA = US Food and Drug Administration; FDM = fat in DM; G' = storage modulus; G'' = loss modulus; G^* = complex modulus; h° = hue angle; ISO = International

Organization for Standardization; q = elevated interaction factor; QCS = quark cheese spreads; QCSCF = quark cheese spread with citrus fiber; $\tan \delta$ = phase angle; TPA = texture profile analysis; WI = whiteness index.

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