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Rheological and Textural Properties of Functional Yoghurt Containing Microencapsulated Saffron Petal Extract with Sodium Caseinate

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ABSTRACT

Saffron petals, as a by-product of saffron processing, are a rich source of bioactive compounds, particularly anthocyanins; however, the high sensitivity of these compounds to environmental conditions limits their direct application in food products. The aim of this study was to evaluate the rheological and textural properties of functional yogurt enriched with sodium caseinate–microencapsulated saffron petal extract. For this purpose, saffron petal extract was microencapsulated using sodium caseinate at a wall-to-core ratio of 7:1 and incorporated into yogurt at levels of 0.1, 0.2, and 0.3%. Rheological properties, including apparent viscosity, shear stress, and flow behavior, were investigated using the Power Law and Herschel–Bulkley models. In addition, textural properties (hardness), syneresis, and anthocyanin content of the samples were evaluated. The results indicated that all samples exhibited non-Newtonian shear-thinning (pseudoplastic) behavior. Increasing the concentration of the microencapsulated powder significantly enhanced apparent viscosity, consistency coefficient, and yield stress. The addition of the microencapsulated extract improved yogurt texture by increasing hardness and significantly reducing syneresis. Moreover, sodium caseinate–based microencapsulation played an effective role in preserving anthocyanins within the yogurt matrix. Overall, the use of sodium caseinate–microencapsulated saffron petal extract can be considered an efficient approach to improving the rheological, textural, and functional properties of functional yogurt.

1- Introduction

Saffron petals are considered one of the primary by-products of saffron processing, with an annual production exceeding 10,000 tons. These petals are a rich source of bioactive compounds, containing various flavonoids (such as kaempferol, rutin, quercetin, luteolin, and hesperidin), tannins, anthocyanins, and their glycosides [1]. Saffron petals consist of 10.2% protein, 5.3% fat, 7% ash, 8.8% fiber, and essential minerals (calcium, potassium, and phosphorus) [2], offering numerous therapeutic properties. Researchers have attributed these medicinal benefits to the high concentration of flavonoids, which exhibit potent antioxidant activities.

Microencapsulation is a technique used to package sensitive components within a coating or wall material to protect them from physicochemical environmental factors, oxidation, and evaporation [3]. In the food industry, microencapsulation is employed for various purposes, including reducing the reactivity of core materials with environmental conditions (such as light, heat, oxygen, and moisture), preventing their degradation, ensuring controlled release over time, and masking undesirable odors or flavors [4].

Sodium caseinate possesses both hydrophobic and hydrophilic regions. Due to its excellent emulsifying properties, film-forming ability, high solubility, and stability, sodium caseinate is one of the most suitable wall materials for microencapsulation in the food industry, particularly for oily or environmentally sensitive compounds [5].

Among functional foods, dairy-based products account for approximately 43% of the market share, consisting almost entirely of fermented dairy products. Yogurt is the most popular dairy product and one of the most widely consumed fermented foods globally; its sensory characteristics significantly influence consumer acceptance [6].

Khalili et al. (2021) prepared saffron petal extract using an enzymatic method and subsequently microencapsulated it with whey protein concentrate and maltodextrin (4:1 ratio) as wall materials. They compared the effects of free and encapsulated extracts on the shelf life and the chemical, microbial, and sensory properties of trout fillets [7]. Popescu et al. (2023) investigated the effect of microencapsulated basil extract on the quality and stability of cream cheese [8]. Cerdá-Bernad et al. (2023) enriched yogurt using microencapsulated extracts from saffron floral by-products and saffron stigma, demonstrating that these extracts can serve as functional ingredients to improve the nutritional and functional value of yogurt [9]. Furthermore, Bayram et al. (2025) examined the functional and phenolic characteristics of concentrated yogurt enriched with medicinal herbs such as marjoram, rosemary, basil, and peppermint [10].

The objective of this study is to promote the optimal utilization of saffron by-products by microencapsulating saffron petal extract. This innovative approach aims to produce a high-value-added product using sodium caseinate—an accessible and cost-effective material—to enhance anthocyanin stability against environmental conditions for use as a natural coloring and medicinal agent in yogurt. To date, no independent research has been conducted on the production of functional yogurt fortified with microencapsulated saffron petal extract. This study focuses on this unique combination to fill the existing research gap and evaluates the physicochemical, sensory, and bioactive properties of the resulting yogurt.

2- Materials and Methods

2-1- Materials

Saffron petals (Crocus sativus L.) were harvested in November ٢٠٢٤ from designated farms in Torbat-e Heydarieh, Khorasan Razavi, Iran. After harvesting and separating the floral parts, the petals were dried at the

Arnica factory in Torbat-e Heydarieh. Sodium caseinate (Sigma-Aldrich, CAS NO.: -٩٠٠٠٥ ٣-٤٦) was purchased for the microencapsulation process. The dried petals were ground using a domestic mill, sieved (١٦ mesh), and stored in airtight dark containers under refrigeration until further use.

2-2- Preparation of Saffron Petal Extract

Ten grams of saffron petals (weighted with ٠,٠١g precision) were placed in a dark bottle. Then, ١٥٠mL of ٪٥٠ethanol (pH adjusted to ٣,٠using ١,٥N HCl) was added. The mixture was stirred for ٢٤hours in a dark room at ambient temperature (°٢٥C). After ٢٤hours, the extract was filtered using Whatman No. ١ filter paper and a vacuum pump. The residual petals on the filter paper were re-extracted with the same volume of solvent (١٥٠mL). To minimize thermal degradation, the pH of the resulting extract was adjusted to ٣,٠using ٠,١ N HCl. The solvent was removed and the extract concentrated using a rotary evaporator at °٤٠C for ٦٠minutes. Finally, the concentrated extract was dehydrated using a freeze-dryer at -°٨٦C and a pressure of ٥ mmHg for ٧٢hours.

2-3- Microencapsulation Process

The wall material (sodium caseinate) and the core material (saffron petal powder) were mixed at three ratios: ٣:١, ٥:١, and ٧:١(w/w). The mixtures were stirred on a magnetic stirrer for ٢٠minutes. Subsequently, the pH was reduced to ٢,٠using ١,٥N HCl to ensure anthocyanin stability. The samples were then freeze-dried at -°٨٦C and ٥mmHg for ٧٢ hours. The resulting solids were immediately pulverized in a porcelain mortar, passed through a ٤٠-mesh sieve, and stored in dark, sealed glass containers in a freezer.

2-4- Yogurt Preparation

To prepare the yogurt, milk was standardized and heated at 90°C for 15 minutes, followed by cooling to the inoculation temperature (45°C). The milk was inoculated with 3% (w/w) commercial starter culture (comprising Streptococcus thermophilus and Lactobacillus bulgaricus). At this stage, the microencapsulated saffron petal extract (produced with the optimal wall-to-core ratio of 7:1 [11]) was added to the inoculated milk at levels of 0.1%, 0.2%, and 0.3% (w/w) and homogenized using a sterile stirrer. The samples were poured into sterile containers and incubated at 42°C until reaching a final pH of 4.6 (the isoelectric point of casein). After fermentation and curd formation, the samples were transferred to a refrigerator (4°C) to stabilize the structure before testing [12].

2-5- Analytical Methods

2-5-1- Syneresis Measurement

The syneresis of yogurt samples was determined using Equation (1) [13]:

Syneresis (%) = (M2 / M1) × 100

Where *M1 is the initial weight of the yogurt before centrifugation, and M2 is the weight of the separated whey after centrifugation.

2-5-2- Texture Profile Analysis

A texture analyzer (Stable Micro Systems, Surrey, England) was used to evaluate the hardness of the yogurt samples at 5°C. A 100 g sample was placed in the device container without stirring. A 20 mm diameter cylinder probe penetrated the sample to a depth of 70 mm at a speed of 1 mm/s with a trigger force of 0.1 N. Hardness was recorded in Newtons (N) [14].

2-5-3- Total Anthocyanin Content

The total anthocyanin content of the yogurt samples was measured using the pH differential method and reported as milligrams of cyanidin-3-glucoside equivalent per gram of dry matter [15].

2-5-4- Rheological Properties

The flow properties of the yogurt samples were measured using a Brookfield rotational viscometer (Model RVDV-III). All tests were performed at °٢٥C under identical conditions. The flow curves were recorded over a shear rate range of ٠to ١٠٠s^{-1}. The viscometer was interfaced with a computer for precise operational control. Due to the observed decrease in viscosity with increasing shear rate (non-Newtonian behavior), four non-Newtonian fluid models, including the Power Law model, Bingham, Herschel-Bulkley, and Casson models were employed.[١٦]

Equation (٢) Power Law Model: $\sigma=k\gamma^{n}$

Where σ is the shear stress (Pa) ,γ is the shear rate (s^{-1}) ,n is the flow behavior index (dimensionless), and k is the consistency index (Pa·s^{n}).

Equation (٣) Herschel-Bulkley Model:

$$\sigma=\sigma_{0H}+k_H(\gamma)^{n_H}$$

Where σ is the shear stress (Pa) ,γ is the shear rate (s^{-1}) ,$_{0H}\sigma$ is the yield stress (Pa) ,n_H is the flow behavior index (dimensionless), and k_H is the consistency index (Pa·s^{n}).

Equation (٤) Bingham Model:

$$\sigma=\sigma\ 0+\eta_B\gamma$$

Where σ is the shear stress (Pa) ,is the shear rate (s^{-1}) ,σ_0 is the Bingham yield stress (Pa), and η_B is the plastic viscosity (Pa·s).

Equation (٥) Casson Model:

$$\sigma^{0.5}=\sigma_{0C}^{0.5}+k_c(\gamma)^{0.5}$$

Where $\sigma 0.5$ is the square root of shear stress ($Pa^{0.5}$) , $\gamma^{0.5}$is the square root of shear rate , $_0\sigma$ is the Casson yield stress (Pa), and k_C is the Casson consistency index (Pa·s^{n})

2-6- Statistical Analysis

All experiments were performed in triplicate, and the results were expressed as mean values. The data were analyzed using a Completely Randomized Design (CRD). One-way Analysis of Variance (ANOVA) was employed to determine significant differences between the samples, and mean comparisons were conducted using Duncan's Multiple Range Test at a ٪٥confidence level .٠,٠٥ Statistical analyses were performed using SPSS software (Version ٢٠, IBM Corp., USA), and Microsoft Excel (Version ٢٠١٣) was used for generating the charts and figures.

3-Results and Discussion

Based on the parameters measured—including moisture content, water activity, anthocyanin content, and powder solubility—as well as the calculated Carr Index and Hausner Ratio for the control and various wall-to-core ratios, the ١:٧core-to-wall ratio was selected as the optimal sample [١١]. This selection was based on the requirement that the final microencapsulated powder must possess desirable flowability and low cohesiveness for effective dispersion in the final product, alongside high anthocyanin content, low moisture and water activity, and high solubility. Consequently, this optimal ratio was utilized in the yogurt formulation.

3-1-Rheological Properties of Yogurt

Viscosity is the most critical rheological property of liquids. Yogurt is a non-Newtonian, pseudoplastic fluid, meaning its viscosity decreases as the shear rate increases. Therefore, specifying the shear rate is essential when determining yogurt viscosity. For a pseudoplastic (shear-thinning) fluid such as yogurt, the apparent viscosity decreases with an increase in the shear rate [17]. Viscosity is a property that significantly influences the development of desirable texture and consistency; the composition, concentration, and quality of the raw material mixture play a decisive role in achieving an appropriate viscosity [18].

The rheograms obtained for the yogurt samples are illustrated in Figures 1 and 2. Preliminary tests indicated that all studied samples were time-independent and non-Newtonian. This non-Newtonian behavior of yogurt has been previously reported by other researchers [19, 20].

The trends in viscosity and shear stress versus shear rate confirmed the pseudoplastic (shear-thinning) behavior of most yogurt samples;

specifically, the apparent viscosity decreased as the shear rate increased (Figure 1). Samples containing higher concentrations of sodium caseinate exhibited higher initial viscosity, and the rate of viscosity reduction with increasing shear rate was more pronounced in these samples. Given that an increased shear rate enhances molecular alignment and internal friction, thereby reducing viscosity, it can be inferred that utilizing sodium caseinate as a wall material for microencapsulating saffron petal extract reinforces these effects. This behavior occurs because molecules are arranged irregularly and only partially aligned at low shear rates, leading to high viscosity. As the shear rate increases, molecular alignment improves, resulting in increased internal friction and a decrease in viscosity. Since the majority of intermolecular bonds are broken at the beginning of the shear application, the reduction in apparent viscosity is more intense at the start of the test and gradually stabilizes thereafter.

The results showed that the viscosity of the control sample was significantly lower than that of all other samples. This can be attributed to the crucial role of sodium caseinate within the microencapsulated saffron petal extract in increasing yogurt viscosity, owing to its superior water-binding capacity and its ability to form a stable gel network. The primary role of stabilizers in yogurt is to provide appropriate consistency and body to the product. Increasing the percentage of sodium caseinate in the yogurt samples shifted the viscosity-shear rate trend further away from the control sample.

A comparison of the shear stress versus shear rate curves for the experimental and control samples indicated that increasing the concentration of the microencapsulated powder up to 0.3% increased the slope of the curve. This implies that at a given shear rate, the shear stress required for samples with higher concentrations is greater (Figure 2). The slope of the curve for the sample containing 0.1% sodium caseinate (as the wall material in the microencapsulated saffron extract) was lower than the other treatments and showed a high degree of similarity to the control sample.

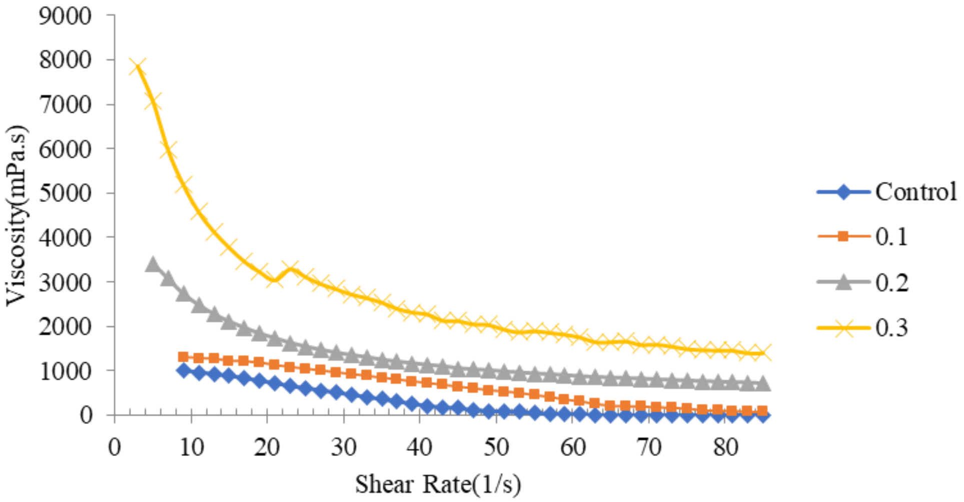

Fig1. Viscosity versus shear rate of yogurt samples containing different percentages of sodium caseinate as the wall material of encapsulated saffron petal extract

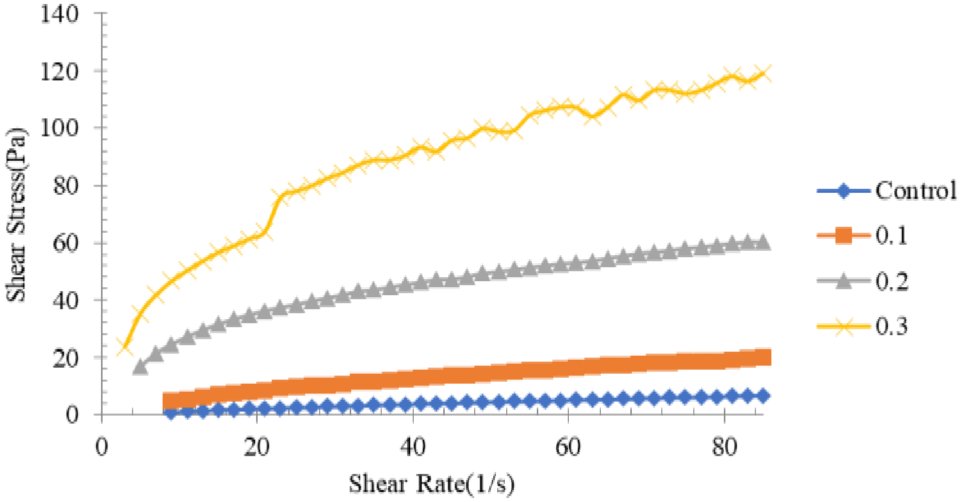

Fig2. Shear stress versus shear rate of yogurt samples containing different percentages of sodium caseinate as the wall material of encapsulated saffron petal extract

3-1-1- Selection of the Appropriate Rheological Model

Given the non-Newtonian nature of all yogurt samples, two common time-independent rheological models—the Power Law and Herschel-Bulkley models—were employed to model and characterize the flow behaviour. To determine the best-fit model, the coefficients of determination (R^2) were calculated for each model. Since these two models exhibited the highest R ٢values and the lowest Mean Square Error (MSE), they were selected as the most suitable models for describing the yogurt samples.

3-1-2- Rheological Parameters

The flow behavior results based on the Power Law model (Table ١) and the Herschel-Bulkley model (Table ٢) indicated that all prepared yogurt treatments exhibited pseudoplastic or shear-thinning behavior, where viscosity decreased as the shear rate increased. These findings are consistent with results reported by other researchers[٢٠ ,١٩] .

3-1-3- Flow Behavior Index (*n*)

The flow behavior index for all samples was less than unity, confirming the shear-thinning (pseudoplastic) behavior of the mixtures. In fact, a decrease in the flow behavior index is the primary factor reinforcing shear-thinning behavior. In other words, the addition and subsequent increase in sodium caseinate concentration did not alter the fundamental shear-thinning property of the product. Previous studies have also highlighted the pseudoplastic nature of yogurt. The reduction in the flow behavior index observed with increasing concentrations of microencapsulated saffron petal extract (using sodium caseinate) in yogurt occurs due to the following reasons:

Increasing the concentration of sodium caseinate leads to the formation of more complex protein networks and enhanced intermolecular interactions, creating dense three-dimensional structures. These structures break down easily under shear (stirring or flow), resulting in a more pronounced drop in viscosity and thus a lower *n* value[٢١] .

Microencapsulation with sodium caseinate introduces more suspended particles into the yogurt system. These particles interact with the yogurt matrix, creating a thicker, more heterogeneous, and shear-sensitive structure. Consequently, as the shear rate increases, the viscosity drop becomes more severe, leading to a smaller n value .

Sodium caseinate acts as a stabilizer and gelling agent that increases viscosity. Its presence raises the apparent viscosity while lowering the flow behavior index, shifting the system closer to a highly shear-thinning state . Therefore, increasing the concentration of sodium caseinate in the microencapsulation process reinforces pseudoplastic behavior by enhancing protein structures and inter-particle interactions, which ultimately leads to a decrease in the flow behavior index (*n*).

Table 1- Flow behavior index, consistency coefficient, and correlation coefficient for the Power Law model of yogurt samples containing different percentages of sodium caseinate as the wall material of encapsulated saffron petal extract

Sample	Flow behavior index	Consistency coefficient (Pa. s ^{n})	R^2
control	0.39	27.20	0.99
0.1	0.32	33.27	0.99
0.2	0.23	42.77	0.99
0.3	0.21	56.85	0.98

Table 2- Flow behavior index, consistency coefficient, yield stress, and correlation coefficient for the Herschel–Bulkley model of yogurt samples containing different percentages of sodium caseinate as the wall material of encapsulated saffron petal extract

Sample	Flow behavior index	Consistency coefficient (Pa. s ^{n})	Yield stress (Pa)	R^2
control	0.51	41.39	22.26	0.99
0.1	0.41	49.64	27.19	0.99
0.2	0.37	66.56	44.01	0.99
0.3	0.29	71.80	56.76	0.99

3-1-4-Consistency Index (*k*)

The consistency index (*k*) is a criterion for measuring the viscous nature of food materials and serves as a major indicator of the magnitude of apparent viscosity. With the addition of sodium caseinate, the consistency index increased in a manner similar to apparent viscosity (Table ١), which can be attributed to the increase in high-molecular-weight molecules in the liquid phase and the subsequent rise in flow resistance. Furthermore, the addition of sodium caseinate can modify the rheological properties of yogurt due to its water-binding capacity and the formation of a quasi-gel network with other components. According to the results, the consistency index of the control sample was lower than that of all other samples. While a slight increase in the percentage of sodium caseinate led to a marginal rise in the consistency index, increasing the concentration from ٪٠,٢to ٪٠,٣resulted in a sudden surge (from ٤٢,٧٧to ٥٦,٨٥). Consequently, the highest consistency index was recorded for the sample containing ٪٠,٣sodium caseinate as the wall material for the microencapsulated saffron petal extract. Thus, increasing the concentration of sodium caseinate in the microencapsulation process led to an increase in the yogurt's consistency index.

When sodium caseinate is utilized as a wall material, a portion of it may be released into or interact with the yogurt matrix. These interactions enhance the protein network, subsequently increasing the consistency of the yogurt. Moreover, an increase in the quantity of microencapsulated particles increases the solid phase of the system. These particles act as micro-fillers, increasing the resistance to flow (i.e., increasing the consistency index). Due to its water-holding capacity, sodium caseinate helps reduce water migration in the yogurt, leading to a more cohesive, uniform, and thicker texture [٢٢] . Increasing the concentration of sodium caseinate in the microencapsulation process elevates the level of functional proteins in the yogurt, which enhances the consistency index by improving the structural network, increasing viscosity, and reducing water migration. A previously published study investigated the fabrication of microcapsules using sodium caseinate and pectin as carriers for saffron extract. The findings indicated that rheological properties (including moduli) increased due to the structural entanglement of the polymers, which led to improved structural properties and stability of the saffron extract [٢١].

3-1-5- Yield Stress

Yield stress is defined as the minimum stress required to initiate flow in a material. Knowledge of yield stress is essential for food process design, sensory evaluation, and rheological modelling. As observed in Table ٢, the yield stress significantly increased with the rising levels of sodium caseinate. Increasing the concentration of sodium caseinate, used as the wall material for microencapsulating saffron petal extract, led to a higher yield stress in the yogurt samples. With the addition of sodium caseinate, the internal structure of the yogurt became denser and more cohesive, creating a stronger network against flow or deformation. Consequently, a greater force is required to initiate the movement of the yogurt, which explains the increase in yield stress values.

The microencapsulation of saffron extract with sodium caseinate increases the dispersed solid phase within the yogurt. These particles become entangled with the yogurt's gel-like matrix and increase internal friction. As a result, the yogurt exhibits higher resistance to flow, leading to an increased yield stress. Furthermore, sodium caseinate possesses hydrophilic properties that prevent serum separation, thereby maintaining the uniformity of the gel structure at a microscopic scale. Consequently, the resulting structure is more robust, requiring higher initial stress to begin flowing [٢١]. Therefore, increasing the concentration of sodium caseinate facilitates the development of a stronger and more continuous internal structure in the yogurt. This structure necessitates higher stress to initiate flow, which is reflected in the elevated yield stress values.

3-2-Syneresis of Yogurt

Syneresis, or whey-off, is a phenomenon commonly observed in dairy products, particularly yogurt, referring to the separation of the liquid whey phase from the product's gel structure. This phenomenon is of significant importance from both qualitative and industrial perspectives [٢٠]. Excessive syneresis may indicate a weak gel structure in the yogurt. While a minor degree of syneresis is considered natural and indicative of a "living" structure, high levels can be problematic, leading to a loose and watery texture, reduced consumer satisfaction, and a decline in apparent shelf life [٢٣] . Proteins, especially caseins, play a crucial role in the formation of the gel network. By increasing the protein content and enhancing water-holding capacity, sodium caseinate prevents the separation of whey. Sodium caseinate facilitates the development of a stronger network within the yogurt matrix, resulting in a more stable gel [٢٤]. This leads to a more uniform structure containing microencapsulated particles that hinder the migration of the liquid phase. Furthermore, particles microencapsulated with sodium caseinate as the wall material exhibit lower sensitivity to agitation and provide additional structural support to the matrix [٤] . The statistical results regarding the effect of various concentrations of sodium caseinate, used as the wall material for microencapsulated saffron petal extract, on the syneresis rate of yogurt are presented in Table 3.

Table 3-Syneresis of yogurt samples containing different percentages of sodium caseinate as the wall material of encapsulated saffron petal extract

Sample	Syneresis (%)
Control	25.59 ± 0.06^{A}
0.1	24.58 ± 0.09^{AB}
0.2	23.30 ± 0.74^{B}
0.3	21.45 ± 0.80^{C}

Different letters within the same column indicate significant differences at the 95% confidence level. Values are expressed as mean ± standard deviation (n = 3).

As indicated by the data in Table 3, no significant statistical difference was observed between the control sample and the sample containing 0.1% sodium caseinate. However, the control sample showed significant differences compared to all other treatments. The sample containing 0.3% sodium caseinate exhibited the lowest syneresis rate among all samples, which was statistically significant compared to the 0.2% concentration and other treatments ($p < 0.05$). Increasing the concentration of sodium caseinate in the microencapsulation formulation enhances the water-holding capacity within the yogurt structure. Particles microencapsulated with higher concentrations of wall material provide a larger surface area for interaction with the gel matrix, thereby preventing the release of whey. Higher levels of sodium caseinate strengthen intermolecular bonds within the yogurt texture. This more cohesive network prevents structural breakdown during storage and effectively reduces syneresis. Furthermore, the use of higher levels of sodium caseinate increases the total solids content (particularly protein) in the yogurt. The resulting higher viscosity leads to better stability against liquid phase leakage [25, 26]. Consequently, sodium caseinate, as it improved the rheological properties (viscosity, consistency) of the yogurt (Figure 1 and data in Tables 1 and 2), significantly reduced syneresis. Therefore, the application of sodium caseinate as a wall material for the microencapsulation of saffron petal extract not only enhances the stability of the extract but also effectively minimizes syneresis by improving the gel structure and increasing the water-holding capacity of the yogurt. In conclusion, by increasing the concentration of sodium caseinate in the microencapsulation formula from 0.1% to 0.3%, the syneresis rate decreased significantly, such that at high concentrations, the syneresis was reduced to approximately 20% of its initial value.

3-3- Textural Properties of Yogurt

The hardness parameter is one of the most critical textural and mechanical characteristics of yogurt, playing a fundamental role in both quality assessment and consumer acceptance. In the context of Texture Profile Analysis (TPA), hardness refers to the amount of force required to induce the initial deformation in the yogurt's structure. In texture measurement tests, hardness is typically defined as the peak force recorded during the first compression cycle of the yogurt sample [۲۷]. Hardness is influenced by various factors, including the type and concentration of proteins (e.g., casein or sodium caseinate), the final pH of the yogurt, processing conditions (temperature, incubation time, and homogenization), and additives (such as polysaccharides, gums, and microencapsulated materials). Measuring hardness enables manufacturers to maintain product consistency over time.[۲۸]
Yogurt with optimal hardness is generally more resistant to serum separation. Conversely, low hardness may indicate a weak structure and a reduction in the textural shelf life of the product. Therefore, hardness serves as a key indicator for determining textural quality, consumer satisfaction, and process control within the dairy industry. Any inappropriate increase or decrease in hardness can directly impact the sensory acceptance and long-term stability of the product.[۲۸]
The statistical results regarding the effect of various concentrations of sodium caseinate, used as the wall material for microencapsulated saffron petal extract, on the hardness of yogurt are presented in Table 4.

Table 4- Hardness of yogurt samples containing different percentages of sodium caseinate as the wall material of encapsulated saffron petal extract

Sample	Hardness (N/m)
Control	1070.17 ± 924.59^{C}
0.1	1151.05 ± 873.21^{C}
0.2	9725.10 ± 567.12^{B}
0.3	22446.12 ± 776.89^{A}

Different letters within the same column indicate significant differences at the 95% confidence level. Values are expressed as mean ± standard deviation (n = 3).

As indicated by the data in Table ٤, the control sample and the sample containing ٪٠٫١ sodium caseinate exhibited the lowest hardness levels, with no significant statistical difference observed between them. However, samples containing ٪٠٫٢and ٪٠٫٣sodium caseinate showed significant statistical differences compared to both the control and the ٪٠٫١concentration samples. The ٪٠٫٣ sodium caseinate sample recorded the highest hardness value.

The role of sodium caseinate as a wall material in the microencapsulation of saffron petal extract significantly influences the hardness parameter in yogurt. Sodium caseinate possesses a high capacity for creating stable matrices and emulsions. When utilized as a wall material, it ensures a more stable and uniform distribution of microencapsulated particles throughout the yogurt matrix [٢٩, ٣٠]. Furthermore, sodium caseinate prevents the degradation of bioactive compounds (such as anthocyanins) in the saffron petal extract, which can also affect the rheological properties of the yogurt. Particles microencapsulated with sodium caseinate may act as fillers within the yogurt's gel matrix, leading to increased density and structural strength [٢٩]. Due to its proteinaceous nature, sodium caseinate interacts with the yogurt's protein gel (casein and whey), thereby reinforcing the gel network [٣١]. This increase in hardness is typically associated with a reduction in syneresis (consistent with the data in Table ٣), as the network structure of the yogurt becomes more robust. Uniform microencapsulation of the saffron extract, facilitated by sodium caseinate, prevents the formation of weak points within the gel matrix.

In conclusion, sodium caseinate, acting as a wall material for microencapsulating saffron petal extract, increases the hardness of the yogurt. This enhancement is attributed to the filler effect of the microencapsulated particles and the protein-protein interactions between sodium caseinate and the yogurt's protein matrix. Additionally, this process leads to improved textural uniformity, reduced syneresis, and enhanced rheological properties in the yogurt.

3-4-Anthocyanin Content of Yogurt

Anthocyanins are compounds that are highly sensitive to light, pH, temperature, and oxygen; consequently, they may degrade rapidly within the yogurt environment (characterized by an acidic pH and cold storage conditions). Therefore, microencapsulation serves as an effective strategy to preserve these beneficial compounds within a food matrix such as yogurt. The role of sodium caseinate as a wall material for the microencapsulation of saffron petal extract is crucial and highly effective in maintaining the anthocyanin content present in the yogurt.

The statistical results regarding the effect of various concentrations of sodium caseinate, used as the wall material for microencapsulated saffron petal extract, on the anthocyanin content of the yogurt are presented in Table .٥

Table 5- Anthocyanin content of yogurt samples containing different percentages of sodium caseinate as the wall material of encapsulated saffron petal extract

Sample	Anthocyanin (mg/100 mL)
Control	Not detected
0.1	770.136 ± 38^{A}
0.2	890.810 ± 24^{A}
0.3	915.240 ± 80^{A}

Different letters within the same column indicate significant differences at the 95% confidence level. Values are expressed as mean ± standard deviation (n = 3).

As shown in Table ٥, no significant statistical difference was observed between the different levels of sodium caseinate used as wall materials.

Due to its proteinaceous structure, sodium caseinate can encapsulate anthocyanins within a protective matrix. This matrix acts as a barrier, preventing direct contact between anthocyanins and oxygen or light, thereby inhibiting their degradation. Sodium caseinate exhibits a high binding affinity for phenolic compounds and anthocyanins [۳۲, ۲۱], which facilitates higher encapsulation efficiency and, consequently, greater retention of anthocyanins within the yogurt. In the acidic environment of yogurt, sodium caseinate enables the gradual release of anthocyanins rather than a sudden burst; this enhances the stability of both the color and the antioxidant properties of the yogurt during storage. While free anthocyanins may react with yogurt proteins or lipids and undergo degradation, their reactivity is significantly reduced and their stability is enhanced when introduced in a microencapsulated form using sodium caseinate.

The increase in sodium caseinate concentration as a wall material has a direct impact on the preservation of anthocyanins in the yogurt. As indicated in Table ٥, higher concentrations of sodium caseinate in the microencapsulated saffron petal extract powder led to improved anthocyanin retention. Increasing the sodium caseinate concentration enhances the thickness and mechanical strength of the wall layer surrounding the extract, resulting in superior entrapment of anthocyanins within the microcapsules and minimizing leakage or degradation within the yogurt matrix. A thicker and denser layer formed by higher sodium caseinate levels prevents the penetration of oxygen and light, which are the primary factors responsible for anthocyanin degradation (Li et al., ۲۰۱۸). Furthermore, this can lead to a more sustained and prolonged release rate of anthocyanins. High concentrations of sodium caseinate contribute to more robust insulation, thereby reducing the direct exposure of anthocyanins to low pH levels, particularly in products such as yogurt.

4- Conclusion

Saffron petals, as a byproduct of saffron processing, represent a rich source of bioactive and antioxidant compounds. In this study, increasing the concentration of sodium caseinate as a wall material in the microencapsulation process of saffron petal extract and its subsequent addition to yogurt significantly improved the physicochemical characteristics of the final product. Enhancing the concentration of this compound increased the structural stability of the microcapsules and facilitated the controlled release of anthocyanins, thereby elevating the concentration of these bioactive compounds within the yogurt matrix. Furthermore, by creating a more cohesive network in the yogurt texture, sodium caseinate effectively reduced syneresis and improved textural hardness by increasing structural resistance. On the other hand, higher concentrations of this material led to an increase in viscosity and more pronounced shear-thinning behavior, indicating more desirable rheological properties in the final product.

Data Availability

All data generated or analyzed during this study are included in this published article

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions

Atie Jalilian Rastgou :Investigation, Data curation, Writing – original draft. Hojjat Karazhiyan :Conceptualization, Methodology, Validation, Data curation, Supervision, Project administration, Writing – review & editing.

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ویژگیهای رئولوژیکی و بافتی ماست فراسودمند حاوی عصاره گلبرگ زعفران ریزپوشانی شده با سدیم کازئینات

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چکیده

گلبرگ زعفران به‌عنوان یکی از محصولات جانبی فرآوری زعفران، منبعی غنی از ترکیبات زیست‌فعال به‌ویژه آنتوسیانین‌ها محسوب می‌شود، اما حساسیت بالای این ترکیبات نسبت به شرایط محیطی، کاربرد مستقیم آن‌ها را در فرآورده‌های غذایی محدود می‌سازد. هدف از این پژوهش، ارزیابی ویژگی‌های رئولوژیکی و بافتی ماست فراسودمند غنی‌شده با عصاره گلبرگ زعفران ریزپوشانی‌شده با سدیم کازئینات بود. بدین منظور، عصاره گلبرگ زعفران با استفاده از سدیم کازئینات در نسبت۷ به ۱ ماده دیواره به هسته ریزپوشانی شد و در سطوح ۰/۱، ۰/۲ و ۰/۳ درصد به ماست افزوده شد. ویژگی‌های رئولوژیکی شامل ویسکوزیته ظاهری، تنش برشی و رفتار جریان با استفاده از مدل‌های قانون توان و هرشل بالکلی بررسی گردید. همچنین خصوصیات بافتی (سختی)، میزان سینرزیس و مقدار آنتوسیانین نمونه‌ها مورد ارزیابی قرار گرفت. نتایج نشان داد که تمامی نمونه‌ها رفتار غیرنیوتنی از نوع سودوپلاستیک از خود نشان دادند و با افزایش غلظت پودر ریزپوشانی‌شده، ویسکوزیته ظاهری، ضریب قوام و تنش تسلیم به‌طور معنی‌داری افزایش یافت. افزودن عصاره ریزپوشانی‌شده موجب بهبود سختی بافت و کاهش قابل توجه سینرزیس ماست گردید. همچنین ریزپوشانی با سدیم کازئینات نقش مؤثری در حفظ آنتوسیانین‌ها در ماتریس ماست ایفا کرد. در مجموع، استفاده از عصاره گلبرگ زعفران ریزپوشانی‌شده با سدیم کازئینات، روشی کارآمد برای بهبود ویژگی‌های رئولوژیکی، بافتی و عملکردی ماست فراسودمند محسوب می‌شود.