

Article

Processing and Quality Evaluation of Cottage Cheese Spread Enriched with Alginate–Pullulan-Encapsulated Herbal Bioactives

Alibek Muratbayev ¹, Sandugash Toleubekova ^{1,*}, Aitbek Kakimov ¹, Aigerim Bepeyeva ¹, Gulmira Zhumadilova ¹, Madina Jumazhanova ¹, Zhadyra Imangaliyeva ², Nazerke Muratzhankyzy ¹, Marzhan Tashybayeva ¹ and Aslan Sovetkanov ¹

¹ Research School of Food Engineering, Shakarim University, Semey 071412, Kazakhstan; mr.muratbayev.a@gmail.com (A.M.); bibi.53@mail.ru (A.K.); bepeyeva1987@gmail.com (A.B.); zhumadilovaga@mail.ru (G.Z.); madina.omarova.89@mail.ru (M.J.); nazerkemuratzhankyzy1990@gmail.com (N.M.); marzhan06081990@gmail.com (M.T.); sovetkanov706@gmail.com (A.S.)

² Department of Food Technology, Almaty Technological University, Almaty 050000, Kazakhstan; zh.imangaliyeva@atu.edu.kz

* Correspondence: sanmak071979@gmail.com

Abstract

This study evaluated the effects of alginate–pullulan-encapsulated herbal bioactives on the processing characteristics, quality, and refrigerated storage stability of cottage cheese spread. Capsules containing rosehip, echinacea, and levezeya extracts were incorporated at levels of 0–5%, and the resulting samples were assessed for physicochemical properties, bioactive composition, antioxidant activity, rheological behavior, capsule integrity, sensory acceptability, and safety. The formulation containing 3% capsules was selected as the formulation providing the best balance between enrichment and product quality. It contained 0.94 mg/100 g vitamin C, 6.75 mg/100 g polyphenols, and 4.50 mg/100 g flavonoids, with DPPH antioxidant activity of 6.0% and a mean sensory score of 4.69/5. Capsule levels of 4–5% further increased bioactive content but reduced sensory scores to 4.11 and 3.71 because of more visible inclusions and lower taste and consistency ratings. During 7 days of refrigerated storage, moisture content and water activity remained statistically stable, and lactic acid bacteria remained close to 7 log₁₀ CFU/g. Meanwhile, pH decreased, whereas titratable acidity and syneresis increased, with sensory deterioration becoming more evident after day 3. By day 7, vitamin C, polyphenols, and antioxidant activity retained 92.6%, 95.6%, and 94.0% of their initial values, respectively. Pathogenic microorganisms were not detected, and the tested safety indicators remained within permissible limits. These results demonstrate that 3% capsule incorporation provides a suitable balance between bioactive enrichment, processability, sensory acceptability, and refrigerated quality retention.

Keywords: cottage cheese spread; alginate–pullulan capsules; herbal bioactives; antioxidant activity; rheological behavior; syneresis; refrigerated storage

Academic Editor: Bing-Huei Chen

Received: 14 July 2026

Revised: 27 July 2026

Accepted: 30 July 2026

Published: 2 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

1. Introduction

Quality control in dairy processing requires the combined evaluation of composition, physicochemical stability, rheological behavior, sensory characteristics, and microbiological safety. This is particularly important for fermented and semi-solid dairy products, in which ingredient addition can alter protein interactions, moisture distribution, acidity, viscosity, syneresis, and storage stability [1,2]. Dairy products are widely consumed, nutrient-dense, and structurally versatile matrices for the incorporation of plant-derived ingredients [3]. However, the technological suitability of an enriched dairy product depends not only on its bioactive composition but also on its ability to retain acceptable structure, sensory quality, and safety throughout processing and refrigerated storage [4].

Medicinal and aromatic plants are rich sources of phenolic acids, polyphenols, flavonoids, tannins, vitamins, and other secondary metabolites associated with antioxidant and antimicrobial activity [5]. In the present study, rosehip, echinacea, and levezeya extracts were selected as sources of herbal bioactives. Rosehip-containing ingredients have previously been investigated in dairy products as sources of phenolic compounds and antioxidant activity [3]. Nevertheless, direct incorporation of plant extracts into semi-solid dairy matrices may cause bitterness, astringency, color changes, poor dispersion, and interactions with proteins and lipids. These effects may modify viscosity, water retention, syneresis, texture, and consumer acceptability [6]. Therefore, a processing strategy is required to limit direct interactions between plant compounds and the dairy matrix while preserving bioactive stability and product quality.

Encapsulation is one of the most relevant strategies for incorporating sensitive bioactives into foods. It can protect compounds from oxygen, light, moisture, heat and adverse pH, reduce undesirable taste or odor, improve dispersibility and support controlled release during digestion [7,8]. Broad reviews identify encapsulation as a way to retain active properties, improve storage stability and maintain organoleptic quality in functional foods [9]. In fermented dairy products, alginate-encapsulated plant extracts have been reported to stabilize polyphenols and improve shelf-life attributes, illustrating the practical relevance of this approach [10].

Food-grade hydrocolloids are central to encapsulation design. Alginate is widely used because it forms calcium-crosslinked hydrogel networks under mild conditions, while polysaccharides such as pectin and pullulan can provide film-forming, stabilizing, and release-modulating properties [9,11]. Polysaccharide-based delivery systems can protect bioactive compounds and enable pH-sensitive release in simulated gastrointestinal environments [12].

In our previous study, an alginate–pullulan capsule system containing rosehip, echinacea, and levezeya extracts was developed using a jet-cutter encapsulation process [13]. That study focused on selecting the capsule-forming polymers and processing conditions, characterizing capsule morphology and gastrointestinal release behavior, and demonstrating the feasibility of incorporating the capsules into a kefir-type fermented milk beverage. The capsules remained stable under simulated gastric conditions and released their contents under simulated intestinal conditions. Their addition to a fluid fermented milk matrix was evaluated mainly in terms of sensory characteristics, viscosity, acidity, and lactic acid bacteria during storage [13]. However, that study did not establish how the capsules behave in a concentrated curd-based matrix or how different incorporation levels affect the combined quality characteristics of cottage cheese spread.

Cottage cheese spread is structurally different from kefir-type fermented milk. It is a dense, semi-solid protein–fat matrix with limited flow, relatively high resistance to deformation, and a tendency toward moisture redistribution and syneresis. In this matrix, capsules may act as dispersed particles that affect mixing, distribution, mechanical integrity, rheological behavior, water retention, color, mouthfeel, and sensory perception. These

matrix-specific effects may differ substantially from those observed in a fluid fermented milk beverage and therefore require separate evaluation in cottage cheese spread. Although curd cheeses enriched with plant-derived ingredients have been studied [14,15], the concentration-dependent behavior of alginate–pullulan capsules and their integrity during the production and refrigerated storage of cottage cheese spread remain insufficiently characterized.

Therefore, the present study investigated the incorporation of alginate–pullulan capsules containing herbal bioactives into cottage cheese spread. The novelty of the study is the comprehensive assessment of capsule behavior and concentration-dependent quality changes in a dense curd matrix, including capsule integrity during processing and storage, rheological properties, syneresis, water-holding capacity, sensory acceptability, bioactive-compound content, and microbiological quality. The study aimed to select a technologically suitable incorporation level that increased the bioactive content while maintaining the quality and acceptability of the cottage cheese spread.

2. Materials and Methods

2.1. Materials

The plant raw materials used for the encapsulated dietary supplements were echinacea (*Echinacea purpurea*), leuzea (*Rhaponticum carthamoides*), and rosehip (*Rosa canina*). These plants were collected from the Abai and East Kazakhstan regions of the Republic of Kazakhstan and served as the botanical sources of bioactive compounds.

Food-grade sodium alginate ($C_6H_7O_6Na$)_n, amidated pectin, and calcium chloride ($CaCl_2$) were supplied by KazKhimBaza LLP (Almaty, Kazakhstan). These materials were used to form and stabilize the capsule matrix. Pullulan (CAS 9057-02-7), obtained from Qingdao Kenco Co., Ltd. (Qingdao, China), was used as an additional coating material. The resulting plant-extract-loaded capsules were incorporated into the cottage cheese spread as the functional ingredient.

Raw cow's milk used for cottage cheese production was obtained from Peasant Farm "Kalikhanuly", located in Semey, Kazakhstan. The raw cow's milk used for cottage cheese production had a density of 1030.0 kg/m³, titratable acidity of 18.2 °T, dry matter content of 10.4%, fat content of 3.14%, protein content of 3.98%, and somatic cell count of 285 thousand cells/cm³. These values confirmed that the milk was suitable for processing into cottage cheese.

A starter culture of mesophilic lactic acid streptococci used for milk fermentation was obtained from Barnaul Biofactory LLC (Barnaul, Russia).

2.2. Capsule Production

The herbal tincture was prepared according to the previously reported procedure [13]. The aerial parts of *Echinacea purpurea*, roots of *Levzeyya officinalis*, and fruits of *Rosa canina* were air-dried to constant weight at ambient temperature, protected from direct sunlight, and milled to a particle size of 3–5 mm. Equal amounts of the three plant materials (100 g each; 300 g in total) were thoroughly mixed. The plant mixture was placed in a stainless-steel mesh basket inside a jacketed percolator, and 35% (v/v) aqueous ethanol was added at a total plant material-to-solvent ratio of 1:5 (w/w).

The mixture was maintained under closed conditions at 20–30 °C for 12 h for initial maceration. It was then continuously agitated for 1 h while the temperature was increased stepwise to 50–70 °C, followed by a further infusion period of 12–24 h. A volume of extract equivalent to the initial plant-material charge was collected. Fresh 35% aqueous ethanol was subsequently added to the remaining plant material at a 1:1 ratio, and a second extraction was performed for 12 h with intermittent mixing. The obtained fractions were

combined and clarified by settling at 5–8 °C for five days. The tincture was then filtered through a cotton–gauze filter and stored in amber glass bottles until encapsulation.

Capsules were produced using the previously developed jet-cutter ionic-gelation process [13]. The clarified tincture was mixed with a 1% (*w/w*) sodium alginate solution at a 1:1 mass ratio to obtain a homogeneous alginate–bioactive feed solution. Approximately 50 mL of the feed solution was processed during each encapsulation run. The mixture was delivered by a peristaltic pump at 5 mL/min to a rotating stainless-steel disc with a diameter of 4 cm operating at 2000 rpm. The generated droplets were dispersed into a circulating 0.15 M CaCl₂ solution maintained at 22 ± 2 °C. The capsules were retained in the CaCl₂ bath for 30 min to complete gelation and strengthen their structure and were then separated using a conical perforated separator with a pore size of 0.5 mm.

For secondary coating, the gelled capsules were immersed in a 5% (*w/w*) pullulan solution at 35–40 °C and gently stirred for 20–25 min. The coated capsules were filtered and dried in a convection oven at 30–50 °C until a uniform, non-tacky surface was obtained. They were stored at 2–6 °C before incorporation into the cottage cheese spread. The resulting capsules were approximately spherical and had an average diameter of 1.00 ± 0.05 mm.

2.3. Production of Cottage Cheese Spread with Encapsulated Dietary Supplements

To evaluate the effect of encapsulated dietary supplement concentration, six cottage cheese spread formulations were prepared: a control sample without capsules (C0) and five experimental samples containing 1–5% capsules (C1–C5). The amount of cottage cheese was adjusted to maintain a constant final product mass of 1000 g, while sugar and vanillin contents were kept constant (Table 1).

Table 1. Formulation of cottage cheese spread samples with different concentrations of encapsulated dietary supplements.

Ingredient	Control Sample		Experimental Samples			
	C0, 0%	C1, 1%	C2, 2%	C3, 3%	C4, 4%	C5, 5%
Cottage cheese, 9% fat, g	899	889	879	869	859	849
Granulated sugar, g	100	100	100	100	100	100
Vanillin, g	1	1	1	1	1	1
Encapsulated dietary supplements, g	0	10	20	30	40	50
Total, g	1000	1000	1000	1000	1000	1000

The production process included two main stages: preparation of cottage cheese and preparation of the cottage cheese spread. Raw milk was accepted for processing only when it met the specified quality criteria, with acidity not exceeding 20 °T. The milk was cleaned using a milk separator-clarifier, pasteurized at 80 ± 2 °C for 15–20 s, and cooled to 4 ± 2 °C. The milk mixture was normalized by fat content and homogenized at 15.0 ± 2.5 MPa and 60 ± 5 °C. The mixture was then pasteurized again at 80 ± 2 °C for 20 s and cooled to the fermentation temperature of 30 ± 2 °C.

A starter culture of mesophilic lactic acid streptococci was added, and fermentation was carried out at 30 ± 2 °C for 8–10 h until a firm curd formed and the pH reached ≤4.69. After fermentation, the curd was processed to promote whey expulsion, after which the whey was separated. The curd mass was then subjected to self-pressing and mechanical pressing until the target moisture content for 9% fat cottage cheese was reached. The obtained cottage cheese was immediately cooled to 3–8 °C to stop further lactic acid fermentation.

For cottage cheese spread production, the cooled cottage cheese was ground and transferred to a mixing machine. Sugar was sieved before use, and vanillin was premixed

with part of the sugar to ensure uniform distribution. Mixing was performed at a cottage cheese temperature not higher than 15 °C until a homogeneous consistency was obtained. The encapsulated dietary supplements were added during the final stage of mixing and distributed by gentle low-shear folding for 0.5–1.5 min to minimize mechanical damage to the capsules. High-speed mixing and homogenization were not used after capsule addition. The finished cottage cheese spread was cooled to a temperature not higher than 6 °C, packed, labelled, and stored at 4 ± 2 °C until further analysis.

The products were initially stored in sealed containers at 4 ± 2 °C. On day 1, each container was opened for sensory evaluation and analytical sampling. After the required portion had been removed, the remaining product was immediately reclosed and returned to refrigerated storage. The same container was reopened and sampled on each subsequent day for seven days. Thus, the experiment simulated refrigerated storage after opening with repeated daily use.

2.4. Determination of Physicochemical Acidity Parameters

The pH of the cottage cheese spread was determined by the potentiometric method according to GOST 32892-2014 [16]. Before analysis, the pH meter was calibrated using standard buffer solutions with known pH values. The samples were thoroughly homogenized to obtain a uniform matrix, after which the electrode was immersed directly into the sample. Measurements were performed at a controlled temperature, and the electrode was rinsed with distilled water between measurements to avoid cross-contamination. The pH value was recorded after stabilization of the instrument reading. Each sample was analyzed in triplicate.

Titrateable acidity was determined by titration according to GOST 3624-92 [17]. A measured amount of cottage cheese spread was mixed with distilled water to obtain a uniform suspension. Phenolphthalein solution was used as an endpoint indicator. The sample was titrated with 0.1 N sodium hydroxide solution until a stable pale-pink color appeared and remained for at least 1 min. Titrateable acidity was expressed in Turner degrees (°T), which indicates the amount of alkali required to neutralize the acids in the product. Measurements were performed in triplicate.

2.5. Determination of Water Activity, Moisture, and Dry Matter

Water activity (a_w) was measured using an aWLife analyzer (Steroglass S.r.l., Perugia, Italy). Before analysis, the instrument was prepared and calibrated according to the manufacturer's instructions using reference standards. A representative portion of the sample was placed in the measuring cup without leaving air gaps or contaminating the rim. The cup was placed in the measuring chamber, and the analysis was started after temperature equilibration. Measurements were performed at 25 °C. The final a_w value was recorded after the instrument reached equilibrium.

Moisture and dry matter contents were determined by the gravimetric drying method according to GOST 3626-73 [18]. A homogenized sample of cottage cheese spread was weighed into a pre-dried and pre-weighed container. The sample was dried in a drying oven at 102 ± 2 °C until constant mass. After drying, the container was cooled in a desiccator and weighed again. Moisture content was calculated from the mass loss during drying and expressed as a percentage of the initial sample mass. Dry matter content was calculated from the mass of the residue remaining after drying and expressed as a percentage of the initial sample mass. The obtained values were used to characterize the water content and concentration of non-volatile solids in the cottage cheese matrix.

2.6. Determination of Syneresis and Water-Holding Capacity

Syneresis was determined by measuring the amount of whey released from the cottage cheese mass. A weighed portion of sample was placed in a pre-weighed container and stored at 4 ± 2 °C for the specified storage period without mechanical disturbance. The released whey was then separated and weighed, and syneresis was expressed as the percentage of whey released relative to the initial sample mass. This indicator was used to evaluate the structural stability of the protein matrix and its tendency to release serum during storage [19].

Water-holding capacity was determined by centrifugation. Approximately 20 g of sample was weighed and centrifuged at 3000 rpm for 10 min at 20 °C. After centrifugation, the separated whey was carefully removed and weighed. Water-holding capacity was calculated from the amount of water retained in the curd matrix relative to the initial sample mass. This method reflects the ability of the cottage cheese structure to bind and retain moisture [20].

2.7. Determination of Nutritional Composition and Energy Value

Protein content was determined by the Kjeldahl method according to GOST 34454-2018 [21]. The sample was digested with concentrated sulfuric acid in the presence of catalysts to convert organic nitrogen into ammonium sulfate. After digestion, the mixture was alkalized, and released ammonia was distilled into boric acid solution. The absorbed ammonia was titrated with standardized acid. Total nitrogen was calculated from titration data, and protein content was obtained using the appropriate nitrogen-to-protein conversion factor for dairy products.

Fat content was determined by the acid butyrometric method according to GOST 5867-2023 [22]. The sample was treated with concentrated sulfuric acid to dissolve proteins and release fat. Isoamyl alcohol was added to improve separation of the fat phase. The mixture was centrifuged in a calibrated butyrometer and thermostated. The separated fat layer was read directly from the butyrometer scale and expressed as g/100 g of product.

Ash content was determined by dry mineralization according to AOAC Official Method 935.42 [23]. A weighed sample was placed into a pre-dried and pre-weighed porcelain crucible. The sample was incinerated in a muffle furnace at approximately 550 °C until a light grey or white ash residue was obtained. The crucible was cooled in a desiccator and weighed. Ash content was calculated from the mass of the mineral residue and expressed as g/100 g of product.

Carbohydrate content was calculated by difference according to the FAO procedure [24]. The measured contents of moisture, protein, fat, and ash were subtracted from 100. The calculation was performed using the following equation:

$$\text{Carbohydrates} = 100 - (\text{moisture} + \text{protein} + \text{fat} + \text{ash}).$$

The result was expressed as g/100 g of product.

The energy value was estimated using the general Atwater conversion factors of 4 kcal/g for protein, 9 kcal/g for fat, and 4 kcal/g for carbohydrates [24]:

$$\text{Energy value} = \text{protein} \times 4 + \text{fat} \times 9 + \text{carbohydrates} \times 4.$$

2.8. Determination of Bioactive Compounds

Vitamin C was determined according to GOST 30627.2-98 [25]. The sample was extracted with metaphosphoric acid solution to stabilize ascorbic acid and prevent oxidation. The extract was filtered, and an aliquot was titrated with standardized 2,6-dichlorophenolindophenol solution until a persistent light-pink color appeared. A blank

determination was performed in parallel. Vitamin C content was calculated from the titrant volume and expressed as mg/100 g of product.

Total polyphenols were determined using the Folin–Ciocalteu spectrophotometric method adapted from GOST R 55488-2013 [26]. A representative portion of each homogenized cottage cheese spread sample was extracted with 70% aqueous ethanol and filtered. Gallic acid working solutions of 0.05, 0.10, 0.15, 0.25, and 0.50 mg/mL were used to construct the calibration curve. For color development, 1 mL of each standard solution or appropriately diluted sample extract was mixed with 10 mL of distilled water, 4 mL of Folin–Ciocalteu reagent, and 6 mL of 20% sodium carbonate solution. The mixture was diluted to 50 mL with distilled water and kept for 2 h before measurement. Absorbance was measured at 765 nm against the reagent blank. The calibration relationship was expressed as:

$$A = aC + b,$$

where A is absorbance and C is the gallic acid concentration. The calibration curve was linear over the investigated concentration range ($R^2 = 0.992$). Results were expressed as mg gallic acid equivalents (GAE) per 100 g of product.

Total flavonoids were determined by the aluminum chloride spectrophotometric method adapted from GOST R 55312-2012 [27]. A 1.000 g portion of the homogenized sample was extracted with 30 mL of 60% ethanol under reflux in a boiling water bath for 30 min. The supernatant was filtered, and the extraction was repeated twice under the same conditions. The combined extracts were cooled to 20 °C and diluted to 100 mL with 60% ethanol.

A 5.00 mL aliquot of the extract was transferred into each of two 25 mL volumetric flasks. Four millilitres of 5% aluminum chloride solution in 60% ethanol were added to one flask, while the second flask, containing no aluminum chloride, served as the sample-specific comparison solution. Both solutions were diluted to 25 mL with 60% ethanol. After 30 min, absorbance was measured against the comparison solution in a 1 cm cuvette at the absorption maximum within 390–420 nm using a UV–Vis spectrophotometer.

The calibration curve was prepared using 0.20, 0.40, 0.60, 0.80, 1.00, and 1.20 mg of rutin in 25 mL of final solution, corresponding to 0.008–0.048 mg/mL. The calibration relationship was expressed as:

$$A = kM,$$

where A is absorbance and M is the amount of rutin in the 25 mL solution. The calibration curve was linear and passed through the origin ($R^2 = 0.994$). Two parallel determinations were performed. Results were expressed as milligrams of rutin equivalents per 100 g of product (mg RE/100 g).

Tanning substances and tannins were determined by titrimetric analysis according to GOST 19885-74 [28]. The sample was extracted with hot water, cooled, filtered, and an aliquot was mixed with indigosulfonic acid solution. The mixture was titrated with 0.02 M potassium permanganate until a faint yellow endpoint persisted. A blank test was carried out under the same conditions. Tannin content was calculated from the difference between sample and blank titration volumes and expressed as mg/100 g of product.

2.9. Antioxidant Activity Analysis Methods

DPPH radical-scavenging activity was determined according to Brand-Williams et al. with modifications [29]. A finely homogenized sample was extracted with 80% ethanol in the dark. The extract was centrifuged or filtered, and the supernatant was used for analysis. An aliquot of the extract was mixed with DPPH solution and incubated for 30 min at

room temperature in the dark. Absorbance was measured at 517 nm. Antioxidant activity was calculated as the percentage inhibition of DPPH radicals relative to the control.

The ABTS solution was prepared by reacting 7 mM ABTS with 2.45 mM potassium persulfate and keeping the mixture in the dark at room temperature for 12–16 h. Before analysis, the solution was diluted with 0.1 M phosphate-buffered saline (pH 7.4) to an absorbance of 0.70 ± 0.02 at 734 nm. A water-soluble extract of each sample was mixed with the diluted ABTS solution and incubated at 30 °C for 6 min. The decrease in absorbance was measured at 734 nm. ABTS radical-scavenging activity was expressed as inhibition percentage using the following equation:

$$ABTS \text{ inhibition (\%)} = [(A_0 - A_s)/A_0] \times 100;$$

where A_0 —the absorbance of the ABTS control;

A_s —the absorbance of the sample reaction mixture. All measurements were performed in triplicate [30].

2.10. Determination of Color Characteristics of Cottage Cheese Spread

Color parameters were determined using a Chroma Meter CR-400 (Konica Minolta, Japan), calibrated with a standard white plate before measurement. The procedure followed the recommendations for instrumental color assessment of dairy products described by Milovanovic et al. [31] and the approach reported by Luna Flores et al. [32]. Results were expressed in the CIE $L^*a^*b^*$ color space, where L^* represents lightness, a^* represents the red–green coordinate, and b^* represents the yellow–blue coordinate.

The total color difference between each enriched formulation and the control was calculated using the equation

$$\Delta E_{ab}^* = \sqrt{(L_i^* - L_0^*)^2 + (a_i^* - a_0^*)^2 + (b_i^* - b_0^*)^2}$$

where L_i^* , a_i^* , and b_i^* are the mean color coordinates of the enriched formulation and L_0^* , a_0^* , and b_0^* are those of the control. Values of $\Delta E_{ab}^* > 3$ were interpreted as indicating a color difference perceptible to the human eye [32].

2.11. Viscosity Measurement

Apparent viscosity was determined using a Brookfield RVT rotational viscometer. Before measurement, samples were equilibrated at 20 ± 1 °C. Measurements were performed at spindle rotation speeds of 2.5, 5, 10, 20, and 50 rpm. The spindle was immersed into the sample without air bubbles, and readings were recorded after stabilization. Results were expressed in mPa·s. This method was used to evaluate the effect of encapsulated additives on the flow behavior and consistency of the cottage cheese spread.

2.12. Microscopic Examination of Capsules

The microstructure and geometric characteristics of the capsules were examined by scanning electron microscopy according to the method described in [33].

2.13. Organoleptic Evaluation

Organoleptic evaluation was carried out by a trained panel of 11 assessors from the Food Safety Laboratory of Shakarim University. The assessors had prior experience in the sensory evaluation of dairy products and were additionally instructed before testing on the evaluation scale, sample attributes, and scoring criteria. The samples were assessed using a five-point scale for appearance, color, odor, taste, consistency, and whey separation. A score of 5 indicated excellent quality, while lower scores reflected the presence of defects or reduced acceptability.

The evaluation was performed in the Food Safety Laboratory under controlled conditions. The room was clean, well ventilated, free from foreign odors, and provided sufficient lighting for visual assessment. Samples were presented under identical conditions and evaluated individually. Assessors were seated separately to avoid discussion and mutual influence during scoring. Mean values were calculated for each attribute and used to determine the most acceptable concentration of encapsulated additives [34].

2.14. Microbiological and Safety Analyses

Microbiological analysis included enumeration of lactic acid microorganisms, yeasts, and molds. Serial dilutions of the samples were prepared under aseptic conditions and plated on appropriate nutrient media. After incubation, colonies were counted and expressed as CFU/g; lactic acid microorganisms were also expressed as log₁₀ CFU/g. Yeasts and molds were determined according to GOST 33566-2015 [35]. Additional microbiological safety indicators included coliforms according to GOST 32901-2014 [36], *Salmonella* according to GOST 31659-2012 [37], and *Staphylococcus aureus* according to GOST 30347-2016 [38]. The safety indicators of the finished cottage cheese spread, including toxic elements, aflatoxin M1, chloramphenicol, organochlorine pesticides, and radionuclides, were analyzed according to the procedures described in [39].

2.15. Statistical Analysis

Each cottage cheese spread formulation was produced in three independent batches. For each batch, separate packages were prepared, including packages assigned to each storage day. Analytical measurements were performed in triplicate, and technical replicate values were averaged before statistical analysis. Results are presented as mean $\pm$ standard deviation (SD), with the production batch considered the experimental replicate.

Statistical analysis was performed using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA). One-way ANOVA was used to compare formulation variants on the day of production. For storage data, two-way ANOVA was applied to evaluate the effects of formulation, storage time, and their interaction. Tukey's HSD test was used for post hoc comparisons, and differences were considered significant at $p \leq 0.05$.

3. Results

3.1. Characterization of Encapsulated Bioactive Additives Before Incorporation into Cottage Cheese Spread

Before incorporation into the cottage cheese spread, the capsules showed uniform dimensional and structural characteristics. The average capsule diameter was 1.00 mm, with an aspect ratio of 1.08, indicating a near-spherical shape. The mass of 100 capsules was 0.55 g. Capsule moisture content was 80.0%, and water activity was 0.970. Capsule integrity remained high, ranging from 98 to 100%. The capsules contained measurable levels of bioactive compounds, including vitamin C at 33.25 mg/100 g, polyphenols at 0.225%, flavonoids at 0.150%, tanning substances at 0.105%, and tannins at 0.038%. Microbiological evaluation showed low yeast and mold counts, both below 10 CFU/g, while coliform bacteria were not detected (Table 2). Overall, the encapsulated additives were characterized by a uniform shape, preserved capsule integrity, bioactive compound content, and acceptable microbiological quality before addition to the cottage cheese spread.

Table 2. Characteristics of dietary supplement capsules before being added to the cottage cheese spread.

Parameter	Mean $\pm$ SD
Capsule diameter, mm	1.00 $\pm$ 0.05
Sphericity/aspect ratio	1.08 $\pm$ 0.03
Mass of 100 capsules, g	0.55 $\pm$ 0.05
Capsule Moisture Content, %	80.0 $\pm$ 2.0
Water Activity, aw	0.970 $\pm$ 0.022
Capsule Integrity, %	98–100
Vitamin C, mg/100 g	33.25 $\pm$ 0.54
Polyphenols, %	0.225 $\pm$ 0.003
Flavonoids, %	0.150 $\pm$ 0.002
Tanning substances, %	0.105 $\pm$ 0.001
Tannins, %	0.038 $\pm$ 0.0005
Yeast, CFU/g	<10
Molds, CFU/g	<10
Coliform bacteria	Not detected

3.2. Physicochemical Characteristics and Nutritional Composition of Cottage Cheese Spread

On the day of production, pH, titratable acidity, water activity, and the main nutritional components showed only minor variation among the control and experimental samples (Table 3). The pH ranged from 4.64 to 4.65, titratable acidity from 170 to 171 °T, and water activity remained at approximately 0.98. Protein content ranged from 13.83 to 14.19 g/100 g, fat from 8.90 to 9.00 g/100 g, carbohydrates from 11.60 to 12.00 g/100 g, moisture from 64.20 to 64.50 g/100 g, and caloric value from 182 to 184 kcal/100 g. No significant differences were observed among samples for these indicators ($p > 0.05$).

Table 3. Physicochemical, structural, and nutritional characteristics of the cottage cheese spread on the day of production.

Parameter	C0-Control	C1	C2	C3	C4	C5
pH	4.65 $\pm$ 0.11 ^a	4.65 $\pm$ 0.12 ^a	4.65 $\pm$ 0.15 ^a	4.65 $\pm$ 0.13 ^a	4.64 $\pm$ 0.11 ^a	4.64 $\pm$ 0.13 ^a
Titratable acidity, °T	171.00 $\pm$ 4.90 ^a	171.00 $\pm$ 4.45 ^a	171.00 $\pm$ 4.60 ^a	171.00 $\pm$ 5.48 ^a	171.00 $\pm$ 4.90 ^a	170.00 $\pm$ 4.97 ^a
Water activity, aw	0.98 $\pm$ 0.03 ^a	0.98 $\pm$ 0.03 ^a	0.98 $\pm$ 0.03 ^a	0.98 $\pm$ 0.03 ^a	0.98 $\pm$ 0.02 ^a	0.98 $\pm$ 0.02 ^a
Syneresis, %	8.50 $\pm$ 0.26 ^e	8.20 $\pm$ 0.24 ^{de}	7.90 $\pm$ 0.24 ^d	7.50 $\pm$ 0.20 ^c	7.20 $\pm$ 0.21 ^b	6.90 $\pm$ 0.18 ^a
Water-holding capacity, %	51.50 $\pm$ 1.31 ^a	52.00 $\pm$ 1.48 ^a	52.50 $\pm$ 1.43 ^{ab}	53.10 $\pm$ 1.57 ^{ab}	53.60 $\pm$ 1.66 ^b	54.20 $\pm$ 1.34 ^b
Protein, g/100 g	14.12 $\pm$ 0.35 ^a	14.19 $\pm$ 0.37 ^a	14.07 $\pm$ 0.45 ^a	14.07 $\pm$ 0.39 ^a	13.94 $\pm$ 0.33 ^a	13.83 $\pm$ 0.39 ^a
Fat, g/100 g	9.00 $\pm$ 0.26 ^a	9.00 $\pm$ 0.23 ^a	9.00 $\pm$ 0.24 ^a	9.00 $\pm$ 0.29 ^a	8.90 $\pm$ 0.26 ^a	8.90 $\pm$ 0.26 ^a
Carbohydrates, g/100 g	11.60 $\pm$ 0.35 ^a	11.70 $\pm$ 0.33 ^a	11.80 $\pm$ 0.31 ^a	11.80 $\pm$ 0.37 ^a	11.90 $\pm$ 0.36 ^a	12.00 $\pm$ 0.33 ^a
Ash, g/100 g	0.80 $\pm$ 0.03 ^a	0.80 $\pm$ 0.02 ^a	0.90 $\pm$ 0.03 ^b	0.90 $\pm$ 0.02 ^b	1.00 $\pm$ 0.02 ^c	1.00 $\pm$ 0.03 ^c
Moisture, g/100 g	64.50 $\pm$ 1.78 ^a	64.40 $\pm$ 1.77 ^a	64.30 $\pm$ 1.94 ^a	64.30 $\pm$ 1.85 ^a	64.30 $\pm$ 1.54 ^a	64.20 $\pm$ 1.53 ^a
Caloric value, kcal/100 g	184.00 $\pm$ 5.68 ^a	184.00 $\pm$ 5.38 ^a	184.00 $\pm$ 5.52 ^a	182.00 $\pm$ 4.73 ^a	183.00 $\pm$ 5.23 ^a	183.00 $\pm$ 4.70 ^a

^{a–e} Different lowercase letters indicate significant differences between samples within the same row ($p < 0.05$).

Ash content increased with the concentration of encapsulated additives. It was 0.80 g/100 g in C0 and C1, 0.90 g/100 g in C2 and C3, and 1.00 g/100 g in C4 and C5. These differences were statistically significant among the three sample groups ($p < 0.05$).

The most pronounced changes were observed in syneresis and water-holding capacity. Syneresis decreased progressively from 8.5% in the control sample to 6.9% in C5, with significant reductions from C2 onward ($p < 0.05$). Water-holding capacity increased

from 51.5% in the control to 54.2% in C5, with the highest values observed in C4 and C5 ($p < 0.05$). Overall, the incorporation of encapsulated additives did not significantly affect acidity, water activity, or basic nutritional composition, but improved structural water retention.

3.3. Content of Bioactive Compounds and Antioxidant Activity in Cottage Cheese Spread

The incorporation of encapsulated additives led to a dose-dependent increase in bioactive compounds in the cottage cheese spread (Table 4). Vitamin C, polyphenols, flavonoids, tanning substances, and tannins were not detected in the control sample, whereas their concentrations increased progressively from C1 to C5. Vitamin C increased from 0.30 mg/100 g in C1 to 1.50 mg/100 g in C5, polyphenols from 2.20 to 10.95 mg/100 g, flavonoids from 1.45 to 7.59 mg/100 g, tanning substances from 1.02 to 5.07 mg/100 g, and tannins from 0.37 to 1.88 mg/100 g. For these bioactive compounds, all experimental samples differed significantly from each other and from the control ($p < 0.05$). Antioxidant activity also increased with the concentration of encapsulated additives. DPPH radical-scavenging activity increased from 4.50% in the control sample to 6.76% in C5. Significant increases were observed from C1 to C4 compared with the preceding lower-dose samples ($p < 0.05$), while C4 and C5 did not differ significantly from each other for this indicator. ABTS radical-scavenging activity increased from 14.29% in the control to 21.43% in C5. The ABTS values increased significantly from C0 to C3 and reached the highest value in C5 ($p < 0.05$), while C3 and C4 were not significantly different from each other. These data indicate that higher concentrations of encapsulated additives increased both the bioactive compound content and antioxidant activity of the cottage cheese spread.

Table 4. Content of bioactive compounds and antioxidant activity of the cottage cheese spread.

Sample	C0-Control	C1	C2	C3	C4	C5
Vitamin C, mg/100 g	nd	0.30 ± 0.01 ^b	0.61 ± 0.02 ^c	0.95 ± 0.03 ^d	1.22 ± 0.03 ^e	1.50 ± 0.04 ^f
Polyphenols, mg/100 g	nd	2.20 ± 0.06 ^b	4.37 ± 0.12 ^c	6.97 ± 0.22 ^d	8.96 ± 0.26 ^e	10.95 ± 0.33 ^f
Flavonoids, mg/100 g	nd	1.45 ± 0.04 ^b	2.91 ± 0.08 ^c	4.63 ± 0.14 ^d	6.22 ± 0.18 ^e	7.59 ± 0.21 ^f
Tanning substances, mg/100 g	nd	1.02 ± 0.03 ^b	2.14 ± 0.06 ^c	3.21 ± 0.09 ^d	4.14 ± 0.10 ^e	5.07 ± 0.15 ^f
Tannin, mg/100 g of product	nd	0.37 ± 0.01 ^b	0.74 ± 0.02 ^c	1.18 ± 0.03 ^d	1.54 ± 0.04 ^e	1.88 ± 0.05 ^f
DPPH antioxidant activity, %	4.50 ± 0.14 ^a	4.85 ± 0.15 ^b	5.31 ± 0.16 ^c	6.17 ± 0.16 ^d	6.41 ± 0.19 ^e	6.76 ± 0.18 ^e
ABTS antioxidant activity, %	14.29 ± 0.24 ^a	15.17 ± 0.27 ^b	17.02 ± 0.32 ^c	19.07 ± 0.48 ^d	19.71 ± 0.42 ^d	21.43 ± 0.51 ^e

^{a–f} Different lowercase letters indicate significant differences between samples ($p < 0.05$). nd—not detected.

3.4. Color Characteristics of Cottage Cheese Spread

The addition of encapsulated additives changed the instrumental color parameters of the cottage cheese spread (Table 5). Lightness (L^*) gradually decreased from 92.8 in the control sample to 88.6 in C5. The decrease became significant in C4 and C5 compared with the control, indicating a darker color at higher additive concentrations ($p < 0.05$). The red–green coordinate (a^*) showed the most pronounced change. It increased from −1.1 in the control sample to 3.6 in C5, reflecting a shift from a slightly greenish tone toward a stronger red component. All experimental samples differed significantly from the control and from each other for this parameter ($p < 0.05$). The yellow–blue coordinate (b^*) also increased with additive concentration, from 8.6 in the control to 10.2 in C5. Significant increases were observed from C2 onward compared with the control ($p < 0.05$). Overall, higher concentrations of encapsulated additives reduced lightness and increased both red and yellow color components, confirming a gradual color shift in the product.

Table 5. Color characteristics of the cottage cheese spread.

Sample	L^*	a^*	b^*	ΔE_{ab}^*	Visual Characteristics of Color
C0-control	92.80 ± 2.29^b	-1.10 ± 0.03^a	8.60 ± 0.26^a	0	Milky white, uniform
C1	91.90 ± 2.39^b	1.10 ± 0.03^b	8.90 ± 0.25^a	2.4	White, with isolated red dots
C2	91.10 ± 2.91^{ab}	1.70 ± 0.05^c	9.20 ± 0.24^b	3.3	White to cream-white, with occasional red spots
C3	90.20 ± 2.47^{ab}	2.30 ± 0.07^d	9.50 ± 0.30^{bc}	4.4	Cream-white, with visible red spots
C4	89.40 ± 2.13^a	2.90 ± 0.08^e	9.80 ± 0.30^c	5.4	Cream-white, with noticeable red inclusions
C5	88.60 ± 2.48^a	3.60 ± 0.11^f	10.20 ± 0.28^d	6.5	Cream-white, with numerous distinct red inclusions

^{a–f} Different lowercase letters indicate significant differences between samples ($p < 0.05$).

3.5. Viscosity of Cottage Cheese Spread at Different Spindle Rotation Speeds

Viscosity decreased in all samples as spindle rotation speed increased, showing a consistent reduction in apparent viscosity under higher shear (Figure 1). In the control sample, viscosity declined from 3615 at 2.5 rpm to 1913 at 50 rpm, and the same pattern was observed in all experimental variants. At each spindle speed, viscosity increased with the concentration of encapsulated additives. The lowest values were recorded in the control sample, while C5 showed the highest viscosity at all tested speeds. At 2.5 rpm, viscosity increased from 3615 in the control to 5254 in C5; at 50 rpm, it increased from 1913 to 2864. All experimental samples differed significantly from the control at each spindle speed ($p < 0.05$). Overall, the results show two clear trends: increasing shear reduced apparent viscosity, while increasing the concentration of encapsulated additives increased the viscosity of the cottage cheese spread.

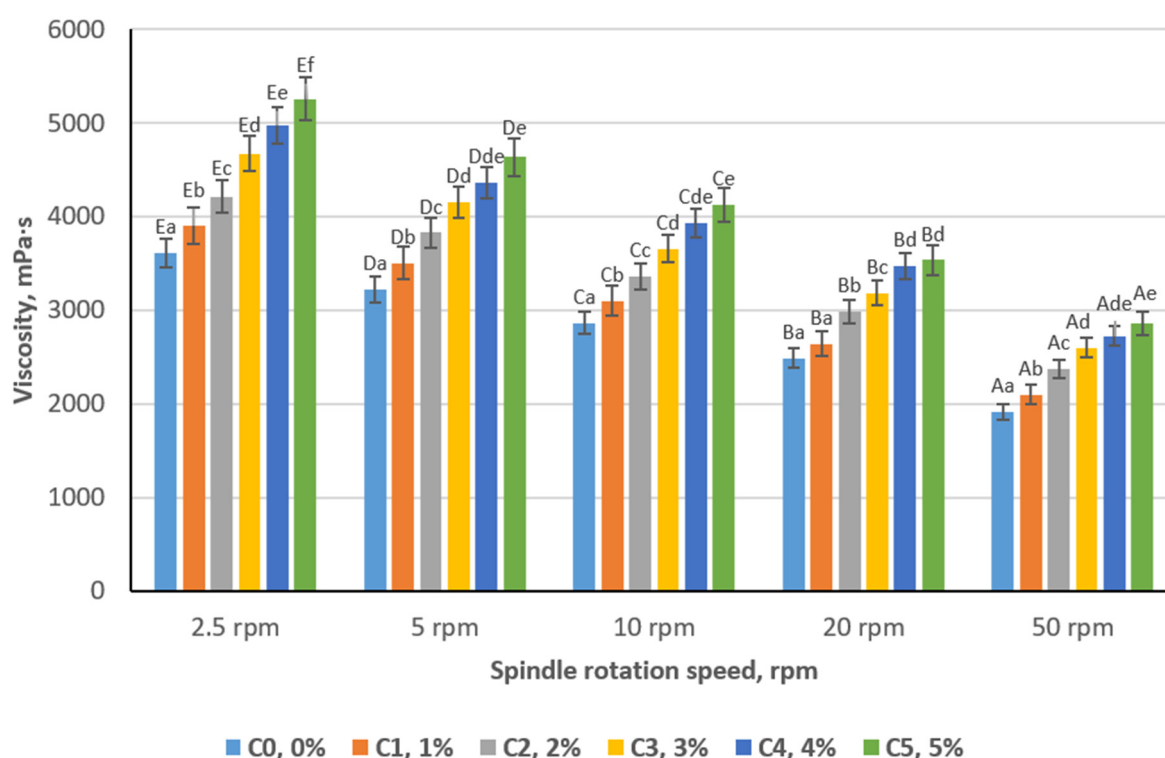


Figure 1. Viscosity of cottage cheese spread samples with different concentrations of encapsulated additives at different spindle rotation speeds. ^{a–f} Different lowercase letters indicate significant differences between samples within the same spindle rotation speed ($p < 0.05$). ^{A–E} Different uppercase letters indicate significant differences within the same sample at different spindle rotation speeds ($p < 0.05$).

3.6. Integrity and Distribution of Capsules in Cottage Cheese Spread After Mixing

After mixing, the capsules remained largely intact in all experimental samples. The proportion of intact capsules ranged from 98.5% in C5 to 99.5% in C1, while the average capsule diameter remained unchanged at 1.00 mm across all variants (Table 6). Capsule distribution was uniform in C1–C4, with C3 showing the most uniform distribution in the cottage cheese matrix. In C1 and C2, only single inclusions were observed. In C4, visible inclusions became more noticeable, while C5 showed a less uniform distribution with more apparent capsule inclusions. The proportion of capsules with minor defects increased slightly with higher additive concentration, from 0.5% in C1 to 1.5% in C5. Overall, the mixing process preserved capsule integrity, although higher capsule concentrations increased the visibility of inclusions and the number of minor mechanical defects.

Table 6. Quantitative characteristics of capsule integrity and distribution in samples after mixing.

Variant	Distribution of Capsules in the Mass	Intact Capsules, %	Capsules with Minor Defects, %	Average Diameter After Mixing, mm
C1	uniform, single inclusions	99.5	0.5	1.00 ± 0.05
C2	uniform	99.3	0.7	1.00 ± 0.05
C3	uniform, optimal	99.5	0.5	1.00 ± 0.05
C4	uniform, noticeable inclusions	98.8	1.2	1.00 ± 0.05
C5	less uniform, with apparent inclusions	98.5	1.5	1.00 ± 0.05

3.7. Sensory Profile of Cottage Cheese Spread Samples

Sensory evaluation showed that samples C0–C3 had high acceptability scores and did not differ significantly in average score ($p > 0.05$; Table 7). The average score ranged from 4.6 to 4.8 points in these samples, indicating that the incorporation of encapsulated additives up to 3% did not significantly reduce the overall sensory quality of the cottage cheese spread.

Table 7. Sensory profile of cottage cheese spread samples with different concentrations of encapsulated additives.

Parameter	C0, 0%	C1, 1%	C2, 2%	C3, 3%	C4, 4%	C5, 5%
Appearance	4.8 ± 0.1 ^c	4.8 ± 0.1 ^c	4.8 ± 0.1 ^c	4.8 ± 0.1 ^c	4.1 ± 0.1 ^b	3.7 ± 0.1 ^a
Color	4.9 ± 0.1 ^b	4.8 ± 0.1 ^b	4.8 ± 0.1 ^b	4.9 ± 0.1 ^b	4 ± 0.1 ^a	4 ± 0.1 ^a
Odor	4.8 ± 0.1 ^a	4.8 ± 0.1 ^a	4.7 ± 0.1 ^a	4.8 ± 0.1 ^a	4.5 ± 0.1 ^a	4.5 ± 0.1 ^a
Taste	4.7 ± 0.1 ^c	4.7 ± 0.1 ^c	4.6 ± 0.1 ^c	4.6 ± 0.1 ^c	4.0 ± 0.1 ^b	3.6 ± 0.1 ^a
Consistency	4.7 ± 0.1 ^c	4.7 ± 0.1 ^c	4.6 ± 0.1 ^c	4.6 ± 0.1 ^c	4.1 ± 0.1 ^b	3.3 ± 0.1 ^a
Feeling of the capsules in the mouth	5.0 ± 0.1 ^d	4.8 ± 0.1 ^{cd}	4.7 ± 0.1 ^{cd}	4.6 ± 0.1 ^c	3.7 ± 0.1 ^b	3.2 ± 0.1 ^a
Sweetness	4.7 ± 0.1 ^b	4.7 ± 0.1 ^b	4.6 ± 0.1 ^b	4.6 ± 0.1 ^b	4.3 ± 0.1 ^a	4.1 ± 0.1 ^a
Sour milk flavor	4.8 ± 0.1 ^c	4.8 ± 0.1 ^c	4.7 ± 0.1 ^c	4.7 ± 0.1 ^c	4.4 ± 0.1 ^b	3.9 ± 0.1 ^a
Off-flavor	5.0 ± 0.1 ^d	4.8 ± 0.1 ^{cd}	4.8 ± 0.1 ^{cd}	4.6 ± 0.1 ^c	3.9 ± 0.1 ^b	3.1 ± 0.1 ^a
Average score	4.8 ± 0.1 ^c	4.7 ± 0.1 ^c	4.7 ± 0.1 ^c	4.6 ± 0.1 ^c	4.1 ± 0.1 ^b	3.7 ± 0.1 ^a

^{a–d} Different lowercase letters indicate significant differences between samples within the same parameter ($p < 0.05$).

For most individual attributes, C0–C3 also showed comparable scores. Appearance, color, taste, consistency, sweetness, sour milk flavor, and average score were not significantly different among these four samples ($p > 0.05$). Odor did not differ significantly among any of the samples, despite a slight numerical decrease in C4 and C5. The main sensory change within C0–C3 was related to the feeling of capsules in the mouth and off-

flavor: C3 had slightly lower scores than the control for these attributes ($p < 0.05$), but the values remained within an acceptable range.

A more pronounced decrease in sensory quality was observed when the additive concentration increased to 4% and 5%. Samples C4 and C5 had significantly lower scores for appearance, color, taste, consistency, sweetness, sour milk flavor, off-flavor, and average score compared with C0–C3 ($p < 0.05$). The average score decreased from 4.6 in C3 to 4.1 in C4 and 3.7 in C5. The lowest scores in C4 and C5 were associated with appearance, consistency, feeling of capsules in the mouth, and off-flavor.

Visual observation supported the sensory results (Figure 2). In C1–C3, red capsule inclusions were visible but remained relatively well distributed in the cottage cheese matrix. In C4 and C5, capsule inclusions became more noticeable and less visually acceptable. Overall, the sensory results showed that C3 retained acceptable organoleptic quality while providing a higher level of encapsulated additives than C1 and C2.

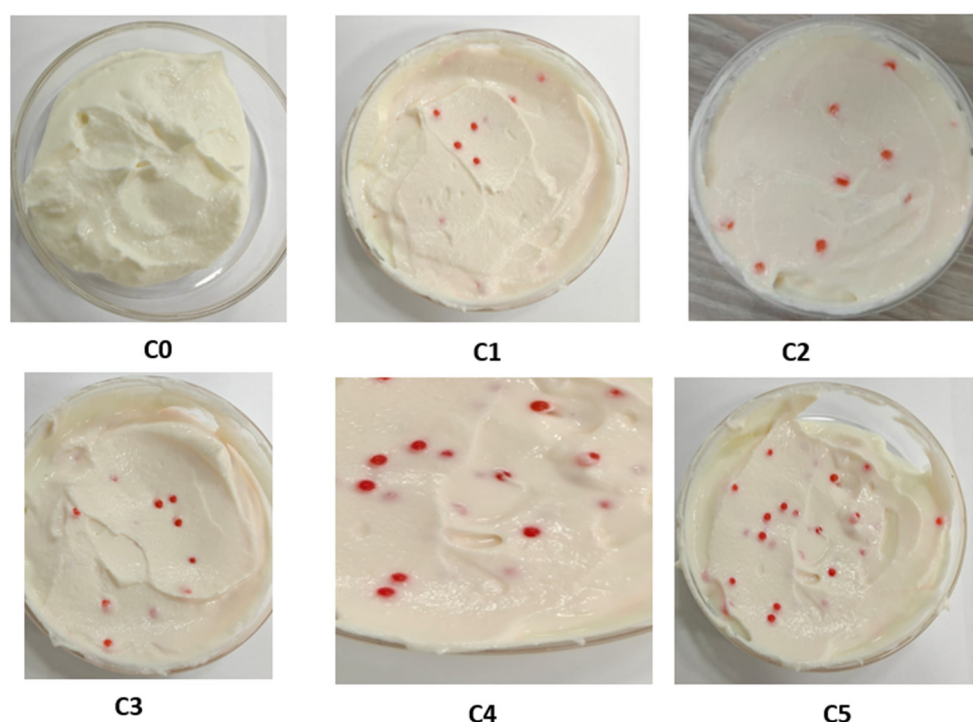


Figure 2. Visual appearance of cottage cheese spread samples with different concentrations of encapsulated additives.

3.8. Selection of the C3 Formulation Containing 3% Encapsulated Additives for Further Storage Study

Following the comparative evaluation of samples C0–C5, C3 was selected for the refrigerated storage study. The selection was based on a combined assessment of bioactive enrichment, sensory acceptability, and technological characteristics. Sensory acceptability, particularly taste, consistency, capsule perception, and overall score, was given the highest priority. Bioactive-compound content and antioxidant activity were the second major criteria, while color, viscosity, syneresis, water-holding capacity, capsule distribution, and capsule integrity were considered supporting technological criteria.

The addition of capsules did not significantly affect pH, titratable acidity, moisture, dry matter, water activity, protein, fat, carbohydrate content, or energy value. Samples C1 and C2 maintained high sensory acceptability but provided smaller increases in bioactive compounds. C3 provided greater enrichment, with vitamin C reaching 0.94 mg/100 g, polyphenols 6.75 mg/100 g, flavonoids 4.50 mg/100 g, and DPPH antioxidant activity 6.0%. It

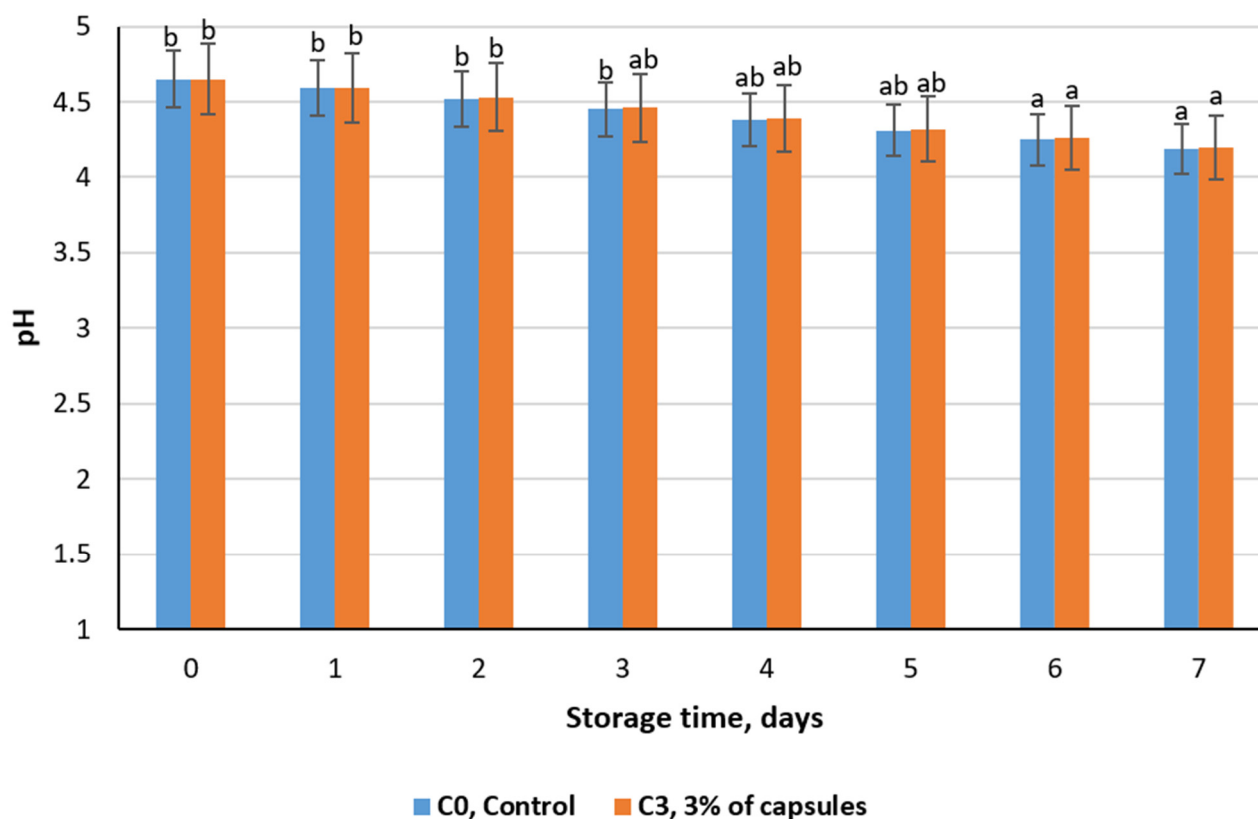
also retained an overall sensory score of 4.69 and showed uniform capsule distribution and high capsule integrity. Compared with C0, syneresis decreased from 8.5% to 7.5%, while water-holding capacity increased from 51.5% to 53.1%. Its viscosity remained at an intermediate level among the enriched formulations.

Although C4 and C5 contained higher levels of bioactive compounds, their increased capsule content resulted in more pronounced color changes, more visible inclusions, stronger capsule perception, higher viscosity, and lower taste and consistency scores. Consequently, the overall sensory score decreased to 4.11 for C4 and 3.71 for C5. C3 was therefore selected as the highest tested capsule concentration that provided meaningful bioactive enrichment without the more pronounced sensory and technological limitations observed at higher concentrations. Subsequent storage studies were conducted using C0 as the control and C3 as the selected enriched formulation.

3.9. Changes in pH and Titratable Acidity During Storage

During storage, both the control and C3 samples showed a gradual decrease in pH and a simultaneous increase in titratable acidity (Figure 3). The initial pH was 4.65 in both samples and decreased to 4.19 in the control and 4.20 in C3 by day 7. In both variants, the decrease became significant from day 5 onward compared with the initial value ($p < 0.05$). Titratable acidity increased more sharply over the same period. In the control sample, it rose from 171 to 258 °T, while in C3 it increased from 171 to 255 °T. Significant differences compared with day 0 were observed from day 2 onward in both samples ($p < 0.05$).

The control and C3 samples showed very similar acidification patterns throughout storage. C3 maintained slightly higher pH and slightly lower titratable acidity than the control from day 2 to day 7, but the differences between the two variants were small.



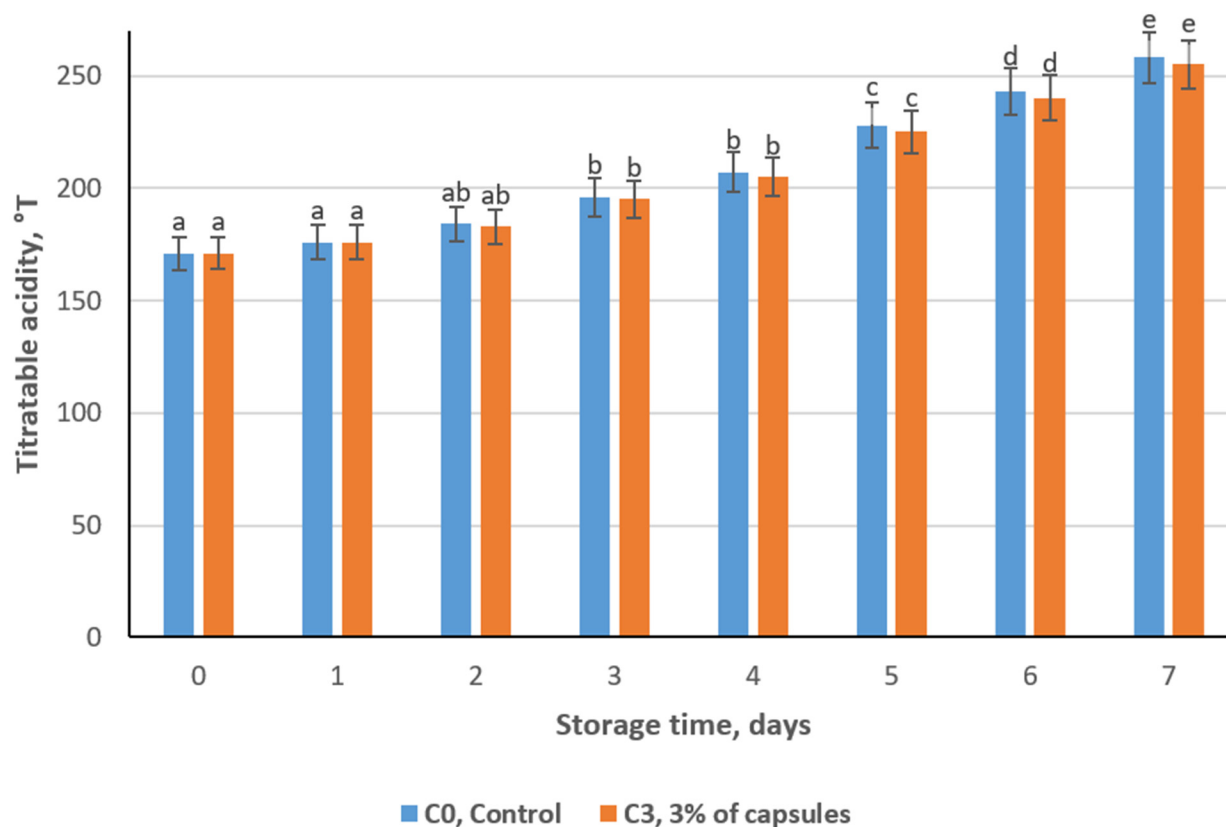


Figure 3. Changes in pH and titrateable acidity during storage. Different lowercase letters indicate significant differences between storage days within the same sample ($p < 0.05$).

3.10. Water Activity and Moisture Dynamics During Storage

Water activity remained high and stable in both samples throughout the 7-day storage period (Table 8). The values ranged from approximately 0.98 to 0.99 in the control and C3 samples, with no significant differences between formulations or storage days ($p > 0.05$). Moisture content showed a slight downward trend during storage. In the control sample, it decreased from 64.50% on day 0 to 63.47% on day 7, while in C3 it decreased from 64.30% to 63.36% over the same period (Table 9). The moisture values remained close between the two formulations throughout storage, and no significant differences were observed between formulations or storage times ($p > 0.05$). Overall, the addition of 3% encapsulated additives did not significantly affect water activity or moisture content during storage. Both samples maintained similar water-status characteristics over the 7 days.

Table 8. Changes in water activity during 7 days of storage.

Sample	0	1	2	3	4	5	6	7
C0—control	0.98 ± 0.02^a	0.98 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a
C3	0.98 ± 0.03^a	0.98 ± 0.03^a	0.98 ± 0.03^a	0.98 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a	0.99 ± 0.03^a

^a The same lowercase letter indicates no significant differences between formulations at the same storage day or between storage days within the same formulation ($p > 0.05$).

Table 9. Changes in moisture content during 7 days of storage, %.

Sample	0	1	2	3	4	5	6	7
C0—control	64.50 ± 1.23^a	64.41 ± 1.25^a	64.33 ± 1.56^a	64.24 ± 1.27^a	64.07 ± 1.16^a	63.90 ± 1.29^a	63.73 ± 0.88^a	63.47 ± 0.93^a
C3	64.30 ± 1.62^a	64.21 ± 1.84^a	64.13 ± 1.16^a	64.04 ± 1.78^a	63.96 ± 1.06^a	63.79 ± 1.11^a	63.62 ± 1.44^a	63.36 ± 1.49^a

^a The same lowercase letter indicates no significant differences between formulations at the same storage day or between storage days within the same formulation ($p > 0.05$).

3.11. Syneresis and Water-Holding Capacity During Storage

Syneresis increased progressively in both samples during seven days of storage. In the control, it increased from 8.5% on day 0 to 13.8% on day 7, whereas in C3 it increased from 7.4% to 11.8% (Figure 4). C3 consistently showed lower syneresis than the control, with significant differences at the indicated storage points ($p < 0.05$). Significant changes over time were also observed within both samples.

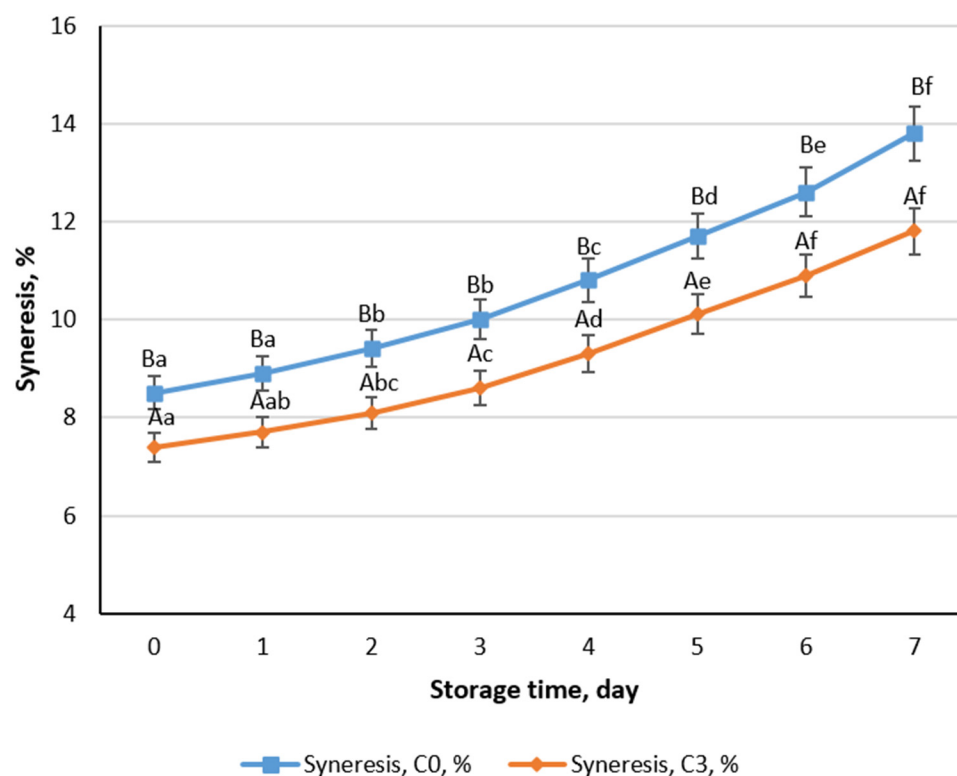


Figure 4. Dynamics of syneresis in control and C3 cottage cheese spread during 7 days of storage. ^{A,B} Different uppercase letters indicate significant differences between samples within the same storage days ($p < 0.05$). ^{a-f} Different lowercase letters indicate significant differences between storage days within the same sample ($p < 0.05$).

Water-holding capacity showed the opposite trend and gradually decreased during storage (Figure 5). It declined from 51.5% to 45.2% in the control and from 53.2% to 47.2% in C3. C3 maintained a higher water-holding capacity, with significant differences between the samples at the storage points indicated in Figure 5 ($p < 0.05$).

Overall, the sample containing 3% encapsulated additives showed better structural stability during storage, as reflected by lower syneresis and higher water-holding capacity compared with the control.

3.12. Organoleptic Evaluation During Storage

Organoleptic scores decreased in both samples during the 7 days of storage. On the day of production, the average score was 4.78 points for the control sample and 4.75 points for C3. Both samples had high scores for appearance, color, odor, taste, consistency, and whey separation, indicating good initial sensory quality (Figure 6). By day 3, the average scores decreased slightly to 4.62 in the control and 4.57 in C3. The scores of individual indicators remained close between the two samples, ranging from 4.5 to 4.8 in the control and from 4.4 to 4.7 in C3. On day 5, a more noticeable decrease in sensory quality was observed. The average score was 3.97 in the control and 4.05 in C3. The C3 sample showed slightly higher scores for taste, consistency, and whey separation, while appearance and

odor were similar between the two samples. By day 7, the average score decreased to 3.27 in the control and 3.38 in C3. The lowest scores were recorded for taste, odor, and whey separation in the control sample. C3 maintained slightly higher scores for appearance, taste, consistency, and whey separation. Overall, both samples showed gradual sensory deterioration during storage, but C3 demonstrated slightly better organoleptic stability, especially from day 5 onward.

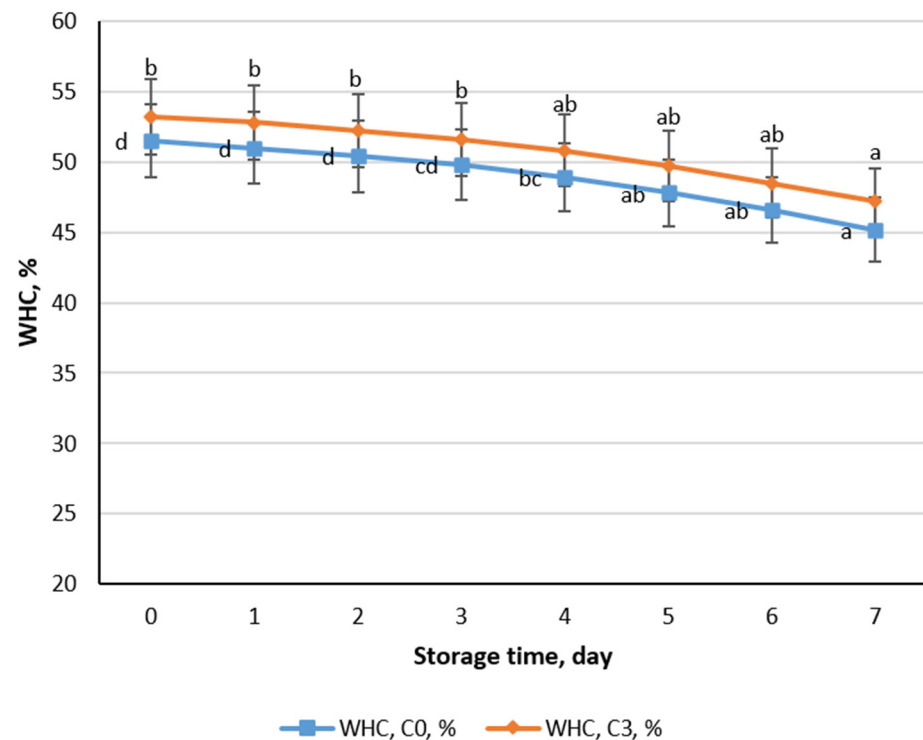
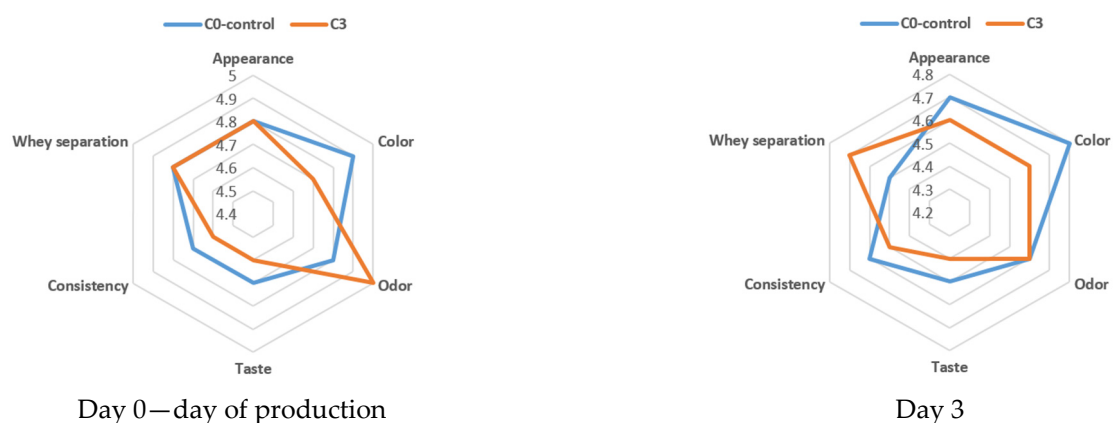


Figure 5. Dynamics of water-holding capacity in control and C3 cottage cheese spread during 7 days of storage. No significant differences between samples within the same storage days ($p > 0.05$). ^{a–d} Different lowercase letters indicate significant differences between storage days within the same sample ($p < 0.05$).



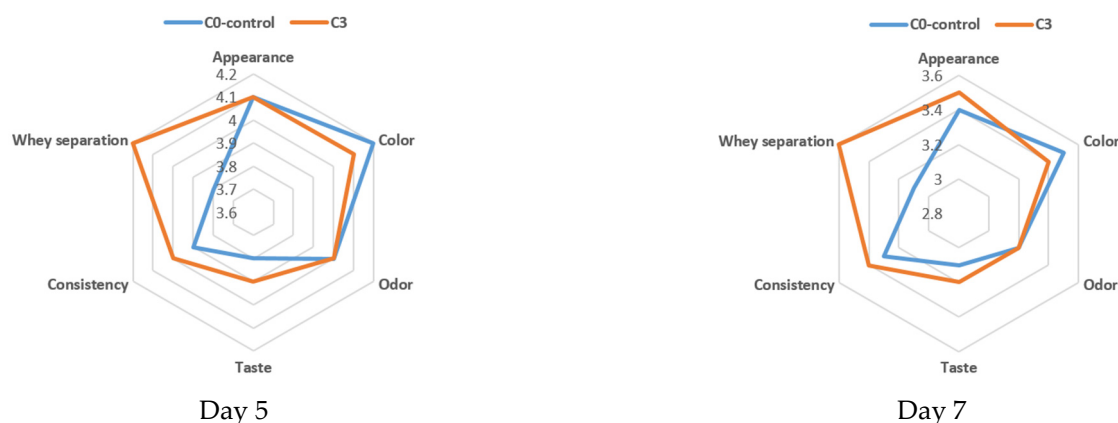


Figure 6. Changes in sensory attributes of cottage cheese spread during 7 days of storage.

3.13. Retention of Bioactive Compounds During Storage

In the C3 sample, the contents of bioactive compounds showed only a slight decrease during 7 days of storage (Table 10). Vitamin C decreased from 0.94 to 0.87 mg/100 g ($p < 0.05$), polyphenols from 6.75 to 6.45 mg/100 g, and flavonoids from 4.50 to 4.32 mg/100 g. Antioxidant activity also declined moderately, from 100.0% on day 0 to 94.0% on day 7, but the differences between storage days were not significant ($p > 0.05$). Vitamin C retention decreased from 100.0% to 92.6%, with a significant reduction by day 7 compared with day 0 ($p < 0.05$). Polyphenol retention remained high, decreasing from 100.0% to 95.6%, without significant differences during storage ($p > 0.05$). Overall, the C3 sample retained more than 90% of vitamin C, polyphenols, and antioxidant activity after 7 days of storage, indicating good preservation of bioactive compounds during the storage period (Figure 7).

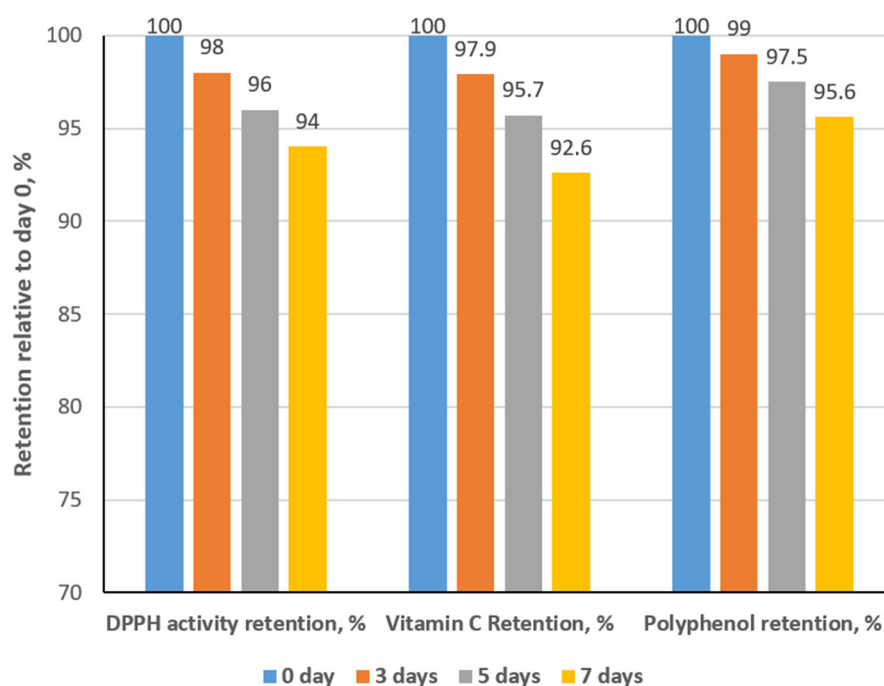


Figure 7. Changes in DPPH radical-scavenging activity, vitamin C retention, and polyphenol retention in the C3 cottage cheese spread during seven days of refrigerated storage after opening. The value measured on day 0 was set at 100%, and the values obtained on subsequent storage days were expressed as percentages of the initial value.

Table 10. Stability of Bioactive Compounds During Storage.

Days	Vitamin C, mg/100 g	Polyphenols, mg/100 g	Flavonoids, mg/100 g
0	0.94 ± 0.02 ^b	6.75 ± 0.19 ^a	4.50 ± 0.14 ^a
3	0.92 ± 0.02 ^{ab}	6.68 ± 0.17 ^a	4.46 ± 0.13 ^a
5	0.90 ± 0.03 ^{ab}	6.58 ± 0.18 ^a	4.40 ± 0.12 ^a
7	0.87 ± 0.02 ^a	6.45 ± 0.21 ^a	4.32 ± 0.14 ^a

^{a,b} Different lowercase letters indicate significant differences between storage days within the same sample ($p < 0.05$).

3.14. Capsule Integrity During Storage

Capsule integrity remained high in the C3 sample throughout 7 days of storage (Table 11). The proportion of intact capsules was 99.5% on days 0 and 3, then slightly decreased to 99.3% on day 5 and 99.0% on day 7. The proportion of damaged capsules remained low, increasing only from 0.5% at the beginning of storage to 1.0% by day 7. The average capsule diameter remained stable at 1.00 mm throughout storage, indicating that no noticeable size changes occurred. Capsule distribution was uniform at all storage points. On day 3, no aggregation was observed, while isolated defects appeared by days 5 and 7.

Table 11. Capsule diameter and integrity of the C3 formulation during seven days of refrigerated storage.

Storage Time, Day	Variant	Intact Capsules, %	Damaged Capsules, %	Average Diameter, mm	Distribution Pattern	Description of Capsules
0	C3	99.5	0.5	1.00 ± 0.03	uniform, capsules intact	The capsules are spherical, and the shell is intact
3	C3	99.5	0.5	1.00 ± 0.02	uniform, no agglomeration	The shape and shell are intact
5	C3	99.3	0.7	1.00 ± 0.05	uniform, isolated defects	The capsules are mostly intact
7	C3	99.0	1.0	1.00 ± 0.04	uniform, isolated defects	The coating is intact; no release has been observed

Visual observations confirmed that the capsules retained their spherical shape and shell integrity during storage (Figure 8). By day 7, the capsule coating remained intact, and no release of capsule contents was observed. Overall, the C3 sample maintained high capsule stability during the 7-day storage period, with only minor isolated defects developing over time.

Microscopic images confirmed the structural stability of the capsules during storage. On the day of production, the capsules had a spherical shape and a clearly preserved outer shell, with a measured diameter of approximately 1.01 mm. Similar morphology was observed on day 3, where the capsule retained its round shape and measured about 0.99 mm. By days 5 and 7, the capsules still maintained their general spherical form, and no visible rupture or release of capsule contents was observed. The measured diameters remained close to the initial value, ranging from 1.02 to 1.04 mm. Slight surface irregularities became more visible during storage, especially by day 7, but the capsule shell remained intact. These microstructural observations support the quantitative data showing high capsule integrity and stable capsule diameter throughout the 7-day storage period.

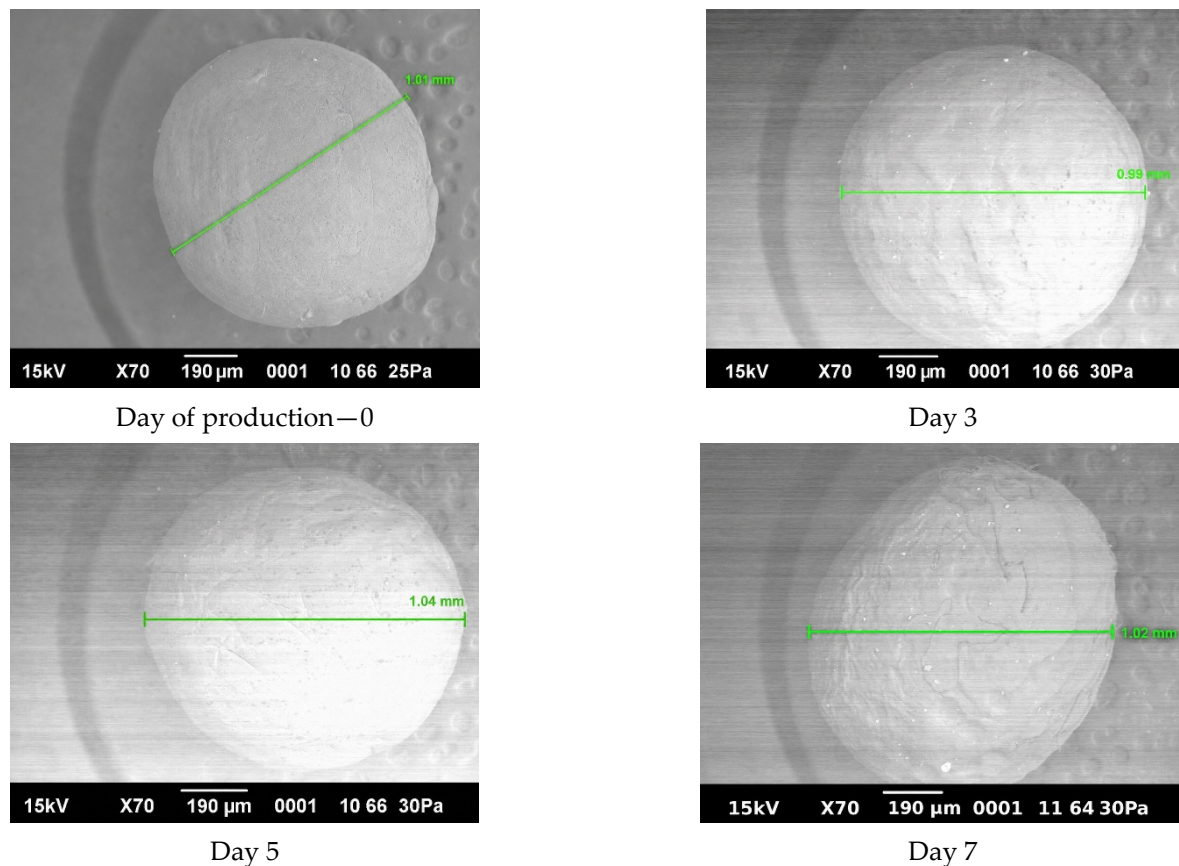


Figure 8. Microstructure and dimensional stability of capsules in the C3 sample during 7 days of storage.

3.15. Microbial Changes and Safety Indicators During Storage

Lactic acid bacteria remained relatively stable in both samples during the 7-day storage period (Table 12). In the control sample, their count decreased slightly from 7.20 to 6.90 log₁₀ CFU/g, while in C3 it decreased from 7.20 to 6.95 log₁₀ CFU/g. No significant differences were observed between formulations or storage times ($p > 0.05$). From day 3 onward, C3 showed slightly higher lactic acid bacteria counts than the control, but the differences were small.

Table 12. Changes in Lactic Acid Bacteria During Storage, log₁₀ CFU/g.

Sample	0	1	2	3	4	5	6	7
C0—control	7.20 ± 0.18	7.18 ± 0.21	7.15 ± 0.22	7.08 ± 0.23	7.04 ± 0.19	7.00 ± 0.22	6.95 ± 0.18	6.90 ± 0.18
C3	7.20 ± 0.19	7.18 ± 0.19	7.15 ± 0.20	7.11 ± 0.19	7.08 ± 0.19	7.04 ± 0.21	6.99 ± 0.20	6.95 ± 0.18

No significant differences were observed between formulations or storage times ($p > 0.05$).

Yeast and mold counts remained low throughout storage (Table 13). Yeasts were below 10 CFU/g in both samples on days 0 and 3. By day 5, yeast counts increased to 15 CFU/g in the control and 12 CFU/g in C3, and by day 7 they reached 30 and 25 CFU/g, respectively. Molds remained below 10 CFU/g in C3 throughout storage. In the control sample, molds were below 10 CFU/g up to day 5 and reached 10 CFU/g on day 7. Overall, C3 maintained comparable lactic acid bacteria counts and slightly lower yeast and mold levels than the control.

Table 13. Changes in Yeast and Mold During Storage.

Storage Time, Day	Yeasts C0	Molds C0	Yeasts C3	Molds C3
0	<10	<10	<10	<10
3	<10	<10	<10	<10
5	15	<10	12	<10
7	30	10	25	<10

Safety assessment of the finished product showed no detection of pathogenic micro-organisms, including *Salmonella*, in either sample. Coliform bacteria and *Staphylococcus aureus* were also not detected. Chemical safety indicators, including lead, cadmium, arsenic, mercury, aflatoxin M1, chloramphenicol, hexachlorocyclohexane, and DDT metabolites, were not detected in the control or C3 sample (Table 14). The radionuclide levels were the same in both samples: Cs-137 was 4.9 Bq/kg and Sr-90 was 6.2 Bq/kg. All safety indicators were within the permissible limits.

Table 14. Safety indicators of the finished cottage cheese spread.

Parameter	Permissible Limit	C0, Control	Variant C3, (3% Capsules)
Lead, mg/kg	no more than 0.3	Not detected	Not detected
Cadmium, mg/kg	no more than 0.2	Not detected	Not detected
Arsenic, mg/kg	no more than 0.2	Not detected	Not detected
Mercury, mg/kg	no more than 0.03	Not detected	Not detected
Aflatoxin M1, mg/kg	no more than 0.0005	Not detected	Not detected
Chloramphenicol	not permitted	Not detected	Not detected
Hexachlorocyclohexane, mg/kg	no more than 1.25	Not detected	Not detected
DDT and metabolites, mg/kg	no more than 1.0	Not detected	Not detected
Cs-137, Bq/kg	no more than 100	4.9	4.9
Sr-90, Bq/kg	no more than 25	6.2	6.2

4. Discussion

The results demonstrate that alginate–pullulan capsules containing herbal bioactive additives can be incorporated into a cottage cheese spread without disrupting the basic identity of the product. The main technological outcome was not a change in protein, fat, moisture, pH, or water activity, but a combined effect on functional enrichment, water retention, viscosity, capsule stability, sensory quality, and safety. This distinction is important because a functional dairy product must provide additional bioactive value while remaining recognizable and acceptable as a cottage cheese spread.

The initial capsule characteristics supported their suitability for incorporation into a semi-solid dairy matrix. The capsules had a diameter of about 1.00 mm, an aspect ratio of 1.08, and 98–100% integrity, indicating a near-spherical and mechanically stable bead population. Their size was larger than the alginate microspheres used in cottage cheese [40] and the xonostle capsules studied in fresh cheese [41], but closer to the millimeter-scale alginate beads reported for carotenoid-fortified stirred yogurt [42]. Thus, the capsules should be considered visible hydrogel beads, which explains why their sensory perception became more important at higher inclusion levels. The presence of vitamin C, polyphenols, flavonoids, tanning substances, and tannins confirmed their role as carriers of antioxidant compounds.

On the day of production, capsule addition did not significantly affect pH, titratable acidity, total moisture, dry matter, or water activity ($p > 0.05$), indicating that the basic physicochemical state of the cottage cheese matrix was preserved. This stability was probably related to the intact capsule structure and the buffering capacity of the dairy matrix.

In contrast, structure-related parameters changed more clearly: syneresis decreased from 8.5% in the control to 6.9% in C5, while water-holding capacity increased from 51.5% to 54.2% ($p < 0.05$). Similar effects have been reported for encapsulated additives in dairy matrices, where wall material and matrix compatibility influenced syneresis and water retention [43,44]. Therefore, the main effect of the capsules was improved serum phase retention rather than a change in acidity or total moisture. The chemical composition confirmed that capsule incorporation did not substantially alter the nutritional profile of the product. Protein, fat, carbohydrate, moisture, and caloric values did not differ significantly among formulations ($p > 0.05$), which agrees with studies on cottage cheese with alginate-microencapsulated plant extracts [40]. Ash content increased from 0.8 to 1.0 g/100 g as capsule concentration rose ($p < 0.05$), most likely due to the mineral contribution of plant materials and calcium-crosslinked hydrogel capsules. Since this increase was not accompanied by undesirable changes in pH, water activity, protein, or fat, it can be interpreted as part of the enrichment effect rather than matrix destabilization.

The functional purpose of the capsules was confirmed by the dose-dependent increase in bioactive compounds. Vitamin C, polyphenols, flavonoids, tanning substances, and tannins were absent from the control but increased progressively from C1 to C5 ($p < 0.05$). Antioxidant activity followed the same pattern: DPPH activity increased from 4.5% to 7.0%, and ABTS values also rose significantly ($p < 0.05$). Comparable dose-response effects have been reported for ricotta cheese with broccoli sprout extract, where DPPH activity increased with extract concentration [45], and for stirred yogurt containing carotenoid-loaded alginate beads, where antioxidant activity exceeded that of the control [42]. Nevertheless, the absolute antioxidant response in the present product was moderate. This is expected in a high-moisture, protein-rich matrix, where some phenolic compounds may remain inside capsules or interact with dairy proteins, limiting extractability in chemical assays.

Instrumental color and rheology showed the main practical limits of increasing capsule concentration. As capsule content increased, L^* decreased from 92.8 to 88.6, while a^* and b^* increased ($p < 0.05$), indicating a shift from a milky-white color toward a creamier tone with visible reddish inclusions. Similar color changes have been reported in fortified dairy matrices containing plant-derived additives [43,46]. Viscosity also increased significantly at all spindle speeds ($p < 0.05$), and all samples showed shear-thinning behavior, consistent with reports for dairy systems containing encapsulated additives [44,47]. Moderate viscosity increase may improve body and reduce whey separation, but excessive capsule levels can make the product denser and less homogeneous. Therefore, color and rheology support the selection of an optimal capsule concentration rather than the highest dose.

Capsule integrity after mixing was an important technological indicator. Across the enriched samples, 98.5–99.5% of capsules remained whole, and the capsule diameter stayed close to 1.00 mm, confirming that late-stage gentle mixing enabled distribution without substantial rupture. C1 and C2 were physically uniform but provided lower functional enrichment, whereas C4 and C5 produced more visible inclusions and stronger textural changes. Based on these results, C3 was selected as the most suitable formulation because it combined increased bioactive compound content with uniform distribution and high capsule integrity.

Storage results further support the selection of C3. During refrigerated storage, both the control and C3 underwent gradual post-acidification. pH decreased from 4.65 to about 4.2, and titratable acidity increased from 171 °T to 255–258 °T, with significant changes during storage ($p < 0.05$). Similar acidification during storage has been reported in yogurts containing microencapsulated propolis and *Hovenia dulcis* preparations [46,47]. Importantly, C3 behaved very similarly to the control, indicating that 3% capsules did not

accelerate acid development or suppress normal fermentation-related changes. This differs from some cheese systems with free or more readily released acidic plant extracts, where pH and acidity changed more markedly [45,48]. The limited effect in the present study is consistent with the high integrity of the capsules and the buffering effect of the cottage cheese matrix.

Water activity remained high and statistically stable during storage ($p > 0.05$), while moisture content decreased only slightly in both samples. Thus, the incorporation of 3% capsules did not significantly modify water activity, and product stability remained dependent on acidification, refrigeration, hygienic processing, and packaging. Similar observations were reported in fortified dairy matrices that maintained high water activity and similar proximate composition during storage [49]. The more relevant storage effect concerned water distribution: C3 showed consistently lower syneresis than the control throughout storage (7.4–11.8% vs. 8.5–13.8%; $p < 0.05$), while water-holding capacity decreased in both samples but remained higher in C3. This agrees with reports of improved water retention in yogurt containing alginate-encapsulated persimmon extract [43]. The hydrophilic alginate–pullulan capsule walls may have retained part of the aqueous phase, while the hydrated capsules may have increased resistance to serum migration through the protein matrix. This interpretation is consistent with the lower syneresis and higher viscosity observed in C3. However, these mechanisms were not directly investigated. The decline in water-holding capacity during storage may have resulted from increasing acidity and structural rearrangement of the casein matrix, together with moisture loss associated with repeated opening and sampling.

The microbiological data indicate that C3 preserved the normal lactic acid microbiota while maintaining low spoilage counts. Lactic acid bacteria remained around 7 log CFU/g during storage, with no significant differences between the control and C3 ($p > 0.05$), which is consistent with reports on fermented dairy products containing encapsulated bioactives [46,50]. Yeasts and molds also remained low in both samples, with slightly lower counts in C3 by the end of storage. This effect may be related to phenolic compounds and reduced syneresis, although antimicrobial activity depends strongly on formulation and storage conditions [47,49].

Sensory evaluation confirmed the same dose-related limitation. Initial acceptability was high for both the control and C3, and both samples retained good sensory quality until day 3. Stronger declines appeared by days 5–7, mainly due to acidity development, texture changes, and whey separation. From day 5 onward, C3 showed slightly better average scores than the control, which agrees with its lower syneresis and higher water-holding capacity. Similar findings have been reported in dairy products enriched with encapsulated plant additives, where suitable doses supported sensory quality, whereas excessive concentrations impaired flavor, appearance, or consistency [47,48]. Therefore, although higher capsule concentrations increased bioactive values, they were less favorable from a technological and sensory perspective, while C3 provided the most balanced formulation.

During refrigerated storage, the measured bioactive compounds showed different patterns of stability. Vitamin C decreased from 0.94 to 0.87 mg/100 g, corresponding to 92.6% retention, and the difference between days 0 and 7 was statistically significant ($p < 0.05$). In contrast, polyphenols decreased from 6.75 to 6.45 mg/100 g and flavonoids from 4.50 to 4.32 mg/100 g, but these changes were not statistically significant ($p > 0.05$). Antioxidant activity also remained statistically stable, retaining 94.0% of its initial value by day 7 ($p > 0.05$). Capsule integrity remained high during the same period, decreasing only slightly from 99.5% to 99.0%, while the average capsule diameter remained close to 1.00 mm. These results indicate that phenolic compounds, flavonoids, antioxidant activity, and the physical structure of the capsules were largely maintained under the tested

refrigerated storage conditions, whereas vitamin C underwent a small but statistically significant loss. Because an equivalent non-encapsulated extract formulation was not included, the observed retention cannot be attributed specifically to the protective effect of encapsulation.

Finally, capsule incorporation did not compromise microbiological or sanitary-chemical compliance, and C3 was confirmed as the most balanced formulation because it provided functional enrichment while limiting the negative effects observed at higher capsule levels, including stronger color changes, increased viscosity, visible inclusions, and reduced sensory acceptability.

5. Conclusions

Incorporation of alginate–pullulan-encapsulated rosehip, echinacea, and levzey extracts affected the physicochemical, rheological, sensory, and storage properties of cottage cheese spread in a concentration-dependent manner. The formulation containing 3% capsules provided the most suitable balance between bioactive enrichment and product quality. It increased bioactive compound content and antioxidant activity, improved water-holding properties, and maintained acceptable sensory characteristics, viscosity, capsule integrity, and distribution. Higher capsule concentrations increased bioactive levels but reduced sensory acceptability because of more visible inclusions and greater capsule perception. During refrigerated storage, moisture and water activity remained statistically stable, while acidity and syneresis increased and sensory scores decreased, especially after day 3. The tested microbiological and sanitary safety indicators remained within permissible limits. These findings identify 3% capsule incorporation as a technologically suitable level for cottage cheese spread. Further work should define shelf-life acceptance criteria, optimize packaging, validate scale-up, and assess consumer acceptance.

Author Contributions: Conceptualization, A.B. and Z.I.; methodology, S.T. and G.Z.; software, N.M. and A.S.; validation, A.B.; formal analysis, M.J.; investigation, A.M., A.B., G.Z., N.M. and M.T.; resources, Z.I. and A.S.; data curation, S.T., A.K., Z.I. and A.S.; visualization, A.K. and M.J.; writing—original draft preparation, A.M., A.K. and M.T.; writing—review and editing, A.M. and S.T.; project administration, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, Grant No. AP22686708 Scientific and practical basis for developing technology and assessing the food safety of dairy products with encapsulated biologically active additives.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of Shakarim University, Semey, Kazakhstan (Protocol No. 13, approved on 12 May 2026).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Salehi, F. Quality, physicochemical, and textural properties of dairy products containing fruits and vegetables: A review. *Food Sci. Nutr.* **2021**, *9*, 4666–4686. <https://doi.org/10.1002/fsn3.2430>.
2. El-Sayed, S.M.; Youssef, A.M. Potential application of herbs and spices and their effects in functional dairy products. *Heliyon* **2019**, *5*, e01989. <https://doi.org/10.1016/j.heliyon.2019.e01989>.
3. Poonia, M.P.; Kumar, A.; Meena, K.K.; Gupta, L.; Wadhawan, N.; Mishra, S.; Goel, S. Recent advances in functional dairy products enriched with herbal extracts: A comprehensive review. *Eur. J. Nutr. Food Saf.* **2025**, *17*, 242–257. <https://doi.org/10.9734/ejnf/2025/v17i71781>.
4. Kandyliari, A.; Potsaki, P.; Bousdouni, P.; Kaloteraki, C.; Christoflea, M.; Almpounioti, K.; Moutsou, A.; Fasoulis, C.K.; Polychronis, L.V.; Gkalpinos, V.K.; et al. Development of dairy products fortified with plant extracts: Antioxidant and phenolic content characterization. *Antioxidants* **2023**, *12*, 500. <https://doi.org/10.3390/antiox12020500>.
5. Barak, S.; Mudgil, D. Application of bioactives from herbs and spices for improving the functionality and shelf life of dairy products—A review. *Biointerface Res. Appl. Chem.* **2023**, *13*, 141. <https://doi.org/10.33263/BRIAC132.141>.
6. Adinepour, F.; Pouramin, S.; Rashidinejad, A.; Jafari, S. Fortification/enrichment of milk and dairy products by encapsulated bioactive ingredients. *Food Res. Int.* **2022**, *157*, 111212. <https://doi.org/10.1016/j.foodres.2022.111212>.
7. Jeyakumari, A.; Zynudheen, A.A.; Parvathy, U. Microencapsulation of bioactive food ingredients and controlled release—A review. *MOJ Food Process. Technol.* **2016**, *2*, 00059. <https://doi.org/10.15406/mojfpt.2016.02.00059>.
8. Raddatz, G.C.; de Menezes, C.R. Microencapsulation and co-encapsulation of bioactive compounds for application in food: Challenges and perspectives. *Cienc. Rural* **2021**, *51*, e20200616. <https://doi.org/10.1590/0103-8478cr20200616>.
9. Zabot, G.L.; Rodrigues, F.S.; Ody, L.P.; Tres, M.V.; Herrera, E.; Palacin, H.; Córdova-Ramos, J.S.; Best, I.; Olivera-Montenegro, L. Encapsulation of bioactive compounds for food and agricultural applications. *Polymers* **2022**, *14*, 4194. <https://doi.org/10.3390/polym14194194>.
10. Popescu, L.; Cojocari, D.; Ghendov-Mosanu, A.; Lung, I.; Soran, M.-L.; Opreș, O.; Kacso, I.; Ciorîță, A.; Balan, G.; Pintea, A.; et al. The effect of aromatic plant extracts encapsulated in alginate on the bioactivity, textural characteristics and shelf life of yogurt. *Antioxidants* **2023**, *12*, 893. <https://doi.org/10.3390/antiox12040893>.
11. Borgogna, M.; Bellich, B.; Zorzin, L.; Lapasin, R.; Cesàro, A. Food microencapsulation of bioactive compounds: Rheological and thermal characterisation of non-conventional gelling system. *Food Chem.* **2010**, *122*, 416–423. <https://doi.org/10.1016/j.foodchem.2009.07.043>.
12. Kumari, K.; Tripathy, S.; Srivastav, P.P. Emerging encapsulation techniques for controlled and targeted delivery of bioactive compounds in food and nutraceutical systems. *Front. Nutr.* **2026**, *13*, 1826702. <https://doi.org/10.3389/fnut.2026.1826702>.
13. Muratbayev, A.; Idyryshev, B.; Kakimov, A.; Bepeyeva, A.; Jumazhanova, M.; Tashybayeva, M.; Zhumadilova, G.; Muratzhankyzy, N.; Imangaliyeva, Z.; Bazanova, A. Development of Alginate–Pullulan Capsules for Targeted Delivery of Herbal Dietary Supplements in Functional Fermented Milk Products. *Foods* **2025**, *14*, 2878. <https://doi.org/10.3390/foods14162878>.
14. Starkute, V.; Lukseviciute, J.; Klupsaite, D.; Mockus, E.; Klementaviciute, J.; Rocha, J.M.; Özogul, F.; Ruzauskas, M.; Viskelis, P.; Bartkiene, E. Characteristics of unripened cow milk curd cheese enriched with raspberry, blueberry and elderberry industry by-products. *Foods* **2023**, *12*, 2860. <https://doi.org/10.3390/foods12152860>.
15. Galimova, A.M.; Smolnikova, F.H.; Konganbayev, E.K.; Okuskhanova, E.K.; Tulkebayeva, G.E.; Tuleubekova, G.K.; Kabdenova, A.T.; Smagulova, M.G. Quality of a cottage cheese product with vegetable components. *Food Process. Ind.* **2021**, *11*, 51–55. (In Russian)
16. GOST 32892-2014; Milk and Milk Products. Method for Measuring Active Acidity. Standartinform: Moscow, Russia, 2015; 13p.
17. GOST 3624-92; Milk and Milk Products. Titrimetric Methods for Determination of Acidity. Standardinform: Moscow, Russia, 2009; p. 9. Available online: <https://files.stroyinf.ru/Data/100/10071.pdf> (accessed on 10 June 2026).
18. GOST 3626-73; Milk and Milk Products. Methods for Determination of Moisture and Dry Matter. Standartinform: Moscow, Russia, 2009; 12p.
19. Shori, A.B.; Baba, A.S.; Misran, M.; Tan, H.W. Enrichment of yogurt made from camel milk with *Allium sativum* and *Cinnamomum verum*: Influence on syneresis, water holding capacity, exopolysaccharides and rheological properties. *Camel Int. J. Vet. Sci.* **2013**, *1*, 51–63.
20. Gavrilova, E.; Anisimova, E.; Gabdelkhadieva, A.; Nikitina, E.; Vafina, A.; Yarullina, D.; Bogachev, M.; Kayumov, A. Newly isolated lactic acid bacteria from silage targeting biofilms of foodborne pathogens during milk fermentation. *BMC Microbiol.* **2019**, *19*, 248. <https://doi.org/10.1186/s12866-019-1618-0>.

21. GOST 34454-2018; Dairy Products. Determination of Protein Mass Fraction by the Kjeldahl Method. Standartinform: Moscow, Russia, 2018.
22. GOST 5867-2023; Milk and Dairy Products. Methods for Determination of Fat. Russian Institute of Standardization: Moscow, Russia, 2024. (In Russian)
23. AOAC 935.42-1935; Ash of Cheese. Gravimetric Method. AOAC International: Rockville, MD, USA, 2015.
24. Food and Agriculture Organization of the United Nations. *Food Energy—Methods of Analysis and Conversion Factors*; FAO: Rome, Italy, 2002. Available online: <https://www.fao.org/3/y5022e/y5022e00.htm> (accessed on 27 July 2026).
25. GOST 30627.2-98; Dairy Products for Infant Nutrition. Methods for Measuring Mass Fraction of Vitamin C (Ascorbic Acid). Standards Publishing House: Moscow, Russia, 2010; pp. 1–22. (In Russian)
26. GOST 55488-2013; Propolis. Method for Determination of Polyphenols. Standartinform: Moscow, Russia, 2014; 6p.
27. GOST R 55312-2012; Propolis. Method for Determination of Flavonoid Compounds; Official Edition. Standartinform: Moscow, Russia, 2020; 6p.
28. GOST 19885-74. Methods for Determination of Tannin and Caffeine Content. Izdatelstvo Standartov: Moscow, Russia, 1975; 5p.
29. Brand-Williams, W.; Cuvelier, M.E.; Berset, C.L.W.T. Use of a free radical method to evaluate antioxidant activity. *LWT-Food Sci. Technol.* **1995**, *28*, 25–30.
30. Aloglu, H.Ş.; Öner, Z. Determination of antioxidant activity of bioactive peptide fractions obtained from yogurt. *J. Dairy Sci.* **2011**, *94*, 5305–5314. <https://doi.org/10.3168/jds.2011-4285>.
31. Milovanovic, B.; Djekic, I.; Miocinovic, J.; Djordjevic, V.; Lorenzo, J.M.; Barba, F.J.; Mörlein, D.; Tomasevic, I. What Is the Color of Milk and Dairy Products and How Is It Measured? *Foods* **2020**, *9*, 1629. <https://doi.org/10.3390/foods9111629>.
32. Luna Flores, M.; Yerena Prieto, B.J.; Ferreira de Souza, S.J.; Telis Romero, J.; Jaramillo Flores, M.E.; Luna Solano, G. Impact of Drying Technologies on the Stability of Bioactive Compounds and the Technofunctional Quality of Habanero Chili (*Capsicum chinense*) Powder. *J. Culin. Sci. Technol.* **2026**, *24*, 1467–1491. <https://doi.org/10.1080/15428052.2026.2648041>.
33. Jumazhanova, M.; Kakimova, Z.; Zharykbasov, Y.; Kassymov, S.; Zhumadilova, G.; Muratbayev, A.; Tashybayeva, M.; Suychinov, A. Effect of the Encapsulation Process on the Viability of Probiotics in a Simulated Gastrointestinal Tract Model Medium. *Processes* **2023**, *11*, 2757. <https://doi.org/10.3390/pr11092757>.
34. GOST R ISO 22935-2-2011; Milk and Dairy Products. Sensory Analysis. Part 2. Recommended Methods for Sensory Evaluation. Standartinform: Moscow, Russia, 2012. (In Russian)
35. GOST 33566-2015; Milk and Dairy Products. Determination of Yeasts and Molds. Standartinform: Moscow, Russia, 2016. Available online: <https://internet-law.ru/gosts/gost/61246/> (accessed on 27 May 2026). (In Russian)
36. GOST 32901-2014; Milk and Dairy Products. Methods of Microbiological Analysis (with Amendments). Standartinform: Moscow, Russia, 2015; 25p. (In Russian)
37. GOST 31659-2012 (ISO 6579:2002); Food Products. Method for the Detection of Bacteria of the Genus Salmonella. Izd-vo standards: Moscow, Russia, 2014.
38. GOST 30347-2016; Milk and Milk Products. Methods for Determination of Staphylococcus Aureus. Standartinform: Moscow, Russia, 2016.
39. Bobreneva, I.V. *Safety of Food Raw Materials and Food Products*; Lan' Publishing House: Saint Petersburg, Russia, 2019; p. 56.
40. Caleja, C.; Ribeiro, A.; Barros, L.; Barreira, J.C.; Antonio, A.L.; Oliveira, M.B.P.; Barreiro, M.F.; Ferreira, I.C. Cottage cheeses functionalized with fennel and chamomile extracts: Comparative performance between free and microencapsulated forms. *Food Chem.* **2016**, *199*, 720–726. <https://doi.org/10.1016/j.foodchem.2015.12.085>.
41. Pérez-Soto, E.; Cenobio-Galindo, A.d.J.; Espino-Manzano, S.O.; Franco-Fernández, M.J.; Ludeña-Urquiza, F.E.; Jiménez-Alvarado, R.; Zepeda-Velázquez, A.P.; Campos-Montiel, R.G. The Addition of Microencapsulated or Nanoemulsified Bioactive Compounds Influences the Antioxidant and Antimicrobial Activities of a Fresh Cheese. *Molecules* **2021**, *26*, 2170. <https://doi.org/10.3390/molecules26082170>.
42. Soliman, T.N.; Nasser, S.A. Characterization of carotenoids double-encapsulated and incorporate in functional stirred yogurt. *Front. Sustain. Food Syst.* **2022**, *6*, 979252. <https://doi.org/10.3389/fsufs.2022.979252>.
43. Okur, Ö.D.; Aboeldahab, M. Fortification of yogurt with free and encapsulated persimmon (*Diospyros kaki* L.) extracts: Effects on antioxidant activity, phenolic contents, sensory and physicochemical characteristics. *Emir. J. Food Agric.* **2025**, *37*, 1–10. <https://doi.org/10.3897/ejfa.2025.160731>.
44. Suwannasang, S.; Zhong, Q.; Thumthanaruk, B.; Vatanyoopaisarn, S.; Uttapap, D.; Puttanlek, C.; Rungsardthong, V. Physicochemical properties of yogurt fortified with microencapsulated Sacha Inchi oil. *LWT* **2022**, *161*, 113375. <https://doi.org/10.1016/j.lwt.2022.113375>.

45. Azarashkan, Z.; Motamedzadegan, A.; Ghorbani-HasanSaraei, A.; Biparva, P.; Rahaiee, S. Investigation of the physicochemical, antioxidant, rheological, and sensory properties of ricotta cheese enriched with free and nano-encapsulated broccoli sprout extract. *Food Sci. Nutr.* **2022**, *10*, 4059–4072. <https://doi.org/10.1002/fsn3.3001>.
46. Hanauer, D.C.; Sehn, G.A.; Cavalheiro, D.; Rigo, E. Microencapsulated Hoveniadulcis: Application in yogurt and evaluation of gastrointestinal digestion *in vitro*. *Rev. Cienc. Tecnol.* **2024**, *42*, 48–56. <https://doi.org/10.36995/j.recyt.2024.42.005>.
47. Taşdemir, Y.; Gölge, E. Rheology and sensory properties of microencapsulated propolis-enriched stirred-type yogurt. *Ital. J. Food Sci./Riv. Ital. Sci. Aliment.* **2023**, *35*, 155–163. <https://doi.org/10.15586/ijfs.v35i3.2187>.
48. Popescu, L.; Cojocari, D.; Lung, I.; Kacso, I.; Ciorîță, A.; Ghendov-Mosanu, A.; Balan, G.; Pintea, A.; Sturza, R. Effect of Micro-encapsulated Basil Extract on Cream Cheese Quality and Stability. *Molecules* **2023**, *28*, 3305. <https://doi.org/10.3390/molecules28083305>.
49. Günhan, R.; Keskin, Ş.; Telli, N.; Takma, Ç.; Kolaylı, S. Effect of Encapsulated Propolis on Microbial Quality and Antioxidant Activity of Yoghurt. *Prog. Nutr.* **2022**, *24*, e2022043. <https://doi.org/10.23751/pn.v24i2.11998>.
50. Šeregelj, V.; Tumbas Šaponjac, V.; Lević, S.; Kalušević, A.; Četković, G.; Čanadanović-Brunet, J.; Nedović, V.; Stajčić, S.; Vulić, J.; Vidaković, A. Application of encapsulated natural bioactive compounds from red pepper waste in yogurt. *J. Microencapsul.* **2019**, *36*, 704–714. <https://doi.org/10.1080/02652048.2019.1668488>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.