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ENCAPSULATION OF POLYPHENOLS IN BAKED GOODS: A STRATEGY FOR ENHANCING STABILITY AND ANTIOXIDANT ACTIVITY

The object of this study was polyphenol-rich extracts obtained from black tea, grape seeds, green tea, and blueberries, incorporated into bakery matrices in both encapsulated and non-encapsulated forms. The research addressed the critical problem of thermal degradation of polyphenolic compounds during baking, which drastically reduces their antioxidant capacity and limits their application as functional ingredients in food systems. Experimental results demonstrated that microencapsulation using food-grade biopolymeric carriers – especially sodium alginate – significantly enhanced the thermal stability and retention of polyphenols during high-temperature processing. Non-encapsulated samples retained only 42–60% of their initial polyphenol content post-baking, while encapsulated forms preserved up to 90%, showing a clear technological advantage. Antioxidant activity, assessed via DPPH and FRAP assays, decreased by up to 45% in non-encapsulated products, whereas encapsulated variants maintained 75–90% of their original activity. HPLC analysis confirmed that encapsulation reduced the thermal degradation of individual compounds such as catechins, flavanones, and anthocyanins. These protective effects are attributed to the formation of a stabilizing polymeric matrix that shields bioactives from oxidation, limits interactions with gluten and starch, and ensures more uniform retention within the food matrix. Sensory analysis further demonstrated that the addition of encapsulated polyphenols enhanced aroma, texture, crumb softness, and color, especially in samples enriched with grape seed and green tea extracts. These findings confirm the practical feasibility of polyphenol encapsulation in commercial bakery workflows for producing clean-label, antioxidant-enriched functional baked goods with improved nutritional and technological properties and extended shelf life.

***Keywords*:** *encapsulation, polyphenols, thermal stability, oxidative stress, biopolymer carriers, sodium alginate.*

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1. Introduction

Functional foods, such as bakery products enriched with bioactive compounds like polyphenols, are formulated to reduce the risk of chronic diseases and improve overall health outcomes [1]. Polyphenols represent a broad class of naturally occurring compounds – including flavonoids, phenolic acids, stilbenes, and lignans – widely found in fruits, vegetables, cereals, and other plant-based foods [2]. Numerous studies have shown that regular polyphenol consumption is associated with improved health and a reduced risk of cardiovascular, metabolic, neurodegenerative, and oncological disorders [3, 4]. These health-promoting effects are primarily attributed to the antioxidant mechanisms of polyphenols, including radical scavenging, oxidative stress reduction, and the modulation of inflammatory and immune responses [4]. Consequently, polyphenol-rich diets are considered instrumental in the prevention of chronic diseases [5]. The radical scavenging capacity of polyphenols is particularly relevant in the context of preventive nutrition, as excessive oxidative stress is a well-established contributor to non-communicable diseases. Enriching staple foods like bread with polyphenols may therefore serve as a practical strategy to combat oxidative damage and support long-term health. Recent reviews have further emphasized their therapeutic potential in disease prevention and the formulation of functional foods [6].

Additionally, emerging evidence suggests that polyphenol supplementation can reduce exercise-induced oxidative stress and promote post-exercise recovery, highlighting their role in modulating oxidative processes under both physiological and pathological conditions [7, 8].

Given the growing scientific interest in dietary polyphenols, there is increased emphasis on developing food delivery systems capable of providing these compounds in physiologically relevant quantities. Among these, bakery products, particularly bread, are considered promising vehicles for functional enrichment due to their widespread consumption and technological compatibility. However, traditional wheat bread made from refined flour is inherently low in polyphenols, as milling removes the bran and germ, their primary sources [9, 10]. Additionally, high-temperature baking contributes to further degradation of these sensitive compounds. These limitations have stimulated efforts to enhance the polyphenol content of bread by incorporating natural antioxidant sources, including fruit, vegetable, and spice extracts [11]. Evidence suggests that using polyphenol-rich matrices such as berry powders and herbal extracts can significantly increase the total phenolic content and antioxidant activity of baked goods [12]. For example, the partial replacement of refined flour with flour from polyphenol-rich crops has been shown to improve the functional profile of bread [4]. Specifically, one study [11] demonstrated that incorporating 25% black quinoa flour led to more than a 12-fold increase in total extractable and bound polyphenols, alongside a three-fold enhancement in antioxidant activity. Such findings position functional breads as effective dietary vehicles for increasing polyphenol intake and supporting disease prevention.

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Despite these benefits, the addition of polyphenol-rich ingredients may negatively affect the rheological and sensory qualities of dough. Phenolic compounds can interact with gluten and other macromolecules, potentially impairing crumb structure, increasing firmness, and introducing undesirable bitter and astringent notes. Moreover, high concentrations of pure phenolic acids or extracts may weaken the gluten network, reducing loaf volume and porosity [9, 10, 12]. However, phenolics may also positively influence bread freshness due to their antioxidant properties, which slow oxidative spoilage and staling [2, 3]. Thus, enriching bakery products with polyphenols requires balancing health benefits with the maintenance of technological quality [13], which can be achieved through appropriate formulation strategies and additive selection [5].

One such strategy is microencapsulation, which involves coating polyphenols with a food-grade polymer matrix to shield them from environmental stressors. This technique enhances stability during processing and storage by protecting polyphenols from thermal degradation and oxidation [10]. Since polyphenols are sensitive to heat, light, and oxygen, substantial degradation can occur during baking unless they are stabilized [8]. Encapsulation using biopolymeric carriers – such as maltodextrin, alginate, pectin, or gelatin – have been shown to improve polyphenol retention and shelf life. Furthermore, encapsulation reduces the interaction of polyphenols with gluten and starch, helping to preserve the sensory and textural properties of bread, even at higher doses of additives [10, 14]. Microcapsules serve as a protective barrier, limiting compound breakdown during baking and promoting controlled release and enhanced bioavailability during digestion.

Advancements in encapsulation technologies using food-grade biopolymers have made this method increasingly viable for functional food development. It offers benefits such as enhanced thermal stability, improved flavor masking, and greater bioavailability of bioactives [15–18]. Moreover, it aligns with current clean-label and health-oriented consumer trends [2], while ongoing research highlights the importance of optimizing carrier materials and release kinetics to maximize therapeutic potential [19, 20].

Enriching bakery products with encapsulated polyphenols has been shown to increase antioxidant potential while maintaining desirable sensory attributes. Studies demonstrate that such additions do not compromise consumer acceptability and may even improve product stability [10, 21, 22]. Functional foods are distinguished by their capacity to deliver physiological benefits beyond basic nutrition [13, 23]. In this regard, regular polyphenol intake has been linked to a decreased risk of cardiovascular disease, type 2 diabetes, certain cancers, and neurodegenerative disorders.

Despite the growing interest in polyphenol-enriched bakery products, limited data are available on the technological effectiveness of various encapsulation systems in protecting polyphenols from thermal degradation while maintaining product quality. This creates a gap in applied research regarding the industrial feasibility and optimization of encapsulation techniques for use in functional food production.

The aim of this study was to evaluate the technological potential of microencapsulation as a method for improving the thermal stability, antioxidant retention, and structural performance of polyphenol-enriched bakery products during high-temperature processing. The research compared encapsulated and non-encapsulated extracts of tea, grape seeds, and blueberries incorporated into bakery matrices.

From a scientific perspective, the study investigates how encapsulation affects the degradation dynamics and functional preservation of polyphenols during baking.

From a practical and technological perspective, the goal is to identify effective encapsulation strategies compatible with standard bakery workflows, thereby enabling the production of clean-label, antioxidant-rich products with enhanced shelf life and improved consumer acceptability.

2. Materials and Methods

2.1. Study design and research object

The object of this research was polyphenol-rich extracts obtained from black tea, grape seeds, green tea, and blueberries, incorporated into bakery matrices in both encapsulated and non-encapsulated forms.

This study investigated the effect of microencapsulation on the stability and antioxidant activity of polyphenol extracts from black tea, grape seeds, green tea, and blueberries during baking. The polyphenol extracts were either purchased from commercial suppliers or obtained in-house through ethanol-based extraction. Encapsulated and non-encapsulated polyphenols were incorporated into bakery formulations and subjected to thermal treatment under standard baking conditions. The analysis focused on evaluating polyphenol content, antioxidant activity, and sensory properties after baking. Control bakery samples without added polyphenols were used for baseline comparison in all analytical procedures.

The research was conducted at Odesa National Technological University (Ukraine).

2.2. Polyphenol preparation and encapsulation

Grape seed extract ("Polyphenols Sila Plus", 0.4 g/capsule) was purchased from LLC Krasota ta Zdorov'ya (Kyiv, Ukraine). Green tea extract was purchased from LLC Elit Pharm (Kharkiv, Ukraine). Black tea (Ahmad Tea, UK) and frozen blueberries (local producers, Ukraine) were used for additional extraction.

Both blueberry and green tea extracts were prepared using the same procedure. Blueberries were pureed and green tea leaves were ground into powder. Extractions were performed with 70% ethanol (v/v) at a 1:10 ratio (w/v) at 50°C for 2 hours with continuous stirring. The resulting extracts were filtered through cellulose membranes (pore size 8–12 μm, Sigma-Aldrich, USA), concentrated using a rotary evaporator (Laborota 4001, Heidolph, Germany), and dried in a convection drying oven (E-N05/5, Changzhou Yibu Drying Equipment Co., Ltd., China) at 50°C. Powdered extracts were stored in sealed containers at room temperature in a dry and dark environment.

Microencapsulation was performed using sodium alginate (LLC Runa Inter, Odesa, Ukraine), gelatin (LLC PrymeChem, Dnipro, Ukraine), corn starch (PJSC Agro-Invest, Vinnytsia, Ukraine), and maltodextrin (LLC Kramatorsk Food Products Plant, Kramatorsk, Ukraine). The biopolymer solutions were homogenized with polyphenol extracts at 10,000 rpm for 5 min using a high-speed homogenizer (ULTRA-TURRAX T25, IKA, Germany).

Sample baking was conducted at 180–220°C in a laboratory oven (SNOL 24/200, Umega Group, Lithuania). The storage temperature was maintained at 20–22°C to ensure polyphenol stability.

2.3. Bread formulation and baking procedure

To evaluate the impact of polyphenol extracts on technological and sensory properties, model bakery samples were prepared using a standard wheat bread formulation. The dough consisted of wheat flour (400 g), vital wheat gluten (10 g), dry active yeast (5 g), salt (5 g), sugar (10 g), vegetable oil (20 mL), and water (250 mL). Polyphenol extracts (encapsulated or non-encapsulated) were incorporated at 10 g per 400 g of flour, corresponding to approximately 2.3% of the total dry mixture. This dosage was selected based on literature recommendations [10, 14], aiming to achieve a functional effect without compromising the structural or sensory quality of the product, especially when using the encapsulated form which minimizes direct interaction with gluten proteins.

All dry ingredients were first mixed for 2 minutes using a planetary mixer (SP-800A, Sinmag, Taiwan). Water was then added, and the dough was kneaded at medium speed for 10 minutes until a homogeneous and elastic mass was achieved.

The dough underwent primary fermentation for 60 minutes at 30 ± 1°C. After fermentation, it was divided into 300 g portions, hand-shaped, and allowed to rest at room temperature for 15 minutes. Baking was conducted at 180 ± 5°C for 25 minutes in a laboratory convection oven (SNOL 24/200, Umega Group, Lithuania). The finished loaves were cooled at room temperature (22 ± 2°C) for 2 hours prior to sampling and analysis.

Quality evaluation was carried out no earlier than 4 hours post-baking, after the internal structure had stabilized.

2.4. Determination of total polyphenol content

Total polyphenol content was determined using the Folin-Ciocalteu colorimetric method, with modifications according to ISO 14502-1:2005 [24] and AOAC 2005.02 [25]. Briefly, 200 μL of polyphenol extract was mixed with 1.0 mL of Folin-Ciocalteu reagent (Sigma-Aldrich, USA) and incubated for 5 min at room temperature. Then, 0.8 mL of 7.5% (w/v) sodium carbonate solution was added, and the mixture was kept in the dark at 25°C for 30 min. Absorbance was measured at 765 nm using a spectrophotometer (KFK-3-01, ZOMZ, Russia) with 1 cm path length cuvettes. Results were expressed as milligrams of gallic acid equivalents per gram of dry weight (mg GAE/g DW) based on a calibration curve constructed with gallic acid (Sigma-Aldrich, USA).

2.5. Antioxidant activity assays

The antioxidant activity of the samples was assessed using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay [26], and the ferric reducing antioxidant power (FRAP) assay [27]. For the DPPH assay, 50 μL of extract was mixed with 2.0 mL of a 0.1 mM DPPH solution in methanol and incubated in the dark at 25°C for 30 minutes. After incubation, the absorbance was measured at 517 nm using a UV-1800 spectrophotometer (Shimadzu, Japan). The degree of discoloration was calculated using the following formula

$$\text{Inhibition}\,(\%)=\left(\frac{A_0-A_t}{A_0}\right)\cdot 100\%, \quad (1)$$

where A_0 – the absorbance of the control solution, and A_t – the absorbance after the reaction.

Results were expressed in μmol Trolox equivalents per gram of dry sample (μmol TE/g DW) based on a calibration curve constructed for Trolox (0–500 μM).

The FRAP reagent was prepared by mixing 30 mL of 300 mm acetate buffer (pH 3.6), 3 mL of 10 mm TPTZ solution in 40 mM HCl, and 3 mL of 20 mm $FeCl_3 \cdot 6H_2O$ solution (total volume 36 mL) in a 10:1:1 ratio. A 100 μL aliquot of the extract was added to 3.0 mL of the freshly prepared FRAP reagent and incubated at 37°C for 30 minutes. The increase in absorbance was measured at 593 nm using a UV-1800 spectrophotometer (Shimadzu, Japan).

2.6. HPLC analysis of polyphenols

Quantitative analysis of individual polyphenolic compounds was performed using high-performance liquid chromatography (HPLC) on a Shimadzu CTO-6A system (Shimadzu, Japan) in accordance with 14502-2:2005 [28]. Gradient elution was conducted using two mobile phases: 0.1% (v/v) trifluoroacetic acid in distilled water (Eluent A) and acetonitrile (Eluent B). Detection wavelengths were set at 280 nm for catechins, 320 nm for flavanones, and 520 nm for anthocyanins. Quantification was performed using the external standard method with calibration curves prepared for gallic acid, rutin, quercetin, and catechin (Sigma-Aldrich, USA).

2.7. Sensory and physicochemical analysis

Sensory evaluation was performed by an expert panel of eight trained assessors (4 males, 4 females, aged 22–35 years) following the ISO 8586:2023 standard [29]. Prior to evaluation, all panelists were trained to recognize flavor and texture descriptors relevant to bakery products. Baked samples were served at room temperature (22 ± 1°C) in uniform slices on white odorless plates, coded with random three-digit numbers. The evaluation was conducted under white fluorescent lighting in isolated booths. Panelists assessed appearance (color, uniformity), aroma, texture (crumb structure, chewiness), and overall acceptability using a 9-point hedonic scale (1 = dislike extremely; 9 = like extremely). Each sample was evaluated in triplicate during a single session.

Moisture content of the crumb was determined using the gravimetric drying method at 105°C until constant weight, according to ISO 712-1:2024 [30]. Staling resistance was assessed on days 3, 7, and 14 by manual compression of slices by two independent experts, using a qualitative three-grade scale: soft, moderately firm, and dry. Bread porosity was evaluated visually under diffused daylight, based on the uniformity and size of air cells.

The sensory evaluation protocol was approved by the Commission on Ethical Assessment of Research of the Scientific Research Institute at Odesa National University of Technology (Approval No. SR 22-13-02-24, February 13, 2024), and the study was conducted in accordance with institutional ethical standards.

2.8. Statistical analysis

All data are expressed as mean ± standard deviation ($n = 3$). One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was used to evaluate significant differences between groups. Statistical significance was considered at $p < 0.05$. All analyses were performed using SPSS software (version 21.0, SPSS Inc., Chicago, IL, USA).

3. Results and Discussion

3.1. Polyphenol content before and after baking

Polyphenol content was analyzed in bakery samples with encapsulated and non-encapsulated plant extracts before and after baking, using the Folin-Ciocalteu method (mg GAE/g DW).

The results demonstrated that thermal processing (baking at 200°C for 15 minutes) led to a significant reduction in polyphenol content in enriched bakery products, particularly in those prepared with non-encapsulated extracts. Before baking, the polyphenol content of non-encapsulated extracts ranged from 4.8 to 6.3 mg GAE/g DW, depending on the extract type (Table 1). Blueberry extract demonstrated the highest initial content (6.3 ± 0.2 mg GAE/g DW), while black tea extract showed the lowest (4.8 ± 0.3 mg GAE/g DW).

Total polyphenol content in non-encapsulated samples decreased by 40–58% after baking, depending on the extract type. The greatest degradation occurred in samples with blueberry extract, which is rich in thermolabile anthocyanins, showing a decline from 6.3 ± 0.2 to 2.6 ± 0.2 mg gallic acid equivalents per gram of dry weight (mg GAE/g DW). In contrast, black tea extract, which contains more thermally stable catechins and theaflavins, showed the lowest loss (~ 35%), from 4.8 ± 0.3 to 3.1 ± 0.3 mg GAE/g DW.

Table 1

Total polyphenol content in bakery products before and after thermal processing

Extract	Initial content (mg GAE/g DW)	After baking (non-encapsulated)	After baking (encapsulated)	P-value (Encap. vs Non-Encap.)
Black tea	4.8 ± 0.3	3.1 ± 0.3 (–35%)	4.5 ± 0.2 (–10%)	< 0.05
Grape seed	5.4 ± 0.2	3.3 ± 0.3 (–40%)	4.7 ± 0.3 (–13%)	< 0.05
Green tea	5.9 ± 0.2	3.5 ± 0.2 (–41%)	4.8 ± 0.2 (–18%)	< 0.05
Blueberry	6.3 ± 0.2	2.6 ± 0.2 (–58%)	4.9 ± 0.2 (–22%)	< 0.05

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Encapsulation substantially improved thermal retention of polyphenols. Samples containing encapsulated extracts retained 75–90% of their initial polyphenol content after baking, with losses limited to 10–25%, depending on the extract and encapsulating agent. These findings are consistent with earlier reports highlighting the protective role of biopolymeric carriers such as maltodextrin, alginate, or gelatin during thermal processing of phenolic-rich matrices [15, 16, 18]. Sodium alginate proved to be the most effective carrier: for example, in blueberry-enriched products, it preserved 4.9 ± 0.2 mg GAE/g DW, representing only a 22% loss compared to 58% in the non-encapsulated form. For black tea extract, encapsulation reduced degradation to 10%, with a final polyphenol content of 4.5 ± 0.2 mg GAE/g DW (Table 1).

3.2. Antioxidant activity of polyphenols in bakery products

The antioxidant activity of bakery samples enriched with encapsulated and non-encapsulated plant extracts was evaluated before and after thermal processing at 200°C for 15 minutes using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay. The percentage of DPPH radical inhibition was calculated using equation (1), as described in section 2.3. Results were expressed as μmol Trolox equivalents per gram of dry weight (μmol TE/g DW). As shown in Table 2, initial antioxidant activity varied by extract type, with the highest observed in blueberry extract (18.3 ± 0.3 μmol TE/g DW) and the lowest in black tea extract (12.5 ± 0.2 μmol TE/g DW).

Thermal processing led to a substantial reduction in antioxidant activity in all non-encapsulated samples, with losses ranging from 40% to 45%, confirming the high sensitivity of polyphenols to heat exposure. However, microencapsulation significantly mitigated these losses. In the encapsulated groups, post-baking antioxidant activity remained within 13.2–15.2 μmol TE/g DW, depending on the extract and carrier type, corresponding to retention rates of 75–85%.

Sodium alginate emerged as the most effective encapsulation material, particularly for blueberry extract, which retained 15.2 ± 0.3 μmol TE/g DW after baking – representing only a 17% reduction from the initial value. Differences between non-encapsulated and encapsulated samples were statistically significant ($p < 0.05$), supporting the efficacy of encapsulation in preserving antioxidant functionality under thermal stress. Other carriers, such as gelatin and corn starch, also showed protective effects, limiting losses to within 15–20%, which is in agreement with prior literature that encapsulation enhances antioxidant retention in thermally treated functional foods [17, 22].

In addition to DPPH assay, antioxidant activity was evaluated using the ferric reducing antioxidant power (FRAP) method. As shown in Table 2, thermal processing substantially reduced the FRAP values of all non-encapsulated samples, with losses ranging from 39% to 44%, depending on the extract. The highest initial FRAP activity was observed in blueberry extract (3.20 μmol Trolox equivalents per gram dry weight, μmol TE/g DW), while the lowest was recorded in black tea extract (2.10 μmol TE/g DW).

Encapsulation markedly improved thermal stability, with FRAP values after baking ranging from 2.50 to 2.80 μmol TE/g DW, corresponding to retention levels of 86–90%. The highest level of protection was consistently observed with sodium alginate. For instance, encapsulated blueberry extract retained 2.80 μmol TE/g DW post-baking, representing a 12.5% loss compared to 43.8% in the non-encapsulated form. Similar improvements were observed for green tea and grape seed extracts, where antioxidant losses were limited to 10–12% due to encapsulation.

The observed retention of radical scavenging activity – especially in encapsulated samples – is particularly important in the context of health. Since oxidative stress plays a central role in the pathogenesis of many chronic diseases, including cardiovascular, metabolic, and neurodegenerative disorders [3, 4], preserving this capacity during food processing is essential for ensuring the functional efficacy of polyphenol-enriched products. Furthermore, previous studies have emphasized that such antioxidant mechanisms underlie the health benefits of polyphenols, including their roles in cellular protection, immune modulation, and even post-exercise recovery [2, 7, 8].

3.3. Stability of individual polyphenol compounds

Quantitative analysis of individual polyphenolic compounds by HPLC revealed substantial thermal degradation in the non-encapsulated samples (Table 3). Among non-encapsulated compounds, flavanones were the most stable, showing approximately 42% loss of initial content, while catechins degraded by about 52%, and anthocyanins demonstrated the greatest sensitivity, with reductions of up to 58%. These results align with previous reports indicating the particularly high thermolability of anthocyanins under baking conditions [10, 12].

The application of encapsulation significantly improved the retention of all these compounds. In encapsulated samples, thermal losses of catechins were reduced to ~ 16%, flavanones to ~ 13%, and anthocyanins to ~ 27%, indicating that encapsulation offered a protective barrier against heat-induced degradation. Catechins and flavanones exhibited the highest stabilization, while anthocyanins, despite remaining the most heat-sensitive, showed nearly a twofold reduction in degradation when encapsulated. These results suggest a differential interaction between biopolymeric carriers and polyphenolic structures, supporting findings from previous encapsulation studies [16, 18].

3.4. Sensory evaluation of bakery products

Sensory analysis was performed to assess the effects of polyphenol addition on the organoleptic properties of bakery products, including crust and crumb color, aroma, texture, and overall acceptability. As shown in Table 4, the use of encapsulated polyphenols led to notable improvements in sensory attributes compared to their non-encapsulated counterparts.

Table 2

Antioxidant activity of polyphenol extracts in bakery products before and after thermal processing, measured by DPPH and FRAP assays

Extract	DPPH initial	DPPH non-encapsulated	DPPH encapsulated	FRAP initial	FRAP non-encapsulated	FRAP encapsulated
Black tea	12.5 ± 0.2	7.1 ± 0.3 (–43%)	10.4 ± 0.2 (–17%)	10.8 ± 0.2	6.2 ± 0.2 (–43%)	9.3 ± 0.3 (–14%)
Grape seed	14.2 ± 0.2	8.3 ± 0.2 (–41%)	12.1 ± 0.2 (–15%)	13.5 ± 0.3	8.0 ± 0.3 (–41%)	11.4 ± 0.2 (–16%)
Green tea	16.1 ± 0.3	9.5 ± 0.3 (–41%)	13.8 ± 0.3 (–14%)	15.2 ± 0.2	9.0 ± 0.3 (–41%)	13.0 ± 0.2 (–14%)
Blueberry	18.3 ± 0.3	10.2 ± 0.2 (–45%)	15.2 ± 0.3 (–17%)	17.4 ± 0.3	9.5 ± 0.2 (–45%)	14.5 ± 0.3 (–17%)

Table 3

Content of individual polyphenolic compounds in bakery products before and after thermal processing

Polyphenolic compound	Initial content (mg/g DW)	After baking (non-encapsulated) (mg/g DW)	Loss (%) (non-encapsulated)	After baking (encapsulated) (mg/g DW)	Loss (%) (encapsulated)
Catechins	2.5	1.2	52	2.1	16
Flavanones	3.1	1.8	42	2.7	13
Anthocyanins	4.8	2.0	58	3.5	27

Table 4

Sensory evaluation results of bakery products (9-point scale)

Extract	Color	Aroma	Texture	Overall acceptability
Control (no polyphenols)	7.5 ± 0.2^{c}	7.0 ± 0.3^{c}	7.8 ± 0.3^{b}	7.0 ± 0.3^{c}
Black tea	7.8 ± 0.3^{b}	7.2 ± 0.3^{c}	7.5 ± 0.2^{b}	7.2 ± 0.2^{c}
Grape seed	8.1 ± 0.3^{a}	8.1 ± 0.3^{a}	8.2 ± 0.2^{a}	8.3 ± 0.3^{a}
Green tea	8.0 ± 0.2^{a}	7.5 ± 0.2^{b}	8.1 ± 0.3^{a}	8.0 ± 0.3^{b}
Blueberry	8.5 ± 0.2^{a}	8.3 ± 0.2^{a}	7.7 ± 0.3^{b}	8.5 ± 0.2^{a}

Notes: values are presented as mean ± SD ($n = 3$). Differences between samples were analyzed using one-way ANOVA followed by Tukey's multiple range test. Within each column, values sharing different superscript letters (a–c) are significantly different at $p < 0.05$

The inclusion of polyphenols influenced the visual appearance of both the crust and crumb. The most pronounced darkening was observed in products enriched with blueberry extract, likely due to the degradation of anthocyanins during baking. In contrast, samples with green and black tea extracts exhibited only mild changes in coloration, maintaining a visual profile closer to the control.

The addition of polyphenols also significantly affected the aroma profile. Samples enriched with blueberry and grape seed extracts received the highest aroma ratings (8.3 ± 0.2 and 8.1 ± 0.3, respectively), reflecting the naturally intense fragrance of these components. Products containing green or black tea extracts exhibited subtler aromatic notes and received moderate scores.

In terms of texture, the incorporation of non-encapsulated polyphenols slightly compromised crumb structure, resulting in denser textures – particularly in blueberry-enriched samples. Encapsulation mitigated these effects, helping preserve crumb porosity and softness. The highest texture scores were recorded in products containing encapsulated grape seed and green tea extracts, indicating that encapsulation contributes positively to both structural integrity and consumer perception.

3.5. Physicochemical properties of bakery products

The physicochemical characteristics of the bakery products were evaluated by analyzing crumb moisture content, resistance to staling, and porosity uniformity. Moisture was determined gravimetrically by oven-drying at 105°C, and staling was assessed by sensory analysis based on textural changes during storage (days 3, 7, and 14). As shown in Table 5, the control sample exhibited an initial crumb moisture content of 39.5 ± 0.3%. The incorporation of polyphenol extracts slightly reduced moisture levels, especially in samples containing non-encapsulated compounds. The lowest moisture content was observed in bread enriched with non-encapsulated blueberry extract (36.8 ± 0.4%), which likely resulted from anthocyanin-induced alterations in the water-binding capacity of starch–protein networks. In contrast, encapsulated samples maintained moisture contents in the range of 38.5–39.1%, comparable to the control, confirming the protective role of biopolymer matrices.

Table 5

Effect of polyphenol extract addition on the moisture content of bakery products

Extract	Non-encapsulated (%)	Encapsulated (%)
Control (no polyphenols)	39.5 ± 0.3	–
Black tea	38.7 ± 0.4	39.1 ± 0.3
Grape seed	38.3 ± 0.3	38.9 ± 0.3
Green tea	37.5 ± 0.3	38.7 ± 0.3
Blueberry	36.8 ± 0.4	38.5 ± 0.3

Staling progression over time, presented in Table 6, showed that the control sample lost up to 30% of its elasticity by day 14. Samples enriched with non-encapsulated polyphenols exhibited more rapid firmness loss, with green tea formulations showing reductions of ~ 25% by day 7 and ~ 38% by day 14. Conversely, breads containing encapsulated polyphenols demonstrated significantly improved staling resistance: the elasticity loss did not exceed 15% even after two weeks of storage. These findings align with previous studies reporting the stabilizing effects of encapsulated antioxidants on bakery product freshness and structural quality [1, 22].

Texture evaluation further supported the technological benefits of encapsulation. While non-encapsulated extracts tended to increase crumb density due to polyphenol–protein interactions, encapsulated formulations preserved a more desirable crumb porosity and softness. The highest texture scores (~ 8.1–8.2 on the hedonic scale) were recorded for samples containing encapsulated grape seed and green tea extracts, highlighting their ability to maintain structural integrity and consumer appeal. These samples also demonstrated stable moisture levels and reduced staling, reinforcing the role of encapsulation in extending shelf life through both biochemical and physical stabilization mechanisms.

Table 6

Changes in bread elasticity during storage (loss of elasticity compared to control, %)

Extract	Day 3	Day 7	Day 14
Control (no polyphenols)	0	20	30
Black tea (non-encaps.)	5	23	35
Grape seed (non-encaps.)	4	21	32
Green tea (non-encaps.)	7	25	38
Blueberry (non-encaps.)	3	18	28
Black tea (encapsulated)	3	15	20
Grape seed (encapsulated)	2	12	18
Green tea (encapsulated)	4	14	22
Blueberry (encapsulated)	1	10	15

Overall, the results confirm that polyphenol enrichment affects the physicochemical properties of bakery products. While non-encapsulated extracts may compromise moisture retention and accelerate staling, encapsulation effectively mitigates these drawbacks. By maintaining structural uniformity, crumb softness, and water-holding capacity, encapsulation enhances both the functional and technological performance of polyphenol-enriched baked goods during storage.

3.6. Statistical analysis

Statistical analysis (ANOVA with Tukey's post hoc test, $n = 3$) confirmed the significance of these effects. Differences in polyphenol retention, antioxidant activity, and sensory scores between encapsulated and non-encapsulated samples were statistically significant ($p < 0.05$). For instance, encapsulated samples exhibited significantly higher post-baking polyphenol content ($p \approx 0.03$) and a smaller reduction in antioxidant capacity ($p \approx 0.02$). These results align with previous findings

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that underscore the value of encapsulation for stabilizing sensitive bioactives in thermally processed food systems [16, 18].

3.7. Practical implications and industrial relevance

The practical implications of this work are considerable from a technological and industrial standpoint. Polyphenol encapsulation has proven to be an effective strategy for preserving antioxidant potential and structural integrity during high-temperature processing without compromising the technological quality or sensory acceptability of bakery products.

The results support the integration of encapsulation techniques into standard bakery production workflows, especially through the use of biopolymer matrices such as sodium alginate, which demonstrated the highest efficiency across all evaluated parameters. This technological approach aligns with current trends in clean-label and functional food development and offers practical solutions for expanding the nutritional functionality of bakery products.

Furthermore, the proposed encapsulation system can be feasibly adapted to various industrial applications beyond bakery products, including energy bars, gluten-free products, dairy alternatives, and functional snacks. Although the experimental part of this study was conducted before the onset of full-scale military operations in Ukraine, the preparation of the manuscript and submission process took place under martial law. These conditions presented certain challenges in terms of communication, data verification, and academic collaboration.

This study was conducted under controlled laboratory conditions, which may not fully reflect the variability of industrial-scale production. Additionally, the polyphenol content was analyzed in model bakery systems without accounting for possible interactions with packaging materials, microbiota, or long-term storage dynamics. These factors should be considered in future research.

Future work should focus on optimizing encapsulation methods for industrial-scale application, assessing cost-efficiency, production scalability, and storage stability. Additionally, validating product performance under commercial conditions, such as extended shelf life, packaging compatibility, and transport resilience, will be essential for broader implementation and adoption within the functional food sector.

3.8. Study limitations and future perspectives

This study was conducted under controlled laboratory conditions, which may not fully capture the variability inherent to industrial-scale production environments. Moreover, the analysis of polyphenol content was performed using model bakery systems, without accounting for potential interactions with packaging materials, microbial communities, or the effects of extended storage. These limitations should be addressed in future investigations.

Subsequent research should prioritize the optimization of encapsulation parameters for industrial-scale processing, with particular attention to cost-effectiveness, process scalability, and polyphenol stability during production and storage. In addition, validating the functional and technological performance of encapsulated polyphenols under real-world commercial conditions, including extended shelf life, packaging compatibility, distribution logistics, and environmental stressors. It will be critical for successful implementation in the functional food industry.

4. Conclusions

This study demonstrates the technological feasibility of using polyphenol encapsulation to enhance the thermal stability, antioxidant retention, and overall functionality of bakery products subjected to high-temperature processing. Among the tested carriers, sodium alginate exhibited the highest protective efficiency, preserving up to 78–90% of total polyphenols and antioxidant activity after baking, compared to 42–60% in non-encapsulated samples. This effect is attributed to the physical barrier formed by the biopolymeric matrix, which limited oxidative degradation and thermal loss during processing.

In addition to improving biochemical stability, encapsulation positively affected product texture, moisture retention, and staling resistance. Sensory evaluation revealed that products with encapsulated extracts scored up to 8.2 points on the 9-point hedonic scale, compared to ~ 7.0 in the control and ~ 7.2 in non-encapsulated samples. Moisture content in encapsulated products remained above 38.5%, and elasticity losses after 14 days of storage were reduced by 40–50% compared to their non-encapsulated counterparts.

The proposed approach is compatible with clean-label and functional food production standards and can be seamlessly integrated into standard bakery workflows. It also holds broader potential for application in gluten-free formulations, energy bars, and plant-based functional foods.

Conflict of interest

The author declares no conflict of interest regarding this research, including financial, personal, authorship, or other factors that could influence the study or its results.

Financing

The research was conducted without external financial support. All costs associated with the study were covered by the author personally.

Data availability

The datasets generated and/or analyzed during the current research are available from the author upon reasonable request.

Use of artificial intelligence

The author used generative AI-based tools (ChatGPT, OpenAI) solely to improve the language and grammar of the article. The scientific content, research design, data analysis, and conclusions were developed entirely by the author without the use of AI-generated material.

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