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DEVELOPMENT OF FUNCTIONAL PROTEIN BARS ENRICHED WITH ENCAPSULATED GREEN TEA POLYPHENOLS

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Aim. To apply encapsulation of green tea polyphenols as a biotechnological solution for enriching protein bars with bioactive compounds of predictable functional effect. The study also aimed to evaluate the impact of encapsulation on antioxidant activity, controlled intestinal release, and the preservation of sensory properties without the use of synthetic additives.

Methods. Polyphenols were encapsulated via spray drying using sodium alginate and incorporated into protein bars. Antioxidant activity (DPPH), texture (TPA), sensory characteristics, and *in vitro* bioavailability were assessed.

Results. Encapsulation increased antioxidant activity by 126%, reduced EGCG degradation in the gastric environment, and enabled its release in the intestine. The bars retained a favorable taste and texture, while increased hardness improved mechanical stability during storage.

Conclusions. The proposed system is an effective means of stabilizing bioactives in functional protein-based products. It ensures EGCG protection, predictable bioactivity, and compatibility with industrial-scale food production, aligning with current directions in food biotechnology and human health.

Key words: polyphenols, encapsulation, antioxidant activity, protein bars, functional foods, bioavailability.

Modern consumers of functional foods are increasingly seeking products that not only replenish energy and protein but also provide physiological benefits, such as reducing oxidative stress, supporting immunity, and aiding post-exercise recovery [1, 2]. One promising approach is the incorporation of polyphenolic compounds, particularly green tea polyphenols, which exhibit potent antioxidant, anti-inflammatory, and neuroprotective properties [3, 4]. Among them, epigallocatechin-3-gallate (EGCG), the primary catechin in green tea, is widely studied for its ability to scavenge free radicals, modulate inflammatory pathways, and protect cells from oxidative damage [5, 6].

Polyphenols, a diverse class of secondary plant metabolites, include flavonoids, phenolic acids, lignans, and stilbenes [6]. Their bioactivity is linked to free radical scavenging, inhibition of pro-inflammatory enzymes, and modulation of metabolic and cellular pathways [7, 8]. Regular intake

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has been associated with a reduced risk of cardiovascular disease, type 2 diabetes, neurodegenerative disorders, and certain cancers [9, 10]. These associations have been comprehensively reviewed in recent literature [11]. Given these benefits, polyphenols are increasingly used in functional food products, including beverages, energy bars, dairy products, snacks, and supplements.

Green tea, one of the richest natural sources of polyphenols, is particularly valued for its high catechin content, with EGCG being the most bioactive [4, 12]. The integration of green tea extracts into functional foods, such as protein bars, offers a convenient means of delivering antioxidant benefits. Commercially, green tea polyphenols are incorporated into beverages, detox teas, chocolate, and energy bars, positioned as natural antioxidant sources for metabolism and immune support [13].

However, polyphenols are highly unstable, degrading in response to heat, light, oxygen, and interactions with other food components, which significantly limits their functionality in processed foods [14, 15]. To overcome these limitations, encapsulation technology is widely used to enhance stability, control release, and improve sensory properties [16, 17]. Encapsulation provides a physical barrier against environmental factors while also masking astringency and bitterness, improving consumer acceptability [18]. It also enhances bioavailability by protecting polyphenols from gastric degradation and facilitating targeted intestinal release [19].

Various encapsulation methods utilize biopolymers such as sodium alginate, gelatin, starch, and maltodextrin to protect bioactives from degradation [15, 21]. Among these, sodium alginate is particularly effective due to its GRAS status, gelling properties, and compatibility with hydrophilic compounds like EGCG [17, 19]. Alginate-based capsules offer controlled release, enhance oxidative stability, and minimize interactions with food components, making them highly suitable for dry snack applications, including protein bars [15, 21].

Despite the growing demand for encapsulated polyphenols in functional and sports nutrition, the integration of such technologies in protein bars remains underdeveloped due to processing constraints and cost implications [22]. While premium formulations have emerged, such as controlled-release EGCG capsules and polymer-encapsulated nutraceuticals, their application in ambient-stable protein bars is still limited. This presents an opportunity for technological advancements in polyphenol stabilization that do not compromise sensory and textural attributes.

Protein bars are among the most widely consumed sports nutrition products due to their macronutrient density, portability, and extended shelf life. Recent trends indicate increasing demand for bars enriched with bioactive compounds, particularly antioxidants, anti-inflammatory agents, and neuroprotective compounds Protein bars are among the most widely consumed sports nutrition products due to their macronutrient density, portability, and extended shelf life. Recent trends indicate increasing demand for bars enriched with bioactive compounds, particularly antioxidants, anti-inflammatory agents, and neuroprotective compounds. Compared to beverages or capsules, bars offer a convenient and stable matrix for bioactive incorporation with minimal degradation during storage [20]. However, few commercial protein bars address oxidative stress induced by intense physical activity, despite its association with muscle damage, inflammation, and delayed recovery.

Green tea polyphenols, particularly EGCG, have been proposed as functional ingredients for sports nutrition due to their antioxidant and anti-inflammatory effects, vascular benefits, and cognitive support [3, 4]. Yet, their instability in ambient-stable and thermally processed products necessitates encapsulation to retain bioactivity. Protein bars fortified with encapsulated green tea polyphenols could offer a practical and effective solution, providing both nutritional and physiological benefits.

This study aimed to develop a protein bar enriched with encapsulated green tea polyphenols to enhance antioxidant potential while maintaining desirable sensory and technological properties. The research evaluated the impact of encapsulated EGCG on antioxidant stability, texture, and storage performance, hypothesizing that encapsulation would preserve key functional attributes while increasing total antioxidant capacity by at least 30% compared to the control formulation without polyphenols.

Materials and Methods

The experimental part of this study was conducted in accredited laboratories of

Ukrainian research institutions, including, but not limited to, Odesa National Technological University and I. I. Mechnikov Odesa National University, depending on the availability of equipment and methodological requirements. All analyses were performed in accordance with standardized protocols under the supervision of qualified personnel.

Two formulations of a 60 g protein bar were developed: a control (C) without polyphenols and an experimental (E) enriched with 0.2% (w/w) of encapsulated green tea polyphenols. A standardized green tea extract (purity standardized to ~20% EGCG) was employed as the core material for encapsulation. The addition level of 0.2% encapsulated powder corresponds to approximately 120 mg per 60 g bar, delivering ≈ approximately 24 mg of EGCG, assuming a 20% EGCG content in the standardized extract. The encapsulation efficiency (78.4%) was considered only for determining the proportion of free and entrapped compounds and did not affect the extract's specification or the calculated EGCG content in the formulation.

The fortification level of approximately 24 mg EGCG per bar was established based on physiological relevance, functional efficacy, and sensory acceptability criteria. Green tea polyphenols, particularly EGCG, are recognized for their potent antioxidant and anti-inflammatory properties, which contribute to maintaining redox balance and supporting recovery processes relevant to sports nutrition [3–5]. Although most human trials have utilized higher catechin intakes (100–600 mg/day), several randomized controlled studies demonstrated that repeated consumption of green-tea beverages or extracts providing moderate EGCG doses improved plasma antioxidant capacity, increased glutathione levels, and attenuated exercise-induced oxidative stress in active and weight-trained adults [23–25]. Furthermore, recent nutritional reviews emphasize the value of polyphenol-enriched functional foods as a feasible dietary approach to support oxidative balance and physical performance [26, 27]. Therefore, the selected EGCG level represents a conservative yet functionally meaningful fortification dose that aligns with physiological evidence and maintains product palatability, acknowledging that validation of this lower range within food matrices requires further clinical investigation.

The protein matrix in both samples consisted of protein ingredients, included whey protein concentrate (Optimum Nutrition, USA), soy protein isolate (SUPRO, IFF, USA), milk protein isolate (Optimum Nutrition, USA), and collagen hydrolysate (Gelita AG, Germany). All ingredients were food-grade and obtained in bulk for laboratory use.

Carbohydrates and fiber components included are isomaltooligosaccharides (LLC Pro-Fiber, Kharkiv, Ukraine), soluble corn fiber (LLC Zdorov'ya, Ukraine), tapioca starch (PJSC Agro-Invest, Ukraine), and glycerol (LLC Biokomplekt, Ukraine). The fat phase comprised refined coconut oil (LLC Ekol, Ukraine) and plant-based cream powder (LLC Technologia Produktu, Ukraine). Additional ingredients included defatted peanut flour, maltitol-based chocolate glaze, cocoa powder (Barry Callebaut, Belgium), freeze-dried raspberries (local supplier, Ukraine), natural flavors, food-grade salt, and a sweetener blend of sucralose and steviol glycosides. All ingredients met commercial food-grade specifications.

Dry and liquid ingredients were weighed to a precision of 0.1 g. The fat phase was pre-melted in a water bath at 40–45 °C. The carbohydrate base was blended separately, followed by the incorporation of the melted fats. Protein powders and cocoa were then added and mixed using manual or low-speed paddle blending to achieve a homogeneous, pliable mass. In sample E, encapsulated polyphenols were added at the final mixing stage at a temperature not exceeding 35 °C to maintain capsule integrity. The mixture was portioned into 60 g bars using molds and cooled at 4–6 °C for 2 hours to stabilize the texture.

2.1. Encapsulation of Green Tea Polyphenols

Encapsulated green tea polyphenols were prepared via spray drying using sodium alginate as the encapsulating matrix. A standardized aqueous extract of green tea containing 2% epigallocatechin gallate (EGCG) was mixed with a 1.5% (w/w) sodium alginate solution.

The sodium alginate concentration of 1.5% (w/w) was selected based on formulation trials and technological considerations related to solution viscosity and spray-drying performance. Literature suggests that alginate concentrations below 1.0% result in poor encapsulation efficiency due to weak matrix formation and low product yield during spray drying [28]. Encapsulated green tea polyphenols were prepared via spray drying using sodium alginate as the encapsulating

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2.2. Microscopic Analysis

Morphological characteristics of the encapsulated powder were examined using scanning electron microscopy (JEOL JSM–35C, Japan). Powdered samples were mounted on standard aluminum stubs and analyzed under vacuum conditions. The SEM assessment provided qualitative insights into particle shape and surface structure.

Particle size measurements were performed using optical microscopy (MICROmed Evolution ES-4130, Ukraine) at 400× magnification with a calibrated eyepiece micrometer, following dispersion of the powder in distilled water.

2.3. Encapsulation Efficiency (EE) Determination

Encapsulation efficiency of EGCG was determined indirectly by quantifying the non-encapsulated (free) polyphenols in the aqueous phase after dispersion and centrifugation, using the Folin–Ciocalteu colorimetric method in accordance with ISO 14502-1:2005 [31]. For this, 500 mg of capsule powder was accurately weighed and suspended in 10 mL of distilled water. The suspension was stirred at 200 rpm for 30 min at room temperature, followed by centrifugation at 5000 rpm for 15 min using a laboratory centrifuge (CLn-16, Biosan, Latvia). An aliquot of 200 µL of the resulting supernatant 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 a 7.5% (w/v) sodium carbonate solution was added. The mixture was incubated in the dark for 30 minutes at 25 ± 1 °C. Absorbance was measured at 765 nm using a visible light spectrophotometer (UV-Vis 752 N, China) with 1 cm path length quartz cuvettes. Gallic acid (Sigma-Aldrich, USA) was used for calibration, and results were expressed in mg GAE/g DW.

Encapsulation efficiency was calculated using the following formula:

$$EE\,(\%) = \left[\frac{\text{Total EGCG} - \text{Free EGCG}}{\text{Total EGCG}}\right] \times 100\%, \quad (1)$$

All determinations were performed in triplicate, and values are expressed as mean ± standard deviation.

2.4. Test for Antioxidant Activity

Antioxidant activity was determined using the DPPH radical scavenging [32]. Methanolic extracts were prepared from homogenized protein bar samples. A 50 µL aliquot of each extract was mixed with 2 mL of 0.1 mM DPPH solution in methanol and incubated at 25 °C in the dark for 30 minutes. Absorbance was measured at 517 nm using a UV-visible spectrophotometer. Radical scavenging activity was calculated as the percentage of DPPH inhibition and expressed in µmol Trolox equivalents per gram of dry matter (µmol TE/g DM), based on a calibration curve (0–500 µM Trolox).

To evaluate antioxidant stability, bar samples were stored in hermetically sealed containers at 18–20 °C, protected from light, and tested at 0, 2, and 4 weeks. The DPPH assay was used to assess changes in antioxidant capacity over time.

This assay provided quantitative data on the antioxidant potential of both control and experimental samples, highlighting the contribution of encapsulated polyphenols to radical scavenging activity and storage stability.

2.5. Sensory Evaluation

Sensory evaluation was conducted with a screened and trained panel (n = 20) in accordance with ISO 8586:2012 [33] for assessor selection, using a structured 9-point liking scale consistent with hedonic testing principles.

The protocol, presentation order, and blinding adhered to good sensory practice (randomized, monadic presentation; controlled booth conditions) and were used to assess appearance, aroma, taste, and texture. The goal was to determine whether the incorporation of encapsulated polyphenols influenced consumer acceptability compared to the control sample.

Prior to testing, the study was approved by the Commission on Ethical Assessment of Research at the Odesa National University of Technology (protocol No. SR 21-13-02-24, February 13, 2024). All panelists gave informed consent prior to participation.

To monitor the effect of storage on product acceptability and polyphenol stability, sensory evaluation and DPPH analysis were repeated at 0 and 4 weeks. Samples were stored in hermetically sealed packaging at 18–20 °C in the dark.

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2.6. Texture Profile Analysis

Texture profile analysis (TPA) was conducted using a Brookfield CT3 Texture Analyzer (AMETEK Brookfield, USA) equipped with a 5 kg load cell and a cylindrical probe (P/36R, 36 mm). Bar samples were cut into 30×30×15 mm portions and equilibrated at 25 ± 1 °C. The compression test involved two consecutive compressions with a 2-second interval between cycles, simulating the mastication process. Test settings included: pre-test speed, 1.0 mm/s; test speed, 1.0 mm/s; post-test speed, 5.0 mm/s; and compression distance, 50% of the original height.

Measured parameters included hardness, cohesiveness, springiness, chewiness, and adhesiveness. Each sample was tested in triplicate, and results were expressed as mean ± standard deviation. Statistical significance between the control (C) and experimental (E) samples was assessed using one-way ANOVA followed by Tukey's post hoc test ($P < 0.05$).

This analysis assessed the impact of encapsulated polyphenols on the mechanical integrity and structural consistency of the bars, providing data relevant to processing behavior and consumer acceptability.

2.7. *In vitro* digestion analysis

In vitro digestion was carried out to evaluate the release profile of EGCG from encapsulated polyphenols under simulated gastrointestinal conditions, following a modified INFOGEST protocol. The standardized INFOGEST protocol [34, 35] was applied with minor modifications, including adjusted enzyme activities and sample-to-fluid ratios to simulate protein-bar matrix digestion.

Approximately 1.0 g of homogenized sample was mixed with simulated gastric fluid (SGF), prepared by dissolving 0.32% (w/v) porcine pepsin in 0.1 M HCl (pH 2.0), and incubated at 37 ± 1 °C for 2 h with constant agitation. After the gastric phase, the pH was adjusted to 6.8 using 1 M NaOH. Simulated intestinal fluid (SIF) containing 1.0% (w/v) pancreatin and 0.5% (w/v) bile salts was added, and the mixture was incubated for another 2 h at 37 °C. At the end of each phase, the samples were centrifuged at 5000 rpm for 10 minutes, and the supernatants were collected for EGCG analysis.

The EGCG concentration was determined using a spectrophotometer (UV-Vis 752 N, China) at 274 nm, with quantification based on a calibration curve prepared from pure EGCG standard (≥ 98% purity; Now Foods, USA) dissolved in the corresponding digestion medium. All measurements were performed in triplicate. EGCG release was expressed as a percentage of the total encapsulated compound using the following formula:

$$\text{Release}\,(\%) = \left[\frac{\text{GCG released at each phase}}{\text{total EGCG encapsulated}}\right] \times 100, \quad (2)$$

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).

Results and Discussion

This section presents the key findings regarding the incorporation of encapsulated green tea polyphenols into protein bars, with a focus on structural characteristics, antioxidant stability, texture, and sensory performance. Given that processing

and storage can compromise polyphenol functionality, special attention was paid to encapsulation efficiency and morphological stability to ensure the preservation of bioactivity in the food matrix. The feasibility of applying this strategy in sports nutrition products is also addressed.

3.1. Morphology and Encapsulation Efficiency

Although no photomicrographs or SEM images are presented in this article, particle morphology was examined using a scanning electron microscope. The visual assessment confirmed that the particles exhibited predominantly spherical to near-spherical shapes with moderately porous surfaces, a typical feature of spray-dried sodium alginate capsules under similar processing conditions. Comparable morphologies have been previously described in the literature for alginate-based encapsulation systems subjected to spray drying at inlet temperatures of 140–160 °C and high-speed homogenization, where shrinkage and surface wrinkling are common outcomes [36, 37].

Particle size was determined via optical microscopy. The average diameter was 45 ± 8 μm, which is within the typical range for encapsulated powders, although exceeding the strict definition of "microcapsules" (generally 1–100 μm). Nevertheless, similar size distributions have been reported in spray-dried encapsulation systems based on sodium alginate [40]. These findings justify the use of the general term "encapsulation" in this work.

The encapsulation efficiency (EE) of EGCG was 78.4 ± 2.5%, a relatively high value for hydrophilic polyphenols. This level of retention ensures that the bioactive fraction remains functional during formulation and processing. Similar efficiencies have been reported for sodium alginate systems under thermal stress [15, 21]. The protective mechanism relies on the gel-like matrix of alginate, which limits exposure to oxygen, light, and heat.

3.2 Antioxidant Activity

To assess the impact of encapsulation on antioxidant potential, DPPH radical scavenging activity was measured in both control (C) and experimental (E) samples. As summarized in Table 1, the incorporation of encapsulated green tea polyphenols resulted in a significant increase in total antioxidant activity (TAA), with the E sample reaching 15.4 ± 1.2 μmol TE/g DM, compared to 6.8 ± 0.5 μmol TE/g DM in the control ($P < 0.05$). This 126% increase in antioxidant activity confirms the effectiveness of encapsulation in preserving EGCG functionality within the protein matrix.

The enhancement in antioxidant activity is attributed to both the protective properties of the alginate matrix and the controlled release behavior of polyphenols. The particle structure enables gradual diffusion into the bar matrix, providing extended radical scavenging effects and mitigating early oxidation.

Long-term stability testing over four weeks showed a retention rate of 85.1% in the E sample, compared to 76.5% in the control, indicating a marked improvement in oxidative stability (Fig. 1).

From a nutritional perspective, sustained antioxidant activity of polyphenols has been reported to help protect against lipid oxidation, thereby contributing to nutrient preservation and bioavailability in various food systems [39-41]. Although the present study did not evaluate the oxidative stability of lipids or proteins in the protein bar matrix, such effects warrant future investigation. Moreover, polyphenols are known for their anti-inflammatory and metabolic health benefits, which support their relevance in sports nutrition applications [23, 24]. Thus, incorporating encapsulated polyphenols may enhance the antioxidant profile of protein bars and offer a natural alternative to synthetic antioxidants (e.g., BHA, BHT, vitamin E), in line with clean-label trends.

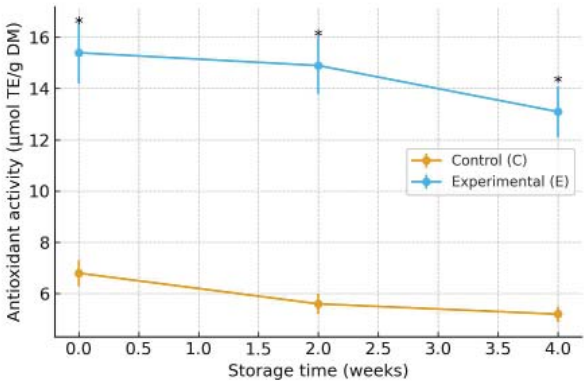

Fig. 1. **Changes in antioxidant activity (DPPH assay) of control and experimental samples during four weeks of storage**

Error bars represent standard deviations (n = 3). Asterisks () indicate statistically significant differences compared with the control ($P < 0.05$).*

Table 1

DPPH Radical Scavenging Activity and Storage Stability of Protein Bars

Parameter	Control Sample (C)	Experimental Sample (E)
Total Antioxidant Activity (TAA),	6.8 ± 0.5	15.4 ± 1.2
μmol TE/g DM	6.8 ± 0.5	15.4 ± 1.2
Antioxidant Activity (DPPH, Week 0),	5.6 ± 0.4	14.9 ± 1.1
μmol TE/g DM	5.2 ± 0.3	13.1 ± 1.0

Note: Values are presented as mean ± SD (n = 3). One-way ANOVA followed by Tukey's post hoc test ($P < 0.05$).

Table 2

Impact of encapsulation on the sensory properties of protein bars

Parameter	Control (C), week 0	Experimental (E), week 0	Control (C4), week 4	Experimental (E4), week 4
Appearance	8.2 ± 0.4	8.0 ± 0.5	7.9 ± 0.4	8.0 ± 0.4
Aroma	8.1 ± 0.5	7.8 ± 0.6	7.6 ± 0.5	7.8 ± 0.5
Taste	8.0 ± 0.6	7.6 ± 0.7	7.4 ± 0.6	7.6 ± 0.6
Texture	8.0 ± 0.4	7.7 ± 0.5	7.5 ± 0.4	7.7 ± 0.4
Overall Impression	8.2 ± 0.5	7.9 ± 0.6	7.8 ± 0.5	7.9 ± 0.5

Notes: Values are presented as mean ± SD (n = 20). No statistically significant differences were observed between samples ($P > 0.05$).

3.3. Sensory evaluation

A sensory evaluation was conducted by a trained panel of 20 participants in accordance with ISO 8586:2012. A blind, randomized protocol was applied to assess appearance, aroma, taste, texture, and overall impression using a 9-point hedonic scale (Table 2).

Both the control (C) and experimental (E) formulations were rated highly across all parameters, with no statistically significant differences observed ($P > 0.05$). Appearance scores were similar (C: 8.2 ± 0.4; E: 8.0 ± 0.5), indicating that the incorporation of encapsulated polyphenols did not negatively affect the visual appeal or structural integrity of the bars. This suggests that encapsulation effectively masked any potential discoloration or instability of polyphenols.

Taste was the most sensitive attribute, with the E sample scoring slightly lower (7.6 ± 0.7) than the control (8.0 ± 0.6). Some panelists noted mild astringent undertones and reduced sweetness, both typical characteristics of green tea polyphenols. However, these effects remained within the acceptable range, and overall impression scores remained high (C: 8.2 ± 0.5; E: 7.9 ± 0.6). Texture scores were also comparable, with a slight but non-significant reduction in springiness for the E sample (C: 8.0 ± 0.4; E: 7.7 ± 0.5).

After four weeks of storage, the experimental sample retained stable sensory attributes. In contrast, the control showed a decline in aroma (from 8.1 to 7.6) and taste (from 8.0 to 7.4), likely due to oxidative changes. The improved stability in the E_4 formulation supports the role of encapsulation in maintaining organoleptic quality during storage, which is critical for commercial applications.

These findings confirm that encapsulated polyphenols can be integrated into protein bars without compromising consumer acceptability. While minor sensory modifications were detected, they were not statistically significant and did not impair overall product perception.

Moreover, future adjustments in formulation, such as optimized encapsulation ratios or the inclusion of flavor-masking agents, may further enhance the palatability of polyphenol-enriched products. Given the close link between texture, sensory quality, and manufacturability, the following section evaluates the mechanical properties of the formulations.

The sensory data for both control and experimental bars are visualized in Fig. 2, *A*. Overall, no significant differences were observed between formulations ($P > 0.05$), confirming that the incorporation of encapsulated polyphenols did not adversely affect product acceptability.

3.4. Texture profile analysis

The instrumental texture parameters corresponding to the sensory texture perception are presented in Table 3 and Fig. 2. Fig. 3 illustrates the comparative values of key texture parameters. At the same time, Fig. 4 shows a magnified view of adhesiveness, which displayed minimal variation between samples. Together, these results provide a comprehensive representation of both sensory and mechanical properties of the protein bars.

Texture profile analysis (TPA) revealed that the incorporation of encapsulated green tea polyphenols slightly modified the mechanical properties of protein bars without compromising their structural integrity (Table 3). The hardness of the experimental sample was higher than the control (46.8 ± 2.8 N vs. 42.5 ± 3.2 N, $P < 0.05$), likely due to additional intermolecular interactions between polyphenols and proteins. Similar effects have been reported by Medina-Torres [21], who demonstrated polyphenol-induced protein cross-linking in food systems.

A non-significant reduction in springiness (7.2 ± 0.4 mm vs. 7.9 ± 0.5 mm, $P > 0.05$) may be attributed to altered hydration dynamics in the protein network, as polyphenols are known to affect water-binding and viscoelastic properties. Cohesiveness and chewiness remained statistically unchanged, and no variation in adhesiveness was observed ($P > 0.05$), indicating that the addition of encapsulated polyphenols did not negatively impact bite quality or mouthfeel.

From a production standpoint, the moderate increase in hardness may be beneficial, as it enhances resistance to mechanical stress during transport and shelf display. The absence of excessive stickiness ensures user-friendly consumption and product stability under varying storage conditions. Significantly, the encapsulated format did not interfere with standard mixing, forming, or shaping processes, and no adjustments were required during formulation. The encapsulation barrier likely minimized direct interactions with other ingredients, contributing to a uniform texture and preventing localized hardening.

These findings confirm that encapsulated polyphenols can be incorporated into protein bars without impairing key textural attributes. On the contrary, the observed improvements in mechanical strength may support broader industrial applicability. To further assess the functionality of the developed product, the following section investigates the digestion and bioavailability of encapsulated polyphenols under simulated gastrointestinal conditions.

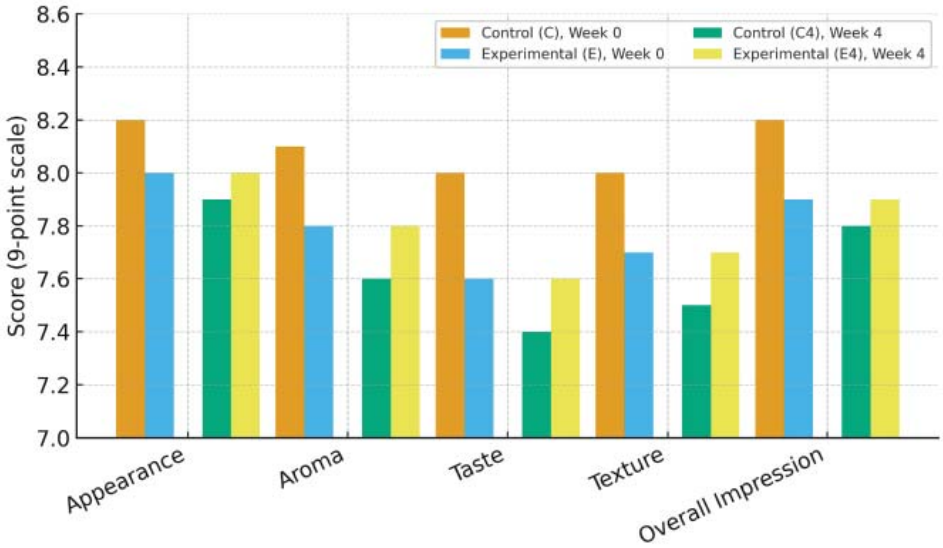

Fig. 2. **Sensory scores of control and experimental protein bars at weeks 0 and 4**

Table 3

Texture Profile Analysis of Protein Bar

Parameter	Control (C)	Experimental (E)
Hardness (N)	42.5 ± 3.2	46.8 ± 2.8
Springiness (mm)	7.9 ± 0.5	7.2 ± 0.4
Cohesiveness	0.89 ± 0.04	0.88 ± 0.05
Chewiness (mJ)	28.6 ± 2.1	29.4 ± 2.0
Adhesiveness (N·s)	0.12 ± 0.02	0.13 ± 0.03

Notes: Values are presented as mean ± SD ($n = 3$). Different superscript letters within a row indicate significant differences ($P < 0.05$).

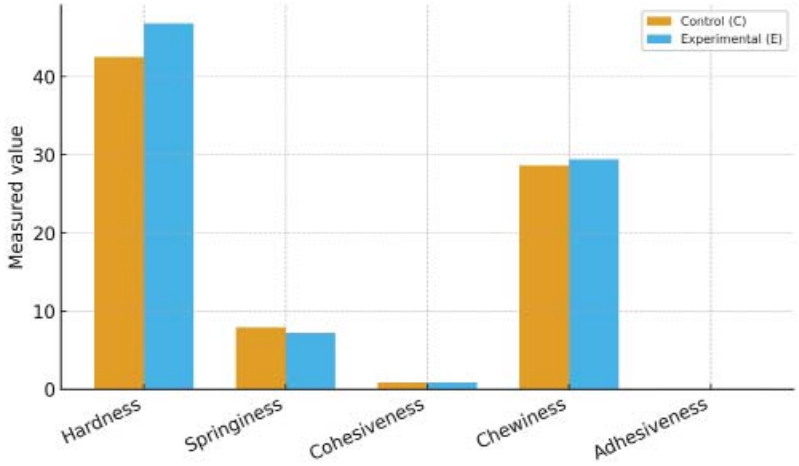

Fig. 3. **Texture profile parameters of protein bars**

Values are mean ± SD (n = 3). An asterisk (*) indicates a significant difference compared to the control ($P < 0.05$; one-way ANOVA, Tukey's test).

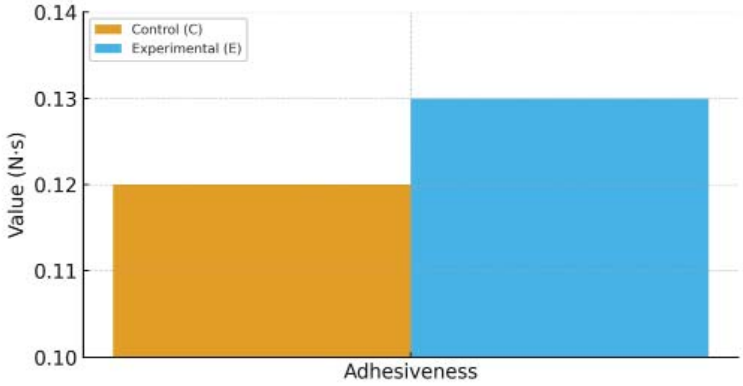

Fig. 4. **Magnified view of adhesiveness illustrating minimal variation between control and experimental samples**

3.5. *In vitro* Digestion

To evaluate the bioavailability of polyphenols, an *in vitro* digestion model was applied. The results demonstrated that encapsulated EGCG exhibited significantly greater resistance to gastric degradation ($P < 0.05$), followed by a controlled release during the intestinal phase. This outcome is particularly relevant, as free catechins are highly unstable under acidic conditions [24], limiting their functional efficacy in conventional food matrices.

During gastric digestion (pH 2.0, 37 °C, 2 h), EGCG release from the control sample reached 74.2 ± 3.5%, while the experimental sample released only 42.7 ± 2.8% ($P < 0.05$). This suggests that alginate-based capsules form

a protective gel barrier at low pH, reducing exposure to pepsin and acidic hydrolysis. Similar mechanisms have been reported in other alginate encapsulation systems [19], where the formation of a dense matrix delays premature release and degradation.

In the intestinal phase (pH 6.8, 37 °C, 2 h), EGCG release from the encapsulated sample, quantified spectrophotometrically at 274 nm, increased to 83.5 ± 3.1%, compared to 66.8 ± 2.9% in the control. This reflects a 25% relative improvement in intestinal release ($P < 0.05$), attributed to the pH-sensitive dissolution of the alginate matrix, which facilitates targeted delivery at the site of optimal absorption.

Release kinetics analysis confirmed that most EGCG in the control group degraded during the gastric phase, leading to reduced intestinal availability. In contrast, encapsulated EGCG maintained structural stability until intestinal exposure, supporting its sustained release and improved functional performance. These findings reinforce previous evidence of alginate's protective capacity and its role in enhancing polyphenol delivery.

From a technological perspective, the use of encapsulated polyphenols in functional foods, such as protein bars, offers several advantages: enhanced storage stability, reduced ingredient interactions, and decreased reliance on synthetic additives. In sports nutrition applications, regulated polyphenol release may prolong antioxidant activity and support metabolic recovery. Furthermore, encapsulation ensures compatibility with conventional processing techniques and aligns with clean-label product trends.

In summary, encapsulation significantly improves the gastric protection, intestinal release, and bioavailability of green tea polyphenols. This delivery system offers a viable strategy for developing functional foods with optimized stability and physiological efficacy. The final section addresses the industrial applicability of these findings, including formulation feasibility, processing compatibility, and economic viability in large-scale protein bar production.

3.6 Practical Implications for Industrial Protein Bar Production

The results confirm the technological feasibility of incorporating encapsulated green tea polyphenols into protein bars without requiring major adjustments to conventional production processes. The powdered form of the encapsulated ingredient allows easy integration into standard operations such as mixing, extrusion, and molding, ensuring homogeneous distribution of bioactives within the matrix and maintaining processing efficiency.

From a storage perspective, improved oxidative stability suggests an extended shelf life, with reduced susceptibility to lipid peroxidation and protein degradation, which is critical for sports nutrition products that often contain unsaturated fats and isolated proteins. The observed moderate increase in hardness enhances mechanical stability, minimizing breakage during packaging and distribution, while unchanged adhesiveness ensures consistent textural perception and consumer satisfaction.

Economically, this approach may reduce production costs by decreasing dependence on synthetic stabilizers, preservatives, and specialized packaging materials. The enhanced stability and targeted release of polyphenols also contribute to greater functional value, which aligns with consumer demand for clean-label, bioactive-enriched food products.

Overall, the encapsulation system demonstrated compatibility with industrial-scale production and storage conditions, supporting its application in the development of commercial protein bars. Future research should focus on optimizing encapsulation parameters to balance functional efficacy, cost-effectiveness, and sensory appeal, facilitating the market introduction of polyphenol-enriched sports nutrition products.

The obtained encapsulated powder was successfully incorporated into the protein bar matrix without altering the formulation's texture, appearance, or processability, indicating technological compatibility. The total antioxidant capacity of the bars (DPPH) was quantified at weeks 0–4. Although chromatographic profiling of individual catechins was beyond the scope, future work should include HPLC speciation to corroborate UV-Vis-based EGCG estimates during digestion and storage.

Conclusions

The study confirmed the effectiveness of sodium alginate-based encapsulation of green tea polyphenols in enhancing the technological and functional properties of protein bars. Capsules with a mean diameter of 45 ± 8 μm exhibited high encapsulation efficiency and structural uniformity, enabling consistent distribution of bioactives within the food matrix. The incorporation of encapsulated

polyphenols resulted in a 126% increase in total antioxidant activity and significantly enhanced polyphenol stability during storage.

In vitro digestion modeling revealed reduced gastric degradation and a 24.9% increase in intestinal release, indicating enhanced bioavailability and prolonged functionality. Sensory evaluation showed that the encapsulated polyphenols did not adversely affect the organoleptic profile, with only minor and acceptable changes in taste and texture. Texture analysis revealed a moderate increase in hardness, which may enhance the mechanical resistance of the bars during processing and storage, while cohesiveness and chewiness remained unchanged.

The encapsulation technique was fully compatible with conventional food production processes, requiring no additional technological adaptation. These findings suggest compatibility with conventional mixing/molding workflows and may support extended shelf life through improved oxidative stability. Nevertheless, full-scale pilot trials and accelerated aging studies are warranted to confirm the robustness of the distribution and long-term quality.

Future research should focus on optimizing the composition of wall materials and microcapsule size to strike a balance between bioactive protection and sensory quality. Further investigation into synergistic interactions with other functional compounds, as well as *in vivo* validation of long-term bioefficacy under real consumption conditions, is also recommended.

Findings

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РОЗРОБЛЕННЯ ФУНКЦІОНАЛЬНИХ ПРОТЕЇНОВИХ БАТОНЧИКІВ, ЗБАГАЧЕНИХ ІНКАПСУЛЬОВАНИМИ ПОЛІФЕНОЛАМИ ЗЕЛЕНОГО ЧАЮ

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Мета. Застосувати мікрокапсулювання поліфенолів зеленого чаю для збагачення протеїнових батончиків біоактивними сполуками з прогнозованим функціональним ефектом. Дослідження також передбачало оцінювання впливу інкапсуляції на антиоксидантну активність, стабільність EGCG, контрольоване вивільнення у кишечника та збереження органолептичних властивостей без синтетичних добавок.

Методи. Поліфеноли інкапсулювали методом розпилювального сушіння з альгінатом натрію та додавали до протеїнових батончиків. Оцінювали антиоксидантну активність (DPPH), текстуру (TPA), сенсорні властивості (ISO 8586:2019) та біодоступність *in vitro*.

Результати. Мікрокапсулювання підвищило антиоксидантну активність на 126%, зменшило деградацію EGCG у шлунковому середовищі та забезпечило його вивільнення в кишечнике. Батончики зберегли смак і текстуру, а зростання твердості покращило механічну стійкість.

Висновки. Запропонована система є ефективним засобом стабілізації біоактивів для функціональних протеїнових продуктів. Вона забезпечує захист EGCG, прогнозовану біоактивність і є сумісною з промисловим виробництвом, що відповідає сучасним напрямам біотехнології продуктів харчування та здоров'я людини.

Ключові слова: поліфеноли, мікрокапсулювання, антиоксидантна активність, протеїнові батончики, функціональні продукти, біодоступність.