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Changes in the Quality of Dried Vacuum-Infused Strawberries Enriched with Encapsulated Pomegranate Peel Extract During Storage

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The low stability of phenolic compounds restricts their use in the food industry. Encapsulation can help protect these compounds during food processing. In this study, pomegranate peel extract (PPE) was encapsulated and then used to produce dried vacuum-infused strawberries. The quality changes of strawberry products enriched with encapsulated pomegranate peel extract (EPPE) were investigated during 90 days of storage at 25°C and compared to those infused with non-encapsulated PPE. During storage, the dried strawberries enriched with EPPE exhibited higher contents of total phenolics and individual phenolics, such as ellagic acid and punicalagin, than the dried strawberries with PPE. The total phenolic content of the strawberry product with EPPE was preserved at 9.40% better after 90 days of storage compared to the product enriched with PPE. Additionally, after storage, the strawberry product with EPPE showed significantly lower microbial counts (total aerobic mesophilic bacteria, yeast, and mold) and reduced browning index compared to the product with PPE. Moisture content changes during storage were controlled to the greater extent in the product with EPPE, contributing to its structural integrity. These results indicate that encapsulation, combined with vacuum impregnation, can effectively enhance the stability, microbial safety, and shelf-life of dried infused strawberries.

Keywords: encapsulation, pomegranate by-product, storage vacuum impregnation, strawberry snack

ABBREVIATIONS

AJC, apple juice concentrate; BI, browning index; EPPE, encapsulated pomegranate peel extract; GAE, gallic acid equivalent; GMO, glycerol monooleate; IQF, individually quick frozen; PPE, pomegranate peel extract; PPs, pomegranate peels; SFO, sunflower oil; TPC, total phenolic content; TSS, total soluble solids; VI, vacuum impregnation.

INTRODUCTION

Researchers have focused on using pomegranate peels (PPs) to extract valuable phenolic compounds and produce natural antioxidant additives for use in the food industry [Kaderides *et al*., 2021]. *In vitro* and *in vivo* studies have shown that these compounds elicit health-promoting effects due to their anti-inflammatory, antimutagenic, anticarcinogenic, and antihypertensive properties [Kandylis & Kokkinomagoulos, 2020].

As a popular processing method that enhances the stability and bioavailability of bioactive compounds, encapsulation was also used to improve PPE, offering improved health benefits and making it a viable functional food ingredient [Hady *et al*., 2022; Marcillo-Parra *et al*., 2021; Rashid *et al*., 2022]. PPE has been encapsulated by different methods, such as spray drying,

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electro-blow spinning, ionic gelation and various emulsion systems [Sanhueza *et al*., 2022; Wilkanowicz & Saud, 2023].

Strawberries are soft fruits with a high water content, susceptible to microorganisms and prone to spoilage. Therefore, various processes involving the use of nanoparticles are applied to extend their shelf-life. Li *et al*. [2023] examined the impact of solid lipid nanoparticles encapsulating cinnamaldehyde (SLN-CA) compared to non-encapsulated cinnamaldehyde on the freshness of strawberries stored for a week. The application of SLN-CA significantly decreased decay and softness, reduced the loss of organic acids, and enhanced the sensory qualities of the strawberries. In another study conducted by Yin *et al*. [2024], a nanoemulsion containing eugenol and citral was developed, exhibiting favorable physicochemical properties and antimicrobial efficacy for strawberry preservation. The findings indicated that the bilayer emulsion demonstrated significant antimicrobial activity against *Staphylococcus aureus*, *Escherichia coli*, and *Aspergillus niger*, and was proved effective in preserving the quality of strawberries during storage. Moreover, Zhu *et al*. [2025] produced cinnamon essential oil nanoemulsions (CEO NEs) and investigated their effect on the shelf-life of strawberries during storage at room temperature. The results indicated that the shelf-life of strawberries can be prolonged for up to 7 days at room temperature, with the group treated with CEO NEs exhibiting a reduced rate of weight loss and mold growth compared to the control groups. Notably, strawberries in the ultrapure water group deteriorated more quickly and became contaminated with mold after just 3 days.

In our previous study, the nanoemulsions with PPE characterized by a high phenolic content and strong antioxidant properties were prepared and their stability during storage was investigated [Ertek *et al*., 2023]. After obtaining the encapsulated pomegranate peel extract (EPPE), the process conditions to produce phenolic-infused strawberries were optimized. As a result, we maintained constant process conditions at 480 bar and 20°C for 20 min. This study continues our previous research and looks at how the quality of strawberry product obtained by vacuum impregnation with EPPE and drying changes over storage time. To the best of our knowledge, no studies have evaluated the quality characteristics of strawberry products containing an encapsulated phenolic-rich extract during storage. Therefore, the aim of this study was to determine the physicochemical parameters, phenolic contents, and microbiological stability of dried vacuum-infused strawberries enriched with EPPE during 90 days of storage and to compare their properties with those enriched with non-encapsulated PPE.

MATERIALS AND METHODS

Materials

Individually quick frozen (IQF) strawberry (var. *Camarosa*) and apple juice concentrate (AJC) (70°Brix) were supplied from Işık Organic Food Company (Kemalpaşa, İzmir, Turkey). AJC was used as the osmotic impregnation solution. PP powder was used to obtain the phenolic extracts. For this purpose, PPs were purchased from a local market (Bornova, İzmir, Turkey). The raw materials were stored at −18°C until processing. Tween 80 (T80, Merck, Rahway, NJ, USA), an encapsulating emulsifier, was purchased from Sigma-Aldrich (Saint Louis, MO, USA).

Preparation of the pomegranate peel extract

First, the PPs were washed and drained. The samples were then dried in an air-circulation oven at 50°C until the moisture content was below 10 g/100 g. The dried peels were ground using a grinder (SCM 2934, Sinbo, İstanbul, Turkey), soaked, and mixed in water at room temperature for 24 h. The solid to solvent ratio was adjusted to 3:100 g/mL. The mixture was then centrifuged using a Universal 320 R centrifuge (Hettich, Kirchlengern, Germany) at 4°C and 12,000×*g* for 15 min to separate the supernatant. Then the liquid extract was freeze-dried (Christ Alpha 1-2LD, lyophilization system, Osterode am Harz, Germany) at −40°C and 0.002 mbar. Finally, the pomegranate peel extract (PPE) was milled and stored at 4°C until encapsulation. The extraction yield was 94.5% as was determined in our previous study [Ertek *et al*., 2023].

Encapsulation of pomegranate peel extract

PPE was encapsulated with T80 and glyceryl monooleate (GMO). Our previous work optimized the encapsulation process [Ertek *et al*., 2023], and emulsions containing PPE were prepared according to the formulation: 1% (*w/w*) PPE, 1% (*w/w*) T80, 1% (*w/w*) GMO, 3% (*w/w*) sunflower oil (SFO), and 94% distilled water. Initially, the organic phase consisting of PPE and SFO and the aqueous phase containing emulsifiers and distilled water were prepared using a magnetic stirrer. Then, both phases were combined and mixed with a homogenizer (Ultra Turrax T25, IKA-Werke GmbH & Co. KG, Staufen, Germany) at 24,000 rpm for 5 min [Donsi *et al*., 2012]. Then, a high-pressure homogenizer (ML-100L microfluidizer, Microfluidics, Westwood, MA, USA) was used to obtain a nanoemulsion from the coarse emulsion (150 MPa, 5 cycles).

Vacuum impregnation of strawberries

The vacuum impregnation (VI) process was conducted using a system available at the Ege University, Department of Food Engineering, where both the vacuum level and temperature can be controlled, and the samples are agitated. The parameters that varied during the vacuum impregnation process included the vacuum pressure (100 to 480 mbar), the duration of the vacuum (10 to 30 min), and the processing temperature (between 20 and 40°C). The process was performed by keeping the optimum processing conditions constant, as determined in a previous study [Ertek *et al*., 2023]. The mass ratio of the strawberries (after being thawed at 4°C for 18 h) to the impregnation solution (AJC) was maintained at 1:1 (*w/w*). PPE solution (1%, *w/w*) or PPE nanoemulsion was added to the AJC at a ratio of 1% (*v/v*). A vacuum pressure of 480 bar was applied to the system for 10 min at 20°C. The mixtures were then kept at atmospheric pressure for 1 h. After impregnation, both groups of vacuum-infused strawberries (with PPE and with EPPE) were drained and dried in a tray dryer (50°C, Weintek, İstanbul, Turkey) until the water activity of the strawberry products was 0.60.

Storage of dried vacuum-infused strawberries

After production of the dried vacuum-infused strawberries with PPE and with EPPE, they were stored as 100 g *per* serving in 175 g polypropylene bags at 25°C (53% relative humidity) for 90 days. Just before storage (day 0) and on days 15, 30, 60 and 90 of storage, samples were taken from both groups, and quality analyses were performed.

Quality analyses of dried vacuum-infused strawberries

Total soluble solid content, moisture content, and water activity

The total soluble solid (TSS) content of the dried vacuum-infused strawberries was measured using a digital refractometer (HI96801, Hanna, Cluj-Napoca, Romania) after the strawberry products were homogenized with water at 1:5 (*w/w*) ratio. Water activity was measured using a digital water activity meter (Testo 645, Lenzkirch, Germany) [Taze & Ünlütürk, 2018]. To determine moisture content (g/100 g), the weighed samples were dried in a vacuum oven at 65±2°C, and drying was completed when the samples achieved a constant weight [AOAC, 2000].

pH and titratable acidity

The pH and titratable acidity were determined using a pH meter (Orion 2 Star, Thermo Fisher Scientific, Waltham, MA, USA) according to the method of AOAC International [AOAC, 2000]. The strawberry products were soaked in water at a 1:10 g/mL ratio and homogenized for 15 s using a homogenizer (Ultra Turrax T25, IKA-Werke GmbH & Co. KG, Staufen, Germany). Titratable acidity was measured using 0.1 M NaOH until the pH of the sample reached 8.1. The titratable acidity was expressed as g citric acid equivalents/100 g of strawberry product.

Firmness

The firmness of the vacuum-infused strawberry products was analyzed using a texture analysis device (TA XT Plus Texture Analyzer, Stable Micro Systems, Godalming, Surrey, UK), as outlined by Tylewicz *et al.* [2019]. The system was equipped with a 5 kg load cell and an 8 mm diameter stainless-steel probe. The test involved penetrating the samples to 90% of their thickness. Analysis was conducted with 8 replicates, and the results were reported as the maximum force (N) values.

Total phenolic content

In the extraction, 10 g of strawberry products were mixed with 10 mL of aqueous methanol (80%, *v/v*) and homogenized (8,000 rpm for 2 min) (Ultra Turrax T25, IKA). Then, the mixture was centrifuged at 4°C for 12,000×*g* for 15 min (Universal 320 R centrifuge, Hettich). The supernatants were stored at 4°C until analyzed.

The total phenolic content (TPC) was determined using the Folin-Ciocalteu'a reagent according to the procedure described by De Ancos *et al.* [2017]. The supernatant (200 µL) was mixed with 1 mL of the Folin-Ciocalteu'a reagent (0.2 N) in a tube and shaken for 5 min. Then, 800 µL of 3.5% (*w/v*) sodium carbonate were added, and the mixture was kept for 1 h at 25°C. After reaction, 300 µL was taken and transferred to a 96-well plate. The absorbance was measured using a microplate reader (Multiskan Go UV/VIS, Thermo Scientific, Waltham, MA, USA) at 750 nm. TPC was expressed as mg gallic acid equivalents (GAE)/100 g dry matter (dm) of strawberry product.

Punicalagin and ellagic acid content

Punicalagin and ellagic acid standards were purchased from Sigma-Aldrich (Sant Louis, MO, USA). The aqueous methanolic extract obtained for the TPC analysis was also used for punicalagin and ellagic acid determination. The high-performance liquid chromatography (HPLC) system (Agilent 1200, Santa Clara, CA, USA) was equipped with a Zorbax C18 (250×4.5 mm, 5 µm, Agilent) column and a diode array detector (DAD) to quantify the phenolics. Analysis was performed using water/acetic acid (98:2, *v/v*) (A) and methanol (B) as the mobile phase at the 1 mL/min flow rate [Çam & Hışıl, 2010]. The gradient was as follows: 5% B for 5 min, 5–70% B for 25 min, and 70–5% B for 10 min. The column temperature was maintained at 35°C. Punicalagin was detected at 280 nm, whereas ellagic acid was detected at 378 nm. Standard curves were prepared at 0–100 mg/L for punicalagin and 0–200 mg/L for ellagic acid. The results of punicalagin and ellagic acid content were expressed as mg/kg dm of strawberry product.

Browning index

The browning index (BI) of vacuum-infused strawberry products was analyzed according to the method previously used by Coskun *et al.* [2013]. For the extraction, a 2.5 g sample was combined with 25 mL of a 2% (*v/v*) acetic acid solution (Sigma Aldrich) and homogenized using an IKA T25 Ultra Turrax at 25,000 rpm for 2 min. The mixture was then centrifuged at 4,032×*g* for 10 min using a Hettich Universal 320 R centrifuge. The supernatant was collected, and the extraction process was repeated under the same conditions. Then, 2.5 mL of the combined supernatants were taken, and an equal volume of ethanol (Merck) was added. The resultant mixture was centrifuged again. Absorbance measurements against a solution of ethanol and 2% acetic acid (1:1, *v/v*) were recorded at 420 nm using a spectrophotometer (Genesys 10S Vis, Thermo Fisher Scientific). The results were expressed as A_{420}/g of strawberry product.

Microbiological analysis

Total aerobic mesophilic bacteria and total yeast and mold enumeration in dried vacuum-infused strawberries with EPPE and with PPE was performed using the AOAC International methods 990.12 and 997.02 [AOAC, 2000]. Total aerobic mesophilic bacteria were determined using plate count agar (PCA, Merck) with the pour-plate method. The plates were incubated for mesophiles at 37°C for 24–48 h. The enumeration of total yeast and molds was carried out in potato dextrose agar (acidified to pH 3.5 with 100 g/L tartaric acid) (PDA, Merck) after incubation at 25°C for 3–5 days. The results were expressed as log CFU *per* 100 g of strawberry product.

Statistical analysis

All treatments were performed in triplicate, and results were expressed as the mean and standard deviation. Statistical analysis was conducted using SPSS 18 software (SPSS Inc., Chicago, IL, USA). The analysis of variance (ANOVA) with Duncan's post hoc test was performed to evaluate the effects of encapsulation and storage time. Differences were considered significant at $p<0.05$.

RESULTS AND DISCUSSION

Total soluble solid content, moisture content, water activity, pH, and titratable acidity of dried vacuum-infused strawberries during storage

The total soluble solid (TSS) and moisture content, water activity, pH, and titratable acidity values of dried vacuum-infused strawberries with PPE and EPPE are shown in **Table 1**.

The TSS is an important parameter that reflects the quality of fruits during storage, as it is closely related to sugar content. An increase in TSS is contributes to the ripening process by enhancing the sweetness and overall flavor profile of the fruit. The more significant the decrease in TSS, the faster the deterioration of fruit quality tends to occur. While this relationship is well established in fresh fruits, where TSS reduction often reflects increased respiration and loss of sweetness, similar trends may also be observed in dried fruits during storage, potentially indicating degradation of sugars and overall product quality under certain conditions [Ghinea *et al*., 2022; Zhang *et al*., 2019]. In our study, there were no significant ($p\geq0.05$) differences in TSS between dried vacuum-infused strawberries at the beginning of storage (day 0) and on day 15 of storage in both groups (**Table 1**). However, a significant ($p<0.05$) increase was observed from day 15 to the end of storage. Strawberries of the EPPE group had significantly ($p<0.05$) higher TSS content then strawberries of the PPE group throughout the storage, which could be attributed to variations in the physical characteristics of the strawberry tissue, such as cell structure, wall integrity, and porosity. Castelló *et al*. [2006] observed differences in TSS contents in distinct tissue regions (especially pores) of the strawberry, indicating the formation of concentration gradients, which may be associated with structural and physiological changes during impregnation.

Strawberries have a short shelf-life because of their delicate tissue and high moisture content. Drying reduces the content of free water, making them microbiologically safer. Water activity of dried vacuum-infused strawberries ranged from 0.58–0.61 (**Table 1**). These values were below the critical a_w required for the growth of microorganisms (>0.65) [Gautam *et al*., 2024]. Similarly to our study, Corrêa *et al*. [2010] observed a notable decrease in the water activity of guava slices subjected to osmotic dehydration, influenced by the application of vacuum pulses and solution concentration. Previous studies have also shown that vacuum impregnation followed by drying can significantly reduce water activity. For instance, Nawirska-Olszańska *et al*. [2020] reported much lower a_w values (0.144–0.207) in impregnated chokeberry fruits, which were notably lower than the a_w range observed in our study (0.58–0.61), though both remain below the microbial growth threshold.

The moisture content of dried strawberries containing EPPE changed from 11.5 to 13.4 g/100 g during storage (**Table 1**). It significantly ($p<0.05$) increased during the 60 days of storage, but no significant ($p\geq0.05$) difference was observed in the moisture

Table 1. The total soluble solid content, moisture content, water activity, pH, and titratable acidity of dried vacuum-infused strawberries with pomegranate peel extract (PPE) and encapsulated pomegranate peel extract (EPPE) during storage.

Parameter	Group	Storage time (day)				
		0	15	30	60	90
Total soluble solid content (°Brix)	Strawberry product with EPPE	58.7 ± 0.16^{Ad}	59.3 ± 0.09^{Ad}	65.5 ± 0.19^{Ac}	72.2 ± 0.50^{Ab}	73.3 ± 0.52^{Aa}
	Strawberry product with PPE	55.2 ± 0.22^{Bd}	55.0 ± 0.05^{Bd}	60.2 ± 0.12^{Bc}	70.0 ± 0.52^{Bb}	71.9 ± 0.52^{Ba}
Moisture content (g/100 g)	Strawberry product with EPPE	11.5 ± 0.02^{Bd}	11.8 ± 0.01^{Bc}	12.5 ± 0.03^{Ab}	13.3 ± 0.14^{Aa}	13.4 ± 0.10^{Ba}
	Strawberry product with PPE	12.5 ± 0.02^{Ac}	12.1 ± 0.06^{Ad}	11.8 ± 0.02^{Be}	13.6 ± 0.08^{Ab}	14.0 ± 0.12^{Aa}
Water activity	Strawberry product with EPPE	0.60 ± 0.005^{Aa}	0.60 ± 0.005^{Aa}	0.58 ± 0.005^{Ac}	0.59 ± 0.005^{Ab}	0.59 ± 0.005^{Ab}
	Strawberry product with PPE	0.60 ± 0.005^{Ab}	0.60 ± 0.005^{Ab}	0.60 ± 0.005^{Ab}	0.60 ± 0.005^{Ab}	0.61 ± 0.009^{Aa}
pH	Strawberry product with EPPE	4.2 ± 0.01^{Aa}	3.8 ± 0.02^{Ab}	3.9 ± 0.01^{Ab}	3.8 ± 0.01^{Ab}	3.9 ± 0.02^{Ab}
	Strawberry product with PPE	4.0 ± 0.01^{Aa}	3.9 ± 0.03^{Aa}	4.0 ± 0.01^{Aa}	3.9 ± 0.01^{Aa}	4.3 ± 0.01^{Bb}
Titratable acidity (g CA/100 g)	Strawberry product with EPPE	8.3 ± 0.46^{Ab}	9.3 ± 0.35^{Aa}	9.7 ± 0.69^{Aa}	9.9 ± 0.23^{Aa}	9.8 ± 0.10^{Aa}
	Strawberry product with PPE	8.7 ± 0.40^{Ab}	9.6 ± 0.45^{Aa}	9.3 ± 0.08^{Aa}	9.1 ± 0.12^{Bb}	9.1 ± 0.07^{Bb}

Results are shown as mean ± standard deviation ($n=3$). Different uppercase letters (A and B) in the same column, separately for each parameter, indicate significant differences between groups ($p<0.05$). Different lowercase letters (a–e) in the same line for each group indicate significant differences between storage times ($p<0.05$). CA, citric acid equivalent.

content during the last month of storage. At the end of storage, the moisture content of strawberries of the EPPE group (13.4 g/100 g) was lower than that of the PPE group (14.0 g/100 g). This difference suggests that the use of EPPE may have contributed to a more stable moisture environment, potentially limiting excessive moisture uptake. In other words, encapsulation may result in a more effective barrier to moisture, thereby preventing excessive hydration of a dry product during storage.

EPPE and PPE-treated strawberries exhibited significant changes ($p<0.05$) in pH relative to their initial levels at the end of storage (**Table 1**). In strawberries of the EPPE group, the pH was highest on the first day, decreased on the 15th day and remained stable until the end of storage. This trend was similar for the strawberry product in the PPE group, although pH decreases continued until 60 days of storage. The pH of strawberries with PPE was significantly ($p<0.05$) higher than that of the product with EPPE after 90 days of storage. The difference in pH between the EPPE and PPE groups can be attributed to the encapsulation process. In the EPPE group, encapsulation may have slowed the release of active compounds, leading to an initial pH stability followed by a gradual decrease. In contrast, the PPE group showed a continuous pH decrease until the 60th day, likely due to the faster release of extract compounds. This suggests that encapsulation helped stabilize the pH during storage. Encapsulation has been shown to enhance the stability of bioactive compounds, including maintaining pH levels during storage, like in a study by Cruz-Molina *et al.* [2021], which demonstrated that maltodextrin encapsulation improved the thermal and pH stability of green tea extract catechins, preserving their chemical structure and antioxidant capacity under varying pH conditions over time.

Similar to the pH values, changes also occurred in the TA of the dried vacuum-infused strawberries during storage (**Table 1**). Moreover, the strawberries with EPPE had significantly ($p<0.05$) higher TA than the strawberries with PPE after 90 days of storage. This may be related to the effect of encapsulation, which has been reported to help maintain TA stability during storage in various food products [Yin *et al*., 2024; Zeng *et al*., 2024]. For instance, in a study on pineapple ready-to-serve beverages enriched with folic acid, the encapsulated form led to a more stable TA over a two-month period compared to the free form, suggesting that encapsulation can help protect organic acids or slow down their degradation during postharvest fruit storage [Pamunuwa *et al.,* 2021]. The TA values obtained in our study (8.3–9.9 g CA/100 g) were high compared to literature data, *e.g.*, the TA of chitosan-coated strawberries containing propolis extract were examined, and the acidity value of the control and treated fruits was determined to be 1.65–1.94 g CA/100 g at the beginning of storage [Akkuzu *et al*., 2024]. The variability in the results is considered due to the variety of the strawberries used in the study.

Firmness of dried vacuum-infused strawberries during storage

Texture is one of the key attributes that shapes the sensory properties of a product and influences consumer perception. The texture quality of food can be assessed by instrumental analysis, the measurements of which often correlate with sensory evaluation [Ribes & Talens, 2023]. Among texture parameters, firmness was determined in our study. Overall, an increase in the firmness of dried vacuum-infused strawberries was observed with increasing storage time in both groups (**Table 2**). There was a significant ($p<0.05$) difference in firmness between the strawberries with EPPE and with PPE on all storage days except for the 15th and 90thday. The absence of a significant difference on the 15th day may be due to a temporary structural equilibrium between strawberries of the EPPE and PPE groups, possibly resulting from similar rates of moisture redistribution or cell wall softening occurring at that specific point in storage. Additionally, reduced enzymatic activity during storage may have slowed down cell wall degradation, helping enhance firmness.

Biegańska-Marecik & Czapski [2007] found that the firmness of vacuum-impregnated apple slices decreased during storage. However, similarly to our study, no significant differences were observed between the treatment groups at certain time points. Similarly, Maslov Bandić *et al*. [2025] did not observe any significant differences in the firmness of untreated strawberries, chitosan-coated strawberries and strawberries coated with chitosan with added apple pomace extract during 9 days of storage.

Total phenolic, punicalagin and ellagic acid contents of dried vacuum-infused strawberries during storage

The changes in the TPC, ellagic acid and punicalagin contents of dried vacuum-infused strawberries during storage are shown in **Table 3**. The results indicate a significant ($p<0.05$) decrease in TPC during the storage. At the end of storage, the TPC was

Table 2. The firmness (N) of dried vacuum-infused strawberries with pomegranate peel extract (PPE) and encapsulated pomegranate peel extract (EPPE) during storage.

Group	Storage time (day)				
	0	15	30	60	90
Strawberry product with EPPE	3.6±0.30^{Bd}	5.0±0.10^{Ac}	4.8±0.30^{Bc}	5.7±0.11^{Bb}	6.4±0.29^{Aa}
Strawberry product with PPE	4.6±0.19^{Ae}	5.1±0.46^{Ad}	5.6±0.20^{Ac}	6.2±0.30^{Ab}	6.6±0.10^{Aa}

Results are shown as mean ± standard deviation (n=3). Different uppercase letters (A and B) in the same column indicate significant differences between groups ($p<0.05$). Different lowercase letters (a–e) in the same line for each group indicate significant differences between storage times ($p<0.05$).

Table 3. The content of total phenolics, punicalagin and ellagic acid of dried vacuum-infused strawberries with pomegranate peel extract (PPE) and encapsulated pomegranate peel extract (EPPE) during storage.

Parameter	Group	Storage time (day)				
		0	15	30	60	90
Total phenolic content (mg GAE/100 g dm)	Strawberry product with EPPE	409 ± 12^{Aa}	325 ± 61^{Ac}	380 ± 4.5^{Ab}	255 ± 14^{Ad}	231 ± 6.6^{Ae}
	Strawberry product with PPE	313 ± 15^{Ba}	250 ± 13^{Bb}	218 ± 15^{Bc}	115 ± 13^{Be}	147 ± 6.6^{Bd}
Punicalagin content (mg/kg dm)	Strawberry product with EPPE	$13{,}367\pm85^{Aa}$	$11{,}333\pm1247^{Ab}$	$9{,}479\pm157^{Ac}$	$8{,}138\pm120^{Ad}$	$6{,}248\pm37^{Ae}$
	Strawberry product with PPE	$9{,}450\pm83^{Ba}$	$8{,}403\pm51^{Bb}$	$7{,}274\pm49^{Bc}$	$7{,}209\pm54^{Bc}$	$5{,}128\pm85^{Bd}$
Ellagic acid content (mg/kg dm)	Strawberry product with EPPE	186 ± 0.8^{Aa}	155 ± 3.9^{Ab}	146 ± 0.3^{Ac}	131 ± 1.3^{Ad}	126 ± 0.5^{Ae}
	Strawberry product with PPE	141 ± 5.0^{Ba}	117 ± 1.7^{Bb}	112 ± 1.5^{Bc}	95 ± 0.2^{Bc}	83 ± 2.8^{Bd}

Results are shown as mean ± standard deviation (n=3). Different uppercase letters (A and B) in the same column, separately for each parameter, indicate significant differences between groups (p<0.05). Different lowercase letters (a–e) in the same line for each group indicate significant differences between storage times (p<0.05). GAE, gallic acid equivalent, dm, dry matter.

230.8 mg GAE/100 g dm for strawberries of the EPPE group and 147.2 mg GAE/100 g dm for strawberries of the PPE group. This could result from phenolic compound degradation due to oxidation, enzymatic activity, or interactions with other food components during storage. Hassanein *et al*. [2024] studied the possibility of shelf-life extension of strawberries using encapsulated pomegranate seed oil, and found that the TPC of the strawberries containing nanoemulsion was higher at the end of storage compared with the samples treated with coarse emulsion (non-encapsulated oil). In turn, Amiri *et al*. [2022] demonstrated that the incorporation of catechin nanoemulsions encapsulated within *Aloe vera* gel effectively preserved the TPC of strawberries during storage by limiting the degradation of phenolic compounds. Pomegranate seed oil-enriched carboxymethyl cellulose coatings effectively preserved the phenolic content of strawberries during storage, enabling to maintain up to 70% of total phenolics, which highlights their potential to reduce oxidative degradation and support antioxidative stability [Melikoğlu *et al*., 2022].

At the end of storage, the strawberries of the EPPE group had a higher TPC than the strawberries of the PPE group (**Table 3**), which clearly demonstrates the positive effect of encapsulation. Kaderides *et al*. [2020] reported that encapsulation significantly affected phenolic retention; the encapsulated pomegranate peel extract in orange juice industry by-products exhibited significantly higher antioxidative activity, TPC, and punicalagin content than the crude PPE. Similarly, Xu *et al*. [2019] reported that the phenolic compounds of the crude mulberry extract degraded more rapidly than the encapsulated mulberry extract and that approximately 80% of the phenolic compounds were preserved in mulberry microcapsules after storage at room temperature for 20 days. Furthermore, the encapsulation was found to improve the stability of phenolic compounds of grape pomace after storage at 60°C for 45 days [Tsali & Goula, 2018].

The phenolic profile of dried vacuum-infused strawberries was related not only to the phenolic profile of strawberries, but also to the phenolic profile of the pomegranate peel extract. The major phenolic compounds in PPs are punicalagin and ellagic acid, which exhibit strong antioxidative and antibacterial activities [Çam & Hışıl, 2010; Firuzi *et al*., 2019; Qu *et al*., 2012a; Soleimanzadeh *et al*., 2024]. Notably, punicalagin isomers constitute most tannins in PPs [Çam & Hışıl, 2010]. However, the content of these compounds in extracts varies depending on factors such as cultivation conditions and plant variety [Faria & Silva, 2024], and also extraction method used [Al-Zoreky, 2009; Zaki *et al*., 2015]. In our study, initially, the punicalagin content in strawberries of the EPPE group was significantly (p<0.05) higher than that in strawberries of the PPE group, which contained approximately 70% of punicalagin determined in product with the EPPE (**Table 3**). As the storage period continued, the amount of punicalagin decreased in both groups, with a significant difference observed compared to the initial values (p<0.05). Although encapsulation can offer some protection to phenolic compounds like punicalagin, preventing their degradation entirely during storage remains challenging. The reduction in punicalagin content observed in both groups during storage may be attributed to several factors, including the ongoing oxidation and hydrolysis reactions, which can still occur despite encapsulation. Furthermore, environmental factors such as temperature, light, and oxygen exposure during storage may contribute to the gradual loss of phenolic compounds [Akkuzu *et al*., 2024; Qu *et al*., 2012b; Xu *et al*., 2019]. While encapsulation helps slow down these processes, it does not completely prevent the degradation of bioactive compounds over time. Another potential reason for the decrease in punicalagin content during storage could be the presence of punicalagin α and β anomers, which may undergo different degradation rates over time, as suggested by Rakshit & Srivastav [2022]. In the cited study, punicalagin, as a compound of the pomegranate peel hydrolysable tannin fraction, dissociated up to 58.48 and 88.34% during storage at neutral and alkaline pH, respectively [Rakshit & Srivastav, 2022]. Qu *et al*. [2012b] found that the punicalagin

Table 4. The browning index (A_{420}/g) of dried vacuum-infused strawberries with pomegranate peel extract (PPE) and encapsulated pomegranate peel extract (EPPE) during storage.

Group	Storage time (day)				
	0	15	30	60	90
Strawberry product with EPPE	4.8 ± 0.25^{Aa}	4.0 ± 0.67^{Ab}	4.2 ± 0.45^{Bb}	4.2 ± 0.13^{Bb}	4.3 ± 0.06^{Bb}
Strawberry product with PPE	4.3 ± 0.13^{Bd}	4.1 ± 0.15^{Ac}	4.5 ± 0.21^{Ab}	4.5 ± 0.04^{Ab}	4.8 ± 0.02^{Aa}

Results are shown as mean ± standard deviation (n=3). Different uppercase letters (A and B) in the same column indicate significant differences between groups (p<0.05). Different lowercase letters (a–e) in the same line for each group indicate significant differences between storage times (p<0.05).

Table 5. The total aerobic mesophilic bacteria and total yeast and mold counts (log CFU/g) of dried vacuum-infused strawberries with pomegranate peel extract (PPE) and encapsulated pomegranate peel extract (EPPE) during storage.

Parameter	Group	Storage time (day)				
		0	15	30	60	90
Total aerobic mesophilic bacteria	Strawberry product with EPPE	1.72 ± 0.10^{Ad}	1.82 ± 0.06^{Bc}	1.91 ± 0.03^{Bb}	1.98 ± 0.01^{Bab}	2.01 ± 0.01^{Ba}
	Strawberry product with PPE	1.85 ± 0.05^{Ac}	1.99 ± 0.04^{Aab}	1.99 ± 0.03^{Ab}	2.03 ± 0.02^{Aa}	2.06 ± 0.04^{Aa}
Total yeasts and molds	Strawberry product with EPPE	1.73 ± 0.03^{Ac}	1.80 ± 0.03^{Ac}	1.98 ± 0.03^{Ab}	2.04 ± 0.03^{Bb}	2.14 ± 0.04^{Ba}
	Strawberry product with PPE	1.76 ± 0.03^{Ae}	1.83 ± 0.03^{Ad}	2.00 ± 0.03^{Ac}	2.13 ± 0.02^{Ab}	2.23 ± 0.02^{Aa}

Results are shown as mean ± standard deviation (n=3). Different uppercase letters (A and B) in the same column, separately for each parameter, indicate significant differences between groups (p<0.05). Different lowercase letters (a–e) in the same line for each group indicate significant differences between storage times (p<0.05).

content in a PP extract significantly decreased even after 1 day of storage at 4°C, independent of pH.

The decrease in ellagic acid content in the vacuum-infused strawberries followed a similar trend to that of punicalagin (**Table 3**). After 90 days, the ellagic acid content was determined at 125.9 mg/kg in the dried strawberries containing EPPE, whereas it was 83.4 mg/kg in the strawberries of the PPE group.

Browning index of dried vacuum-infused strawberries during storage

The changes in color of fruits can be evaluated using the browning index based on the loss of red pigment and an increased content of yellow pigment [Wigati *et al*., 2024; Zeng *et al*., 2024]. The BI of dried vacuum-infused strawberries ranged from 4.0 to 4.8 A_{420}/g (**Table 4**). The browning index of the strawberries containing EPPE was significantly (p<0.05) lower than that of the strawberries of the PPE groups after 30–60 days of storage. These findings indicate that encapsulation of PPE improved the protection of strawberries against environmental factors, particularly oxygen, thereby inhibiting their browning [Wigati *et al*., 2024]. Despite its high content of antioxidants, PPs is sensitive to oxidation at high pH, and its browning rate has been correlated with its antioxidant content [Silveira *et al*., 2023].

A similar browning phenomenon was observed during the storage of grape pomace extract [Tsali & Goula, 2018]. This effect was attributed to the loss of anthocyanin-derived red pigments. In contrast to our results, for strawberries coated with starch and calcium propionate and stored in cold conditions (4°C and 85% RH), the highest BI was observed in the control fruits (uncoated) after 16 days of storage [Wigati *et al*., 2024]. The BI values of uncoated and coated strawberries in the cited study ranged from 0.525 to 1.524 and were lower than those of vacuum-infused strawberries in our study, probably due to the drying process we used after the VI.

Counts of total aerobic bacteria and total yeast and mold in dried vacuum-infused strawberries during storage

Due to short shelf-life of strawberries, which is caused by high water activity and the associated vulnerability to microbial and enzymatic degradation, strawberries are frequently subjected to various processing techniques such as drying, impregnation, and coating [Kowalska *et al*., 2018; Maslov Bandić *et al*., 2025; Yin *et al*., 2024]. In our study, the total aerobic mesophilic bacteria and mold-yeast counts of dried vacuum-infused strawberries were 2.06 and 2.23 log CFU/g after 90 days of storage, respectively (**Table 5**). These counts of microorganisms were low, due to the low moisture content and water activity of products. Although the effect of PPE encapsulation was not observed on the first day of storage of dried vacuum-infused strawberries, the antimicrobial effect of EPPE against aerobic bacteria became significantly (p<0.05) better than that of EPP after the 15th day. The trend of mold and yeast count in strawberries during storage was similar to that of total aerobic bacteria count.

The antimicrobial effect was likely due to the presence of punicalagin in PPE. Phenolic compounds possess various

antifungal and antimicrobial properties [Kaderides *et al*., 2020]. The antimicrobial effect of phenolic compounds is attributed to their hydroxyl groups, which lower the pH of the bacterial cell membrane surface and disrupt bacterial metabolism, leading to bacterial death [Pisoschi *et al*., 2018].

In a review encompassing studies on the use of PPE as an edible film, it was noted that films containing PPE exhibited excellent antioxidative and antimicrobial properties [Soleimanzadeh *et al*., 2024]. In turn, Yin *et al*. [2024] demonstrated that strawberry samples coated with a bilayer emulsion containing eugenol/citral exhibited strong antimicrobial activity against *E. coli*, *S. aureus*, and *A. niger*.

CONCLUSIONS

In conclusion, this study effectively highlights the impact of PPE encapsulation on the preservation and quality of dried vacuum-infused strawberries over a 90-day storage period. The findings demonstrate that while total soluble solids remained stable between days 0 and 15, a significant increase was observed thereafter, indicating the beneficial effects of strawberry processing on maintaining sugar content during storage. The relatively low water activity and moisture content changes reinforce the efficacy of the drying process, while also supporting the viability of the product over time.

Notable changes in pH and titratable acidity provide additional insight into the varying retention of active compounds in strawberries of the EPPE and PPE groups. The encapsulation promoted a slow release of these components, maintaining a stable pH in strawberries of the EPPE group while resulting in a more significant decrease in the PPE group. Moreover, the findings indicate a continued decrease in the total phenolic content during storage; however, strawberries in the EPPE group retained significantly higher levels of phenolics by the end of the study, which highlights the importance of encapsulation in enhancing antioxidant properties. After 90 days, strawberries in the EPPE group showed lower browning indices, indicative of better protection against oxidative damage when compared to the PPE group. This attribute may be particularly advantageous for maintaining product appeal and quality in storage conditions. Furthermore, the microbial analysis confirmed the safety of the dried strawberries, with low total aerobic mesophilic bacteria, and mold and yeast counts detected during the storage.

Overall, this study presents clear evidence that the use of encapsulated PPE plays a crucial role in enhancing the quality and shelf-life of vacuum-infused strawberries, suggesting significant potential for commercial applications in fruit preservation and value-added processing. Future studies may explore different encapsulation techniques and their effects on other fruit varieties, thus expanding the knowledge in this essential area of food science.

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CONFLICT OF INTERESTS

The authors confirm that they have no competing interests related to the research described in this manuscript.

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