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Nutrient enhanced yogurt dressing using microencapsulated anthocyanins from red onion by-products for functional food applications

Florina Stoica¹, Roxana Nicoleta Rațu^{2,3}, Doina Georgeta Andronoiu³, Iuliana Aprodu³, Nicoleta Stanciuc³, Gabriela Rapeanu³✉ & Gerard Jităreanu¹

Red onion skins, typically discarded as waste, are a rich source of anthocyanins—bioactive compounds with antioxidant properties but low stability. This study developed a yogurt dressing enriched with microencapsulated red onion (*Allium cepa* L.) skin extract to enhance anthocyanin stability and bioavailability. Microencapsulation using biopolymer blends improved protection, with powder G1 (higher in polysaccharides than G2) showing greater encapsulation efficiency ($87.18 \pm 0.92\%$) and storage stability. In vitro results confirmed that increased carbohydrate concentration offers better anthocyanin protection.

The resulting stable powder was incorporated into yogurt dressing at 1% and 3% concentrations. These formulations were evaluated for physicochemical properties, antioxidant activity, and sensory quality. The addition of the microencapsulated extract increased antioxidant activity ($15.64\text{--}23.05 \mu\text{mol TE/g dw}$) and protein content ($7.74\text{--}7.82 \text{ g/100 g}$), while also acting as a natural colorant. Higher powder concentrations improved texture and rheological properties, contributing to better structural integrity and compaction with higher powder concentrations. Sensory evaluation indicated favorable consumer acceptance.

This study demonstrates that microencapsulation effectively preserves anthocyanin bioactivity and enhances the functional and visual properties of yogurt dressing. The approach offers a sustainable solution for utilizing red onion skin by-products in functional food development.

Keywords Onion skins, Natural antioxidants, Anthocyanins, Microencapsulation, Nutritional enhancement, Yogurt dressing

Onion (*Allium cepa* L.), a widely cultivated *Allium* species, is the second most important horticultural crop globally after tomatoes, in Asia, Africa, Europe, and North America. Over the past two decades, global onion production has increased by at least 25%, reaching an annual output of approximately 47 million tons. The onion is utilized globally for its significant nutritional, medicinal, and economic benefits. Onion is frequently used in many culinary dishes to augment flavour, sensory qualities, and useful capabilities. It is a significant source of phytoconstituents, including flavonoids and organosulfur compounds^{1,2}.

Onions are consumed raw, cooked, or processed into various products. During processing, about 37% of the plant, including onion skins (OS) and layers, becomes a waste by-product. These by-products pose an ecological and economic challenge, and the primary difficulty in their management is their heterogeneous nature. These losses require the development of processing technologies, both for protecting the environment and valorizing natural bioactive compounds³.

¹Department of Pedotechnics, Faculty of Agriculture, "Ion Ionescu de La Brad" Iasi University of Life Sciences, 3 Mihail Sadoveanu Alley, 700489 Iasi, Romania. ²Department of Food Technologies, Faculty of Agriculture, "Ion Ionescu de La Brad" Iasi University of Life Sciences, 3 Mihail Sadoveanu Alley, 700489 Iasi, Romania. ³Department of Food Science, Food Engineering, Biotechnology and Aquaculture, Faculty of Food, Science and Engineering, "Dunărea de Jos" University of Galați, 111 Domneasca Street, Building E, Room 202, 800201 Galați, Romania. ✉email: Gabriela.Rapeanu@ugal.ro

Red onions, a variety of *Allium cepa*, are primarily used in culinary practices and have their skins utilized as natural colorants. Red onions and their by-products possess antibacterial, anticancer, antioxidant, analgesic, and anti-inflammatory properties, potentially aiding in blood sugar regulation, providing cardioprotective benefits, reducing cholesterol, controlling blood pressure, and enhancing immunological function^{4,5}.

The OS contains quercetin, which belongs to the class of flavonoids and accounts for more than 60% of its polyphenolic content. Other prominent flavonoids in OS include kaempferol, anthocyanin, myricetin, and isorhamnetin derivatives and glycosides^{1,6}.

Recent interest has focused on plant-derived compounds to enhance the health-promoting qualities of food. Also, increasing awareness of the adverse health effects associated with synthetic colorants has led to a rapid rise in the use of natural pigments as safer, health-promoting alternatives⁷. OS is rich in phenolics, anthocyanins, and phenolic acids, offering strong free radical scavenging capacity and notable health benefits. Flavonoids are sensitive to light, temperature, and pH, making polyphenols unstable and limiting their use in food. Processing can degrade beneficial phytochemicals in onion by-products⁸.

While red onions are primarily valued for their characteristic flavor and potential health benefits, they are also a rich source of natural pigments, particularly anthocyanins. These pigments are concentrated in the outer skin layers, making the typically discarded peels a valuable and underutilised resource. Anthocyanins are gaining increasing attention in the food and cosmetics industries as natural alternatives to synthetic colorants due to their vibrant hues and potential health benefits⁹.

Anthocyanins, natural water-soluble pigments, are linked to different health advantages, including anti-inflammatory, anti-carcinogenic, and cardioprotective properties. Anthocyanins may help prevent cardiovascular disease by improving the lipid profile and platelet function of healthy volunteers and reducing hyperlipidemia by inhibiting LDL oxidation. It improves dyslipidemia, increases antioxidant capacity, and prevents insulin resistance in human subjects with type 2 diabetes, having antidiabetic effects^{10–13}.

Alternative approaches are being investigated to maintain flavonoid stability, improve their bioavailability, and prolong the shelf life of onion-derived products. Microencapsulation is a commonly utilized method for protecting the phytochemicals and antioxidants in food goods and supplements. The choice of wall material is crucial, since it influences encapsulation efficiency (EE) and powder properties¹⁴. Various biopolymers, including pectin (P), maltodextrin (MD), and proteins, can serve as wall materials. Soy protein isolates (SPI) are regarded as effective encapsulating materials for various bioactive compounds due to their wide availability and cost-effectiveness. Moreover, in comparison to other protein sources, SPI represents a more sustainable and renewable raw material. Maltodextrins with differing dextrose equivalents are extensively utilized as wall materials owing to their excellent water solubility, low viscosity, minimal sugar content, and colorless solutions. Pectin possesses gelling qualities, high biocompatibility, and biodegradability, and it is acceptable for enhancements in solubility and hydrophobicity¹⁵. Selecting an appropriate encapsulation method requires careful consideration of the characteristics of the bioactive compound, the properties of the encapsulating materials, and the intended attributes of the final product¹⁶.

Freeze-drying is widely used for the long-term preservation of heat-sensitive compounds and is considered one of the most effective methods for encapsulating anthocyanins¹⁷. Gelation is another widely used technique for encapsulating biologically active compounds, involving the formation of hydrogels that serve as protective matrices¹⁸. Hydrogels are three-dimensional networks formed by the random linkage of polymeric chains through either physical or chemical interactions¹⁹. Combining physical and chemical encapsulation techniques can produce more stable micro- or nanoparticles with significantly higher encapsulation efficiency compared to using a single method alone²⁰.

Several new studies have demonstrated the feasibility of microencapsulated the bioactives derived OS and harnessing their functional properties such as: OS nano liposomes⁶; ultrafine fibers from sweet potato starches with red OS extract²¹; microparticles formulations with strawberry pulp, *Lactobacillus casei*, and red OS extract²²; oil-in-water emulsion from alginate, carboxymethyl cellulose, and red OS²³ etc. However, few studies have focused on encapsulating red OS anthocyanins and testing the microcapsules on food product formulation.

The primary objective of this study was to develop and evaluate microencapsulated formulations derived from red onion OS anthocyanins using biopolymeric carriers—SPI, P, and MD—through gelation and freeze-drying techniques.

Specifically, the research aimed to compare the EE, phytochemical content, and antioxidant activity of the resulting powders. Additionally, the study sought to assess anthocyanin bioavailability under simulated gastrointestinal conditions, as well as evaluate the color properties and storage stability of the phytochemicals of the encapsulated powders. The most effective encapsulation formulation was then incorporated into a yogurt dressing to investigate its functionality. The enriched yogurt dressing was further analyzed for its physicochemical properties, phytochemical content, antioxidant activity, texture, rheological behavior, microstructure, and sensory acceptability.

Materials and methods

Reagents and chemicals

All the following chemicals were acquired from Sigma-Aldrich (Steinheim, Germany): apple pectin, soy protein isolated (90%), maltodextrin, ethanol, methanol, 2,2-diphenyl-1-picrylhydrazyl, Folin–Ciocalteu reagent, gallic acid, aluminium chloride, citric acid, and sodium hydroxide. Greek yogurt, extra virgin olive oil, red wine vinegar, granulated garlic, black pepper, and salt were provided from the local market in Iasi, Romania.

Red OS powder preparation

The red onion ("*Rosie de Arieș*" variety) was procured from a local producer in Galați County, Romania. The onions were first washed, and their skins were carefully removed. The skins were then rinsed with distilled water

and dried in an oven (Stericell 111, MMM Medcenter, München, Germany) at 40 °C for 2 h until reaching a moisture content of 10.80%. After drying, the skins were ground into a fine powder using a blender (Philips HR2656/90 China), then stored in a dark container at 20 °C for future extraction.

Extraction of Phytochemicals from Red OS Powder

The phytochemical characterization of red OS extract involved the conventional extraction of active components, as conducted by Milea et al.²⁴. 1 g of red OS powder was mixed with 13 mL of ethanol (70%) and 1 mL of citric acid (1%). The obtained mixture was maintained on the ultrasonic bath (Elmasonic S 180 H, Elma, Germany) for 40 min, at 25 °C and 40 kHz. The extraction process was performed at least three times to acquire anthocyanin-enriched extracts, followed by centrifugation (Centurion Scientific, K241R, UK) of the extract for 10 min at 5000 rpm (2380 G) and 8 °C, after which the supernatant was collected. The supernatant was subsequently evaporated to dryness employing a reduced pressure concentrator at 40 °C (AVC 2–18, Christ, UK) and analyzed for phytochemical composition.

Extract characterization

Determination of total anthocyanin contents

The total anthocyanin (TA) content was measured using the pH-differential method with two buffer solutions: 0.04 M sodium acetate (pH 4.5) and 0.025 M potassium chloride (pH 1.0), as described by Condurache et al.²⁵. The results were expressed in milligrams (mg) of cyanidin 3-O-glucoside (C3G) per gram of dry weight (dw).

$$\begin{aligned} \text{TA} &= (A \times \text{Mw} \times \text{DF}) / \epsilon \times L \times m, \text{ mg C3G/g dw} \\ A &= \text{absorbance} = (A_{520} - A_{700})_{\text{pH}=1.00} - (A_{520} - A_{700})_{\text{pH}=4.5} \\ \text{Mw} &= \text{molecular weight (449.2 g/mol)}; \\ \text{DF} &= \text{dilution factor/ volume of extract}; \\ \epsilon &= \text{molar absorptivity of the major compound from the extract (26,900 L x mol}^{-1} \times \text{cm}^{-1}); \\ L &= \text{optical path length of the cuvette (1 cm for 2.5 mL cuvettes)}; \\ m &= \text{mass of solubilized extract.} \end{aligned}$$

Determination of total flavonoid contents

The total flavonoid (TF) content was quantified following the method described by Milea et al.²⁶. The aluminum chloride technique was employed, and the results were expressed as mg of quercetin equivalent (QE)/g dw. TF content was determined by comparing the extract's absorbance with a quercetin standard curve (0–0.6 mg/mL, $y = 1.46x - 0.008$, $R^2 = 0.9978$), with a maximum absorbance at 510 nm.

Determination of total polyphenol contents

The total polyphenol (TP) content was determined using the Folin–Ciocalteu method, with results expressed as mg of gallic acid equivalent (GAE)/g dw, as Condurache et al.²⁵ described. The absorbance of the extract was compared with a gallic acid standard curve ($y = 1.6991x - 0.0256$, $R^2 = 0.9837$), to estimate the concentration of TP content in the sample (0–0.6 mg/mL), with a maximum absorbance at 765 nm.

Determination of the antioxidant activity

The antioxidant activity (AA) of the extract was evaluated by its ability to scavenge DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals, following the method described by Condurache et al.²⁵. Results were expressed as μmol of Trolox equivalent (TE)/g dw. A calibration curve ($y = 0.45x + 0.0075$, $R^2 = 0.993$) using Trolox as standard was used (0–2.5 μmol /mL), with a maximum absorbance at 515 nm.

Microencapsulation of anthocyanins from red OS extract

Soy protein isolate–maltodextrin–pectin (SPI–MD–P) hydrogels containing anthocyanins derived from red OS were synthesized employing a modified gelation technique as described by Serrano-Cruz et al.²⁷. This work employed soy protein isolate (SPI), maltodextrin (MD), and pectin (P) as wall materials, resulting in two experimental powder variants (G1 and G2). For variant G1, 2% SPI, 4% MD, and 4% P were combined and dissolved in ultrapure water at roughly 40 °C for 3 h while stirring at 400 rpm using a magnetic stirrer (IKA RCT Basic, Staufen, Germany). In order to create variant G2, 4% SPI, 2% MD, and 2% P were combined with ultrapure water. The mixture was then hydrated for 3 h at 40 °C and 400 rpm using a heated magnetic stirrer. Subsequently, the resultant solutions were refrigerated at 4 °C overnight to guarantee complete hydration. Consequently, the red OS anthocyanin extract (25 mg/mL) was included in each solution comprising the wall materials. For 2 h at 25 °C and 400 rpm, the solutions were vigorously stirred with a magnetic stirrer until they were completely homogenized. The pH readings were recorded at 3.5. The dispersions were frozen at –20 °C and subsequently subjected to freeze-drying at –42 °C at a pressure of 0.10 mBar for 48 h (BIOBASE BK-FD10T equipment, Jinan, China). Powders were enclosed in plastic tubes, sealed, and preserved in darkness until analysis.

Powders characterization

Encapsulation efficiency

The resulting powders' TA, TF, TP, and AA contents were examined. The EE was calculated using the powders' surface anthocyanin and TA contents, as described by Condurache et al.²⁵.

For TA content analysis, 200 mg of each powder sample was mixed with 5 mL of a solvent solution consisting of methanol, acetic acid, and water in a volume ratio of 25:4:21. The mixtures were vortexed for 1 min, followed by sonication for 20 min at 40 ± 1.0 °C to facilitate microcapsule disruption. Afterward, the samples were centrifuged at 6000 rpm for 10 min at 4 °C.

For surface anthocyanin content determination, 200 mg of each powder was combined with 5 mL of an ethanol:methanol solution (1:1, v/v) and vortexed for 1 min. The mixtures were then centrifuged under the same conditions (6000 rpm, 10 min, 4 °C). The TA content and surface anthocyanin content in the resulting supernatants were quantified spectrophotometrically using the pH-differential method. The EE of anthocyanins was then calculated.

$$EE (\%) = \frac{TA \text{ content} - \text{surface anthocyanin content}}{TA \text{ content}} \times 100$$

Storage Stability Studies

The powders (G1, G2) were enclosed in plastic tubes and stored at 20 °C in darkness. Their bioactive contents and AAs were examined over 0, 14, and 28-day storage periods.

Color evaluation

The powders' color characteristics (L^* , a^* , b^* , Chroma, Hue Angle, ΔE) were assessed accordingly by Mocanu et al.²⁸. The color parameters determined were L^* (lightness/darkness), a^* (red/green), and b^* (yellow/blue). Chroma, representing color intensity, is calculated as $\sqrt{(a^*)^2 + (b^*)^2}$; Hue angle representing visual color appearance, is calculated as $\arctan(b^*/a^*)$ for quadrant I ($+a^*$, $+b^*$); The total color difference, ΔE , is calculated as $\sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2}$, where L_0 , a_0 , and b_0 are control values.

Determination of the in Vitro release of anthocyanins from microcapsules

The release of anthocyanins from microcapsules under simulated in vitro digestive environments was examined by Minekus et al.²⁹. Simulated gastric fluid (SGF) containing porcine pepsin (40 mg/mL in 0.1 M HCl, pH = 3) was employed to replicate gastric digestion. Simulated intestinal fluid (SIF), comprising pancreatin sourced from porcine pancreas (2 mg/mL in 0.9 M sodium bicarbonate, pH = 7), was utilized to model intestinal digestion.

Value-added yogurt dressing preparation

Enriched yogurt dressing was prepared using G1 powder in two ratios (1% and 3%) to test its functionality (1%-YD1, 3%-YD2). The control sample (C) consisted of yogurt dressing without added powder. The recipe of yogurt dressing contains the following ingredients: 2% Greek yogurt (80 g), extra virgin olive oil (11 g), red wine vinegar (10 g), granulated garlic (1.5 g), ground black pepper (0.2 g), salt (0.6 g) and red OS encapsulated powder (G1:YD1 – 1%, YD2 – 3%). The yogurt dressing preparation involves mixing the ingredients shown above, adding red OS powder, and adjusting the amount of yogurt dressing. It was homogenized until the composition was uniform in color and texture and kept at 4 °C for analyses. The mixture was homogenized at 1000 rpm for 5 min, 800 W, at room temperature using a vertical mixer (Philips HR2656/90 China).

Characterization of physicochemical and phytochemicals of value-added yogurt dressings

The supplemented yogurt dressing's physicochemical properties (moisture, lipids, sugars, protein, ash, and energetic values) were evaluated using AOAC procedures³⁰.

Ash content was determined using a standard reference method involving calcination of the samples under controlled conditions (slow ashing at 550–650 °C). Moisture content was measured using the oven-drying method at a temperature range of 130–150 °C. Total protein content was determined by the Kjeldahl method, while total fat content was assessed using the Soxhlet extraction method. Carbohydrate content was calculated using the Schrool method, and the energy value was determined by calculation, in accordance with HG-106/2002 and Regulation (EU) No. 1169/2011.

The TA, TF, TP contents, and AA of value-added yogurt dressings enhanced with G1 powder were estimated using the procedures described in the Section above.

Storage stability

In darkness, the yogurt dressing samples were stored in light-resistant PET glass containers at 4 °C. As previously outlined, their bioactive constituents and AAs were analyzed over 0, 7, and 14-day storage periods.

Color evaluation

The enriched yogurt dressings and control color were determined for CIELAB color parameters (L^* , a^* , b^* , Chroma, ΔE , and Hue Angle) using a Minolta Chroma Meter CR-410 (Konica Minolta, Osaka, Japan), as assessed by Mocanu et al.²⁸. For accurate color analysis, a homogeneous sample uniformly distributed over a flat surface is essential to ensure consistent and reliable color measurements. The color analysis was carried out in triplicate.

Texture analysis

The texture analysis was performed using a Brookfield Ametek CT3 Texture Analyser, applying the TPA method²⁸. A cylindrical acrylic probe (43 mm diameter, 30 mm height) was employed to penetrate the samples to a depth of 15 mm. Two sets of penetration cycles were performed at a speed of 1 mm/s using a load cell with a capacity of 0.067 N.

The textural parameters (firmness, adhesiveness, cohesiveness, and elasticity) were determined by processing the force–deformation profiles using TexturePro CT V1.5 software. Each sample was replicated three times.

Rheological analysis

Rheological experiments were conducted utilizing a control-stress rheometer (AR2000ex, TA Instruments, Ltd, New Castle, DE)²⁸. The rheological characteristics of the samples were assessed under oscillatory flow in small amplitude conditions (strain sweep and frequency sweep tests) and under forced flow conditions (stepped flow tests). Frequency sweep tests were performed over a frequency range of 0.1–100 Hz, with strain values maintained within the linear viscoelastic region. Stepped flow tests were conducted with a shear rate increasing from 0.1 to 100 s⁻¹. Strain sweep tests were carried out at a constant frequency of 1 Hz, across an oscillatory strain range of 0.01% to 100%. All measurements were conducted at 20 °C using a plate geometry with a 40 mm diameter and a gap of 1000 μm. During dynamic viscoelastic testing, the storage modulus (G') and loss modulus (G'') were evaluated, while in steady shear viscosity measurements, shear stress and apparent viscosity were recorded.

Scanning electron microscopy analysis

A scanning electron microscope (SEM) (Quanta 450, FEI, Thermo Fisher Scientific, Hillsboro, OR, USA) was used to characterize the morphology of the microencapsulated powders and value-added yogurt dressing samples. The samples were prepared as described by Li et al.³¹. The yogurt dressing samples were initially fixed in 2.5% glutaraldehyde and subsequently rinsed with phosphate buffer (pH 7.2). Dehydration was carried out using a graded ethanol series, followed by defatting with chloroform. After a final rinse in absolute ethanol, the samples were freeze-dried (BIOBASE BK-FD10T equipment, Jinan, China) and sputter-coated with a thin layer of gold under vacuum for SEM observation. The samples were analyzed under low vacuum circumstances at 6.1×10^{-4} Pa, with an electron acceleration voltage of 15 kV and a magnification of 500 × (100 μm).

Sensory evaluation

Twenty untrained panelists were selected for sensory analysis, including students and staff from the Faculty of Agriculture ("Ion Ionescu de la Brad" Iasi University of Life Sciences). The yogurt dressings were evaluated through Quantitative Descriptive Analysis (QDA) in accordance with ISO 13,299³², enabling the identification and quantification of the sensory attributes of the yogurt dressings samples. The sensory evaluation test was carried out in agreement with the protocol number. 3738/03.02.2025 of the "Ion Ionescu de la Brad" Iasi University of Life Sciences Ethics Commission. The samples underwent sensory examination using the hedonic test method (1-extremely dislike, 9-extremely like). The sensory attributes such as appearance, smell, consistency, color, taste, aroma, aftertaste, firmness, cohesiveness, and general acceptability were assessed.

Statistical analysis

This study reports the mean and standard deviation from three investigations. Data normality and homoscedasticity were assessed using Minitab 19 (Minitab Inc., PA, USA), followed by one-way ANOVA and Tukey's test to identify significant differences ($p < 0.05$).

Results and discussions

Phytochemical characterization of red OS extract

The red OS extract highlighted a TA content of 1.41 ± 0.02 mg C3G/g dw, a TFs of 180.92 ± 1.19 mg QE/g dw, and a TPs of 120.97 ± 1.05 mg GAE/g dw. The DPPH scavenging capacity of the extract presented 49.35 ± 0.48 μmol TE/g dw (Table 1).

Singh et al.³³ extracted bioactives from onion waste by solvent extraction combined with an ultrasound-assisted technique, and the results indicated that 70% ethanol was the most effective, giving a TP content of 418.0 ± 34.4 mg GAE/g and TF content of 212.3 ± 14.6 mg QE/g. Sagar et al.³⁴ examined the phytochemical composition of red OS (*Pusa Red* cultivar), noting a higher phenolic content (251.71 ± 1.21 mg GAE/g dw) but a lower flavonoid content (89.62 ± 0.70 mg QE/g dw) relative to the present findings, which demonstrated a DPPH scavenging activity of 69.97% attained through ultrasound extraction with methanol. Katsampa et al.³⁵ found that 90% aqueous glycerol extracts of red OS caused an increased TA concentration (1.87 ± 0.39 mg C3G/g dw) than the current study. The composition of red onion by-products is determined by factors such as variety,

Sample	Storage stability	TA content, mg C3G/g dw	TF content, mg QE/g dw	TP content, mg GAE/g dw	AA, μmol TE/g dw	EE, %
Extract	–	1.41 ± 0.02^A	180.92 ± 1.19^A	120.97 ± 1.05^A	49.35 ± 0.48^A	–
G1	0	1.45 ± 0.02^{bA}	111.14 ± 0.46^{bB}	89.67 ± 0.33^{bB}	50.29 ± 0.12^{bA}	87.18 ± 0.92^{aA}
	14	1.52 ± 0.06^{bA}	111.96 ± 0.51^{bA}	91.20 ± 0.44^{bA}	52.71 ± 0.20^{bA}	87.37 ± 0.83^{aA}
	28	1.61 ± 0.03^{aA}	113.97 ± 0.62^{aA}	92.83 ± 0.65^{aA}	55.14 ± 0.16^{aA}	87.76 ± 1.03^{aA}
G2	0	1.40 ± 0.02^{bA}	107.20 ± 0.93^{bC}	84.91 ± 0.74^{bC}	47.92 ± 0.21^{bB}	84.30 ± 1.02^{aB}
	14	1.46 ± 0.03^{bB}	108.76 ± 0.91^{bB}	86.33 ± 0.65^{bB}	50.02 ± 0.23^{bB}	84.58 ± 0.93^{aB}
	28	1.53 ± 0.02^{aB}	109.12 ± 0.89^{aB}	87.15 ± 0.59^{aB}	51.88 ± 0.27^{aB}	84.89 ± 1.11^{aB}

Table 1. Characterization of the powders and extract. Values with distinct lowercase letters indicate a statistically significant difference among each phytochemical parameter and storage duration ($p < 0.05$). Values sharing distinct superscript uppercase letters a significant difference among each phytochemical parameter and powder variant ($p < 0.05$).

agronomic conditions of the cultivation area, extraction techniques (including solvent type, temperature, pH, and light exposure), and the evaluation methods used.

Powders phytochemical characterization, EE and storage stability

The analysis revealed that varying quantities of wall materials resulted in substantial changes in anthocyanin EE, as shown in Table 1 ($p < 0.05$). Consequently, G1 powder with an elevated content of polysaccharides exhibited the greatest anthocyanin EE. Therefore, the EE improved with the concentration of carbohydrate polymers, varying from $87.18 \pm 0.92\%$ for G1 to $84.30 \pm 1.02\%$ for G2 ($p < 0.05$). Presented data corroborate findings from prior investigations. Akhavan et al.³⁶ suggested that EE depends on the type of encapsulating material and the active compound/encapsulating material ratio. These authors used maltodextrin, Arabic gum, and gelatin for microencapsulated anthocyanins using the bilberry (*Berberis vulgaris*) extract spray drying method. They reported EE values from 89.06% to 96.21%, the combination of maltodextrin and Arabic gum being highly effective. Stoll et al.³⁷ documented EE values of 90% while employing polysaccharides to encapsulate anthocyanins via freeze-drying.

Means denoted by distinct lowercase letters in the table indicate a statistically significant difference among each phytochemical parameter and storage duration ($p < 0.05$). Means sharing distinct superscript uppercase letters in the table indicate a significant difference among each phytochemical parameter and powder variant ($p < 0.05$).

The TA level in the encapsulated sample (G1) relative to the red OS extract highlights the protective properties of microencapsulation, which stabilizes anthocyanins against degradation and enhances their retention and recovery during analysis. This finding aligns with previous studies demonstrating that microencapsulation can preserve and stabilize the apparent concentration of sensitive compounds such as anthocyanins (e.g., Condurache et al.³⁸), particularly when well-selected wall materials are used. The TA content of the eggplant peel extract was 0.58 ± 0.03 mg delphinidin-3-glucoside/g dw, whereas the encapsulated form using a Carboxymethyl cellulose / Pectin/Whey protein isolate (1:1:0.4) matrix exhibited a TA content of 1.25 ± 0.25 mg delphinidin-3-glucoside/g dw, likely due to the enhanced protection and stabilization provided by the encapsulation system.

This high efficiency is also reflected in the increased concentrations of biologically active compounds from the ingredients with higher AA values. The powders demonstrated that TA, TPs, TFs, and AA values were considerably higher in G1 than G2 ($p < 0.05$). Using carrier materials with higher polysaccharide concentrations than protein concentrations enabled greater retention of phytochemical compounds from the red OS extract. Also highlights the synergistic role of MD and P as dominant carriers, with SPI enhancing matrix binding and bioavailability without compromising stability. MD and P form the primary carbohydrate matrix, acting as a gelling agent and emulsifier^{39,40}.

Akdeniz et al.⁴¹ encapsulated the phenolic compounds from OS in maltodextrin and casein in a ratio of 6:4, and the EE was 89.15%. They reported a TP content of 183.81 ± 1.09 mg GAE/g dw and an AA of 15 mM Trolox/g dw. The remarkable AA of powders is attributed to the presence of flavonoids and antioxidant peptides. Hamid et al.⁴² studied the effect of varying maltodextrin concentrations on the microencapsulation of polyphenols from wild pomegranate peel using lyophilization. Their findings revealed that microencapsulation improved the retention of phenolic compounds (78.47 ± 0.39 mg GAE/g) but resulted in lower flavonoid concentrations (4.18 ± 0.03 mg QE/g) compared to the results of this study. Milea et al.²⁶ encapsulated phenolics from yellow OP using maltodextrin, pectin, and hydrolyzed whey proteins as coatings and reported lower levels of polyphenols, flavonoids, and AA (TF content of 98.12 ± 0.55 to 103.75 ± 0.57 mg QE/g dw; polyphenols from 53.53 ± 1.70 to 69.26 ± 1.03 mg GAE/g dw, and AA from 280.60 ± 3.08 to 337.57 ± 0.89 mM Trolox/g dw). Therefore, the encapsulation matrix including MD, P, and SPI efficiently generated colloidal particles that successfully encapsulated the bioactive substances of the red OS extract.

Powder stability was assessed after 14 and 28 days of storage at 20 °C. From a statistical perspective, both G1 and G2 powders exhibited a significant increase ($p < 0.05$) in TA, TP, TF contents, and AA over the 28-day storage period. In G1, although values rose steadily from day 0 to day 28, the differences between day 0 and day 14 were not statistically significant ($p > 0.05$), suggesting a plateauing effect. G2 showed the same trend, statistically significant increases over time ($p < 0.05$).

The TA content of G1 and G2 increased significantly ($p < 0.05$). Over the 28-day storage period, both G1 and G2 powders showed statistically significant increases in TA content. For G1, TA increased from 1.45 ± 0.02 mg C3G/g dw at day 0 to 1.52 ± 0.06 at day 14, and to 1.61 ± 0.03 at day 28 ($p < 0.05$). In G2, TA rose from 1.40 ± 0.02 to 1.46 ± 0.03 , and then to 1.53 ± 0.02 , also significantly different across all time points. An enhancement in the stability of TFs and TPs was seen for the G1 sample encapsulated with elevated polysaccharide contents, with a marginal rise of about 3% and 4% noted after 28 days of storage. Regarding the AA, G1 presented significantly higher values than the initial values and G2 ($p < 0.05$). Moreover, the G1 powder AA increased by 10% until the end of the storage period. The elevation in flavonoid and polyphenol content and the associated AA of powder G1 may result from the hydrolysis of conjugated polyphenols, as shown by Zhang et al.⁴³. During storage, the structure of phenolic compounds may undergo alterations, as certain compounds may decay while new phenolics may emerge, increasing TP content. The retention of total anthocyanins, flavonoids, and phenolics during storage, as observed in G1 and G2 powders, enhances antioxidant synergy. Moreover, matrix components like P and soy protein may protect polyphenols from early degradation, preserving their bioactivity.

The observed increase in phytochemicals may be attributed to the gradual release of bound phenolic compounds from the encapsulation matrix over time. As storage expands, minor structural relaxation or moisture interaction within the powder matrix (e.g., in the presence of MD or P) might facilitate molecular diffusion and enhance the availability of bioactive compounds, resulting in better extractability during analysis⁴⁴.

A further contributing component may be pigment modifications, including the creation of anthocyanin-derived pigments or stabilized flavylium ions, which can endure and maintain robust antioxidant capabilities despite structural alterations. This corresponds with prior data^{45,46} indicating enhanced AA during storage as a

result of the formation of persistent, bioactive degradation products. Tsali and Goula⁴⁷ indicated an increased stability of grape pomace polyphenols encapsulated in maltodextrin, whey protein isolate, and skimmed milk powder after 17 days of storage at 60 °C in darkness, Çam et al.⁴⁸ reported that the TP content of pomegranate skin encapsulated in MD decreased from 129.1 to 119.3 mg GAE/g sample after 60 days at 4 °C. The results indicate that mixtures with elevated polysaccharide concentrations and reduced protein content as wall materials improved the encapsulation and stability of anthocyanins derived from red OS extract during storage.

EE% remained statistically stable in both G1 and G2, reflecting effective protection of bioactives regardless of storage duration. Consequently, the freeze-drying of red OS extract employing a combination of reduced protein concentrations and elevated polysaccharide concentrations yielded more stable powders, rich in anthocyanins and possessing significant AA, suitable for use as a functional ingredient in diverse food products.

Color evaluation of powders

Table 2 presents the color measurement data after acquiring the microcapsules and after 28 days of storage at ambient temperature. The L* values, indicating the lightness of the samples, varied from 22.64±0.36 to 21.54±0.32 for G1 and G2 powders, respectively. The lightness of both powders diminished significantly(*p*<0.05) over 28 days of storage.

The powder samples exhibited elevated values of the a*, with the G1 powder displaying the greatest value, attributable to its greater anthocyanin content, as Jiménez-Aguilar et al.⁴⁹ noted. The positive value of the a* indicates a propensity to produce the red hue. The b*, representing the blue-to-yellow intensity, indicates a shift toward blue shades when negative. The a* and b* values significantly increased (*p*<0.05) in all samples after being stored for 28 days. The increase in the a* value during storage may be associated with the release of anthocyanidins from proanthocyanidins and the subsequent formation of anthocyanin-derived pigments, which contribute to the stabilization of the red-colored flavylium cation⁵⁰. Elevated b* values can be ascribed to the diminution of co-pigmentation effects and the synthesis of pyranoanthocyanins, as Tsali and Goula⁴⁷ noted.

Means denoted by distinct lowercase letters in the table indicate a statistically significant difference among each color parameter and storage duration (*p*<0.05). Means sharing distinct superscript uppercase letters in the table indicate a significant difference among each color parameter and powder variant (*p*<0.05).

G1 powder exhibited relatively stable color parameters throughout storage. The L* value (lightness) decreased only slightly from 22.64±0.36 to 22.43±0.40, with no statistically significant difference across time points. Similarly, a* (redness) increased moderately from 18.58±0.13 to 19.32±0.30, with no significant difference between day 14 and day 28 (*p*>0.05). Chroma values followed a minor upward trend (from 18.66 to 19.36), indicating slightly increased color intensity. Overall, ΔE remained under 1.0, suggesting visually minimal color change.

For G2 powder, changes were more pronounced. The L* value showed a significant decrease from 21.54±0.32 to 20.81±0.29 over 28 days, indicating darkening. The a* and b* values increased slightly, while Chroma showed a small but statistically significant rise. Importantly, ΔE reached 0.93±0.05 by day 28, indicating a perceivable color shift. However, the hue angle remained stable for both powders, showing no significant shift in the dominant color tone.

Chroma corresponded to the trend of the a* value, indicating that the red hue was the most significant in determining the color of the powder. The hue angle was located in the first quadrant of the color solid, signifying the redness of all samples, as angles of 0 and 360 are associated with red. The hue angle demonstrated a little increase for all samples examined during storage. a* value and Chroma exhibited a substantial rise (*p*<0.05) after 28 days of storage, with G1 demonstrating the highest level of color saturation, a favourable characteristic. ΔE is the feature of total color change, ranging from 0.89 to 0.93 for the sample at 14 days of storage. Consequently, the samples exhibited a decrease in brightness, and their coloration darkened after storage. The results for the values of a* and b* indicated that all data were located in the fourth quadrant (+ a*, − b*), implying a propensity for blue and red, typical of anthocyanins.

In vitro release of anthocyanins from the microcapsule

The variations in anthocyanin concentrations in the powders were observed over 4 h during in vitro exposure to simulated gastrointestinal fluids (Fig. 1). The results demonstrated the protective effect of coating polymers for releasing encapsulated anthocyanins. Hence, biopolymeric matrices exhibited a protective role for anthocyanins during the gastric phase while facilitating their release in the intestinal phase. Anthocyanins in the testing

Sample	Storage Time	L*	a*	b*	Hue Angle	Chroma	ΔE
G1	0	22.64±0.36 ^{aA}	18.58±0.13 ^{bA}	−1.72±0.08 ^{aA}	359.91±0.01 ^{aA}	18.66±0.04 ^{bA}	–
	14	22.49±0.38 ^{aA}	18.81±0.26 ^{abA}	−1.47±0.06 ^{aA}	359.92±0.01 ^{aA}	18.87±0.05 ^{abA}	0.37±0.04 ^{bA}
	28	22.43±0.40 ^{aA}	19.32±0.30 ^{aA}	−1.28±0.06 ^{aA}	359.93±0.02 ^{aA}	19.36±0.07 ^{aA}	0.89±0.04 ^{aA}
G2	0	21.54±0.32 ^{aB}	17.95±0.17 ^{bB}	−0.98±0.07 ^{aB}	359.94±0.01 ^{aA}	17.98±0.06 ^{bB}	–
	14	21.16±0.30 ^{aB}	18.14±0.19 ^{abB}	−0.88±0.06 ^{aB}	359.95±0.01 ^{aA}	18.16±0.06 ^{abB}	0.44±0.04 ^{bA}
	28	20.81±0.29 ^{bB}	18.51±0.22 ^{aB}	−0.82±0.05 ^{aB}	359.96±0.02 ^{aA}	18.53±0.07 ^{aB}	0.93±0.05 ^{aA}

Table 2. Color parameters of the powders. Values with distinct lowercase letters indicate a statistically significant difference among each color parameter and storage duration(*p*<0.05). Values with distinct superscript uppercase letters indicate a significant difference among each color parameter and powder variant (*p*<0.05).

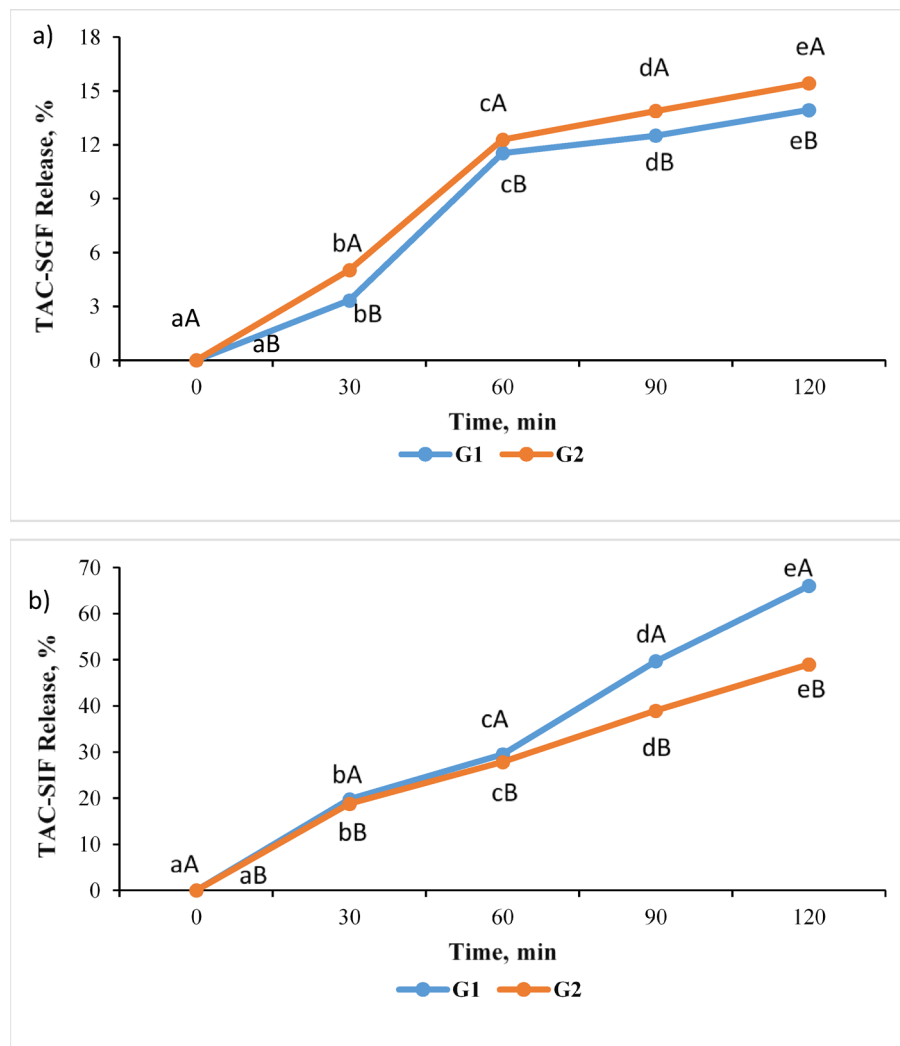


Fig. 1. The release of anthocyanins from the microcapsule powders throughout the simulated *in vitro* gastric (a) and intestinal (b) digestion (Values with the same color that do not share the same lowercase letter for the same sample and different digestion times are significantly different ($p < 0.05$). Values with different colors that do not share the same uppercase letter for the same digestion time and different samples are significantly different ($p < 0.05$). Measurements are expressed as the mean $\pm$ standard deviation of three replicates).

powders remained constant over the 2-h incubation in the SGF (Fig. 1a). The powders moderately elevated the anthocyanin content during stomach digestion, with approximately 14% for G1 and 15.41% for G2 after 120 min. The results indicated that microcapsules resisted the gastric environment of the stomach, effectively protecting anthocyanins. In SIF (Fig. 1b), the results suggested that the release of anthocyanins after 120 min of digestion exceeded 66% for G1 and 49% for G2.

The data demonstrated a controlled release of anthocyanins under intestinal conditions, indicating that a substantial portion was retained within the microcapsules. The findings are consistent with other investigations. Condurache et al.²⁵ documented a significant protective impact of anthocyanins derived from eggplant skins, encapsulated with whey protein isolate and polymers (P and sodium carboxymethyl cellulose), achieving a maximal intestine release of 50% after 30 min of digestion and a complete release after 120 min of digestion. Mansour et al.⁵¹ encapsulated anthocyanins from red raspberry using a combination of SPI and gum Arabic. They reported favorable release properties for anthocyanins during SGF and SIF compared to the non-encapsulated anthocyanin extract. The study showed that SPI, MD, and P efficiently inhibit the release of anthocyanin in SGF, enhancing their bioavailability by reducing the chemical degradation of anthocyanins in the gastrointestinal environment. A greater protective impact of anthocyanins is shown with increased polysaccharide concentration (G1).

Characterization of bioactive potential and storage stability of value-added yogurt dressings

The G1 powder was incorporated into a yogurt dressing recipe at 1% and 3% to evaluate its chosen applicability. The phytochemical composition and AA of control and experimental dressings are detailed in Table 3. Adding the ingredient in the yogurt dressing increased the content of biologically active compounds compared to the

Phytochemical Characteristics	Storage Time	C	YD1 (1%)	YD2 (3%)
TA content, mg C3G/100 g dw	0	–	30.02 ± 2.47 ^{aB}	53.25 ± 2.28 ^{aA}
	7	–	29.48 ± 1.11 ^{abB}	52.88 ± 1.09 ^{abA}
	14	–	29.30 ± 1.08 ^{bbB}	52.23 ± 1.07 ^{baA}
TP content, mg GAE/g dw	0	1.64 ± 0.06 ^{aC}	3.40 ± 0.03 ^{aB}	5.67 ± 0.02 ^{aA}
	7	1.69 ± 0.06 ^{aC}	3.49 ± 0.02 ^{aB}	5.73 ± 0.03 ^{aA}
	14	1.76 ± 0.02 ^{aC}	3.62 ± 0.04 ^{aB}	5.78 ± 0.03 ^{aA}
TF content, mg QE/g dw	0	1.97 ± 0.05 ^{aC}	5.44 ± 0.06 ^{aB}	8.30 ± 0.18 ^{aA}
	7	2.06 ± 0.05 ^{aC}	5.49 ± 0.07 ^{aB}	8.33 ± 0.12 ^{aA}
	14	2.11 ± 0.06 ^{aC}	5.52 ± 0.07 ^{aB}	8.40 ± 0.09 ^{aA}
AA, μmol TE/g dw	0	2.28 ± 0.19 ^{bC}	15.64 ± 0.14 ^{aB}	23.05 ± 0.14 ^{baA}
	7	2.39 ± 0.21 ^{abC}	16.09 ± 0.17 ^{abB}	23.62 ± 0.16 ^{abA}
	14	2.43 ± 0.15 ^{aC}	16.44 ± 0.25 ^{bbB}	24.01 ± 0.10 ^{aA}

Table 3. Phytochemical characteristics of control and value-added yogurt dressings. Values accompanied by distinct superscript lowercase letters within the same column differ substantially ($p < 0.05$). Values accompanied by distinct superscript uppercase letters within the same row are considerably different ($p < 0.05$).

control. The experimental dressings had anthocyanin contents ranging from 30.02 ± 2.47 to 53.25 ± 2.28 mg C3G/100 g. Adding the G1 powder into the yogurts' formulation also increased flavonoid and polyphenol levels. This increase led to a product with higher AA; the control dressing had the lowest value, while YD2 showed the highest scavenging activity, with 10% higher. The polyphenolic content of Italian and Thousand Island salad dressings fortified with wine grape pomace was reported as 58.5 mg GAE/100 g for the Italian dressing and 134 mg GAE/100 g, respectively, for Thousand Island⁵².

Mean values accompanied by distinct superscript lowercase letters within the same column differ substantially ($p < 0.05$). Mean values accompanied by distinct superscript uppercase letters within the same row are considerably different ($p < 0.05$).

Across the 14-day storage period, the phytochemical parameters of both YD1 (1%) and YD2 (3%) yogurt dressings remained statistically stable or slightly increased, indicating good retention of bioactivity. For TA content, both YD1 and YD2 showed minor decreases from day 0 (30.02 ± 2.47 and 53.25 ± 2.28) to day 14 (29.30 ± 1.08 and 52.23 ± 1.07 , respectively), but the differences were not statistically significant ($p > 0.05$), indicating anthocyanin stability over time. TP showed a statistically significant increase in both control and enriched samples over time (e.g., YD1 rose from 3.40 ± 0.03 to 3.62 ± 0.04 mg GAE/g dw, $p < 0.05$). TF followed a similar trend, with significant increases observed in YD1 and YD2, indicating a possible release of bound flavonoids during storage⁵³.

Antioxidant activity (AA) also increased significantly ($p < 0.05$), particularly in the YD2 sample, rising from 23.05 ± 0.14 at day 0 to 23.62 ± 0.16 μmol TE/g dw at day 7, and 24.01 ± 0.10 μmol TE/g dw at day 14. This suggests that the encapsulated anthocyanins and phenolics not only remained stable but may have become more bioavailable or extractable during storage.

Furthermore, DPPH scavenging activity diminished in all samples after 14 days, whereas YD1(1%) and YD2(3%) exhibited stronger activity than the control. Milea et al.²⁴ developed a new soft cheese formulation incorporating 1% microencapsulated OS powder, reported a decrease of 43% in flavonoid content, 35% in polyphenol levels, and 8% in AA. The research by Arts et al.⁵⁴ indicates that the binding relationship between dairy protein and polyphenol is responsible for this reduction.

Table 3 illustrates that incorporating G1 powder into yogurt dressings enhances their levels of anthocyanins and polyphenols. These natural substances facilitate the production of food products with adequate AA.

Physico-chemical characterization

The value-added yogurt dressing was analyzed from a physico-chemical perspective; the results are presented in Table 4. Incorporating G1 powder into yogurt dressings significantly enhanced its chemical composition relative to the control. The proximate composition of the yogurt dressings with G1 powder and the control exhibited a significant variation ($p < 0.05$) between the samples.

Values that do not share the same superscript lowercase letter significantly differ for each physicochemical parameter and sample at $p < 0.05$.

In addition, the enrichment of yogurt dressings with G1 powder induced a moisture and lipid decrease, which was followed by a protein, ash, and sugar increase with the increase in amounts of added G1. Moisture content decreased in both enriched samples (72.10 ± 3.11 in YD1 and 71.92 ± 5.21 in YD2) compared to the control (75.86 ± 1.56), likely due to the incorporation of dry encapsulated powder. Protein content increased significantly with the addition of the encapsulated powder, from 6.52 ± 0.76 g/100 g in the control to 7.82 ± 0.03 and 7.74 ± 0.01 in YD1 and YD2, respectively, reflecting the contribution of biopolymeric carrier (SPI, P, and MD) in the encapsulation matrix. Lipid content remained statistically unchanged across all samples ($p > 0.05$), indicating the added powder did not affect fat composition. However, the differences in the energy value at the initial control were statistically significant ($p < 0.05$). The average energy value for C was 156.47 ± 4.77 kcal/100 g, whereas for YD2 it was 167.25 ± 5.45 kcal/100 g which is consistent with the rise in protein and sugar content.

Physical–chemical characteristics	C	YD1 (1%)	YD2 (3%)
Moisture, (g/100 g)	75.86 ± 1.56 ^a	72.10 ± 3.11 ^b	71.92 ± 5.21 ^b
Lipids, (g/100 g)	12.61 ± 0.91 ^a	12.11 ± 0.09 ^a	12.01 ± 1.03 ^a
Protein, (g/100 g)	6.52 ± 0.76 ^b	7.82 ± 0.03 ^a	7.74 ± 0.01 ^a
Sugars, (g/100 g)	3.04 ± 0.05 ^b	5.56 ± 0.01 ^a	5.81 ± 0.02 ^a
Ash, (g/100 g)	2.10 ± 0.03 ^b	2.41 ± 0.02 ^a	2.52 ± 0.06 ^a
Energetic value, kcal/100 g	156.47 ± 4.77 ^b	167.48 ± 1.01 ^a	167.25 ± 5.45 ^a
kJ/100 g	654.04 ± 6.79 ^b	700.07 ± 4.18 ^a	699.10 ± 9.68 ^a

Table 4. Physico-chemical characteristics of control and value-added yogurt dressings. Values that do not share the same superscript lowercase letter significantly differ for each physicochemical parameter and sample at $p < 0.05$.

Samples	Storage time (Day)	L*	a*	b*	Chroma	Hue Angle	ΔE
C	0	91.15 ± 0.85 ^{aA}	2.32 ± 0.25 ^{aC}	21.66 ± 0.89 ^{aA}	21.78 ± 0.20 ^{aC}	1.46 ± 0.03 ^{aA}	–
	7	90.94 ± 0.71 ^{aA}	2.33 ± 0.11 ^{aC}	21.31 ± 0.21 ^{aA}	21.44 ± 0.20 ^{aC}	1.46 ± 0.03 ^{aA}	0.41 ± 0.13 ^{aC}
	14	90.65 ± 0.78 ^{bA}	2.35 ± 0.03 ^{aC}	21.07 ± 0.11 ^{aA}	21.20 ± 0.19 ^{aC}	1.45 ± 0.02 ^{aA}	0.77 ± 0.13 ^{aC}
YD1 (1%)	0	63.15 ± 0.07 ^{aB}	24.17 ± 0.08 ^{bB}	13.02 ± 0.12 ^{aB}	27.45 ± 0.25 ^{bB}	0.49 ± 0.02 ^{aB}	–
	7	61.79 ± 0.20 ^{bB}	25.97 ± 0.23 ^{bB}	12.66 ± 0.12 ^{bB}	28.89 ± 0.26 ^{bB}	0.45 ± 0.02 ^{aB}	2.28 ± 0.13 ^{bA}
	14	59.63 ± 0.33 ^{bB}	28.16 ± 0.35 ^{aB}	12.39 ± 0.15 ^{bB}	30.77 ± 0.26 ^{aB}	0.41 ± 0.02 ^{aB}	5.36 ± 0.18 ^{aA}
YD2 (3%)	0	41.95 ± 0.87 ^{aC}	34.02 ± 0.10 ^{aA}	9.78 ± 0.06 ^{aC}	35.40 ± 0.28 ^{aA}	0.28 ± 0.01 ^{aC}	–
	7	40.57 ± 0.61 ^{bC}	34.17 ± 0.33 ^{aA}	8.46 ± 0.21 ^{bC}	35.20 ± 0.22 ^{aA}	0.24 ± 0.01 ^{aC}	1.92 ± 0.22 ^{bB}
	14	39.61 ± 0.54 ^{bC}	34.22 ± 0.78 ^{aA}	7.55 ± 0.40 ^{bC}	35.04 ± 0.27 ^{aA}	0.22 ± 0.01 ^{aC}	3.24 ± 0.29 ^{aB}

Table 5. Colorimetric attributes of control and value-added yogurt dressings. Values with distinct lowercase letters in the table signify a statistically significant difference among each color parameter and storage duration ($p < 0.05$). Values with distinct superscript uppercase letters in the table indicate a significant difference among each color parameter and sample ($p < 0.05$).

These are in line with those reported in studies carried out with jelly formulation supplemented with encapsulated barberry’s anthocyanin and new light-formulated mayonnaises with encapsulated grape skin’s anthocyanin^{36,55}.

Color evaluation

The results of the color measurements of the yogurt dressings on the first control day and after 14 days of storage are presented in Table 5. The inclusion of G1 significantly affected the color of the yogurt dressings, as indicated by the analysis of the color parameters. The experimental yogurt dressings exhibited the lowest lightness (L*) and blueness (b*) values, alongside the highest redness (a*) values.

Means denoted by distinct lowercase letters in the table signify a statistically significant difference among each color parameter and storage duration ($p < 0.05$). Means sharing distinct superscript uppercase letters in the table indicate a significant difference among each color parameter and sample ($p < 0.05$).

According to the results presented in Table 5, the value-added dressing (YD1 and YD2) is characterized by shades of dark red. The a* value increases, thus the intensity of the color is directly proportional to the percentage of encapsulated red OS powder added. The increase in redness could be attributed to the typical red color of G1 powder caused by polyphenols, especially anthocyanins. The L* value decreased with the incorporation of powder; thus, the colored pigments in the powder mostly caused the decrease in brightness. A similar trend was also found for the b* parameter. The addition of natural dye in emulsions results in decreased brightness due to less light being reflected to the detector, as explained by Kaltsa et al.⁵⁶. YD1 and YD2 had higher values of a*, most likely due to the pigments (especially anthocyanins) of the G1 powder. A similar trend was also found for mayonnaises with encapsulated grape skin’s anthocyanin⁵⁵. Statistically significant changes were seen in yogurt dressings’ L*, a*, and b* values in 14 days of storage ($p < 0.05$).

Colorimetric values exhibited significant changes ($p < 0.05$) during storage, particularly in the value-added formulations (YD1 and YD2). For the C sample, L*, a*, and b* values showed minor variations over 14 days (e.g., L* from 91.15 ± 0.85 to 90.65 ± 0.78), with ΔE increasing only to 0.77 ± 0.13, indicating minimal perceptible change and high color stability.

In contrast, YD1 (1%) and YD2 (3%) exhibited statistically significant changes across all color parameters. For YD1, L* decreased from 63.15 ± 0.07 to 59.63 ± 0.33, and a* increased significantly from 24.17 ± 0.08 to 28.16 ± 0.35, suggesting a darkening and intensification of red hue. Chroma also increased, and ΔE reached 5.36 ± 0.18, a level considered visibly noticeable. YD2 showed the most pronounced shift: L* decreased from 41.95 ± 0.87 to 39.61 ± 0.54, while a* remained statistically stable. b* and Chroma decreased slightly, and ΔE increased from 1.92 ± 0.22 at day 7 to 3.24 ± 0.29 at day 14, indicating moderate visual change. When G1 powder was added, there was an increase in ΔE during storage. The color’s Chroma, which shows how intense and

saturated it is, was greatest in the YD2 yogurt dressings. Since the hue angles were around 0°, the hue angle value was related to the color received and showed that both samples were red. Most of the time, an angle of 0° or 360° stands for red, while an angle of 90°, 180°, or 270° stands for yellow, green, or blue⁵⁷.

Texture analysis

From the results presented in Table 6, it can be noted that adding encapsulated G1 powder improved the firmness of the yogurt dressing, leading to a denser structure⁵⁸. Thus, the firmness of the yogurt dressing increased by approximately 38% in the YD1 and 70% in the YD2. The increase in firmness can be associated with increased resistance to deformation, which denotes good stability. Roman et al.⁵⁹ and Vathsala et al.⁶⁰ also observed these findings in value-added mayonnaise sauces. The lowest adhesion value, 0.42 mJ, was recorded for the control sample, indicating that adding powder increases the adhesion of the yogurt dressing. Higher values were recorded for the enriched samples. Thus, the addition of G1 powder in the composition of the yogurt dressing improved the adhesion, giving the product a fine and creamy texture⁶¹. Samples with G1 addition exhibited elevated cohesiveness values. This may be associated with the elevated protein content, resulting in a denser sample form. It was observed in the case of springiness that the YD2 recorded the highest value. These results are associated with the values of each of the textural parameters. Instrumental texture analysis revealed that adding powder obtained by microencapsulation of red OS extract improves the textural characteristics of the yogurt dressing in proportion to the concentration of added powder.

Rheological properties

The linear viscoelastic region specific to each yogurt dressing sample was initially established by performing rheological tests that followed the scanning of the deformation range. Analyzing the results presented in Fig. 2, it can be observed that the critical deformation value (γ_c) representing the limit of the linear viscoelastic range did not vary depending on the amount of microcapsule powder added to the yogurt dressings. Subsequently, flow tests were performed, the results being presented in Fig. 2c, d, in the form of rheograms indicating the variations of shear stress and apparent viscosity as a function of shear rate for all samples analyzed. Independent of the powder concentration introduced into the yogurt dressing-based matrix, a continuous increase in shear stress and a decrease in apparent viscosity are observed over the entire range of shear rates. The value-added yogurt dressings presented higher rheological parameter values than the control. Analyzing the results presented in Table 6, it can be observed that the apparent viscosity increased significantly with the powder concentration ($p < 0.05$). The strain applied to the different samples during the subsequent frequency scanning tests was selected in such a way as to guarantee the collection of a response in the linear viscoelasticity range. In the entire frequency range considered in the study, values of the modulus G' higher than G'' were recorded (Fig. 2a, b). All samples showed a slight dependence of the G' and G'' values on frequency. Incorporating the powder into the yogurt dressing's matrix increased the values of both moduli compared to the control. For example, Table 6 presents the comparative rheological parameters recorded at a frequency of 1 Hz for all samples considered in the study. In agreement with Sanz et al.⁶², who investigated the effect of adding asparagus fibers on the rheological properties of yogurt, the increase in G' and G'' values with the addition of functional powder in the investigated samples indicates the formation of a better-structured matrix. Although a better compaction of the samples is noted under the conditions of increasing the powder concentration from 1 to 3%, it should be pointed out that the $\tan(\delta)$ value did not register significant changes, indicating that the structural organization model mainly due to the interactions established between the molecules in the matrix did not undergo important changes⁶².

Microstructure analysis

Figure 3 displays the SEM pictures of the G1 powder and the yogurt dressing samples. The G1 powder exhibited an irregular structure with varying particle sizes and shapes. The SEM image of G1 powder (Fig. 3a) demonstrated the formation of aggregates composed of seemingly unstructured plates. The observed features can be clarified by incorporating wall materials such as soy protein, P, and MD, along with the interactions between polyphenols

Parameter		C	YD1	YD2
Texture properties				
Firmness, N		0.26 ± 0.03 ^c	0.42 ± 0.03 ^b	0.88 ± 0.02 ^a
Adhesiveness, mJ		0.42 ± 0.06 ^c	1.67 ± 0.07 ^b	3.01 ± 0.10 ^a
Cohesiveness, -		0.55 ± 0.01 ^a	0.75 ± 0.02 ^a	0.86 ± 0.01 ^b
Springiness, mm		8.13 ± 0.11 ^a	8.72 ± 0.01 ^a	8.85 ± 0.02 ^b
Rheological properties				
Frequency sweep tests	G' , Pa	71.54 ± 4.29 ^c	197.6 ± 2.55 ^b	1097.2 ± 6.79 ^a
	G'' , Pa	21.4 ± 0.88 ^c	54.85 ± 1.34 ^b	303.55 ± 19.45 ^a
	Tan(δ)	0.30 ± 0.01 ^a	0.278 ± 0.003 ^b	0.278 ± 0.003 ^b
Viscosity (Pa·s) at a shear rate of	1 s ⁻¹	3.29 ± 0.31 ^c	7.58 ± 0.42 ^b	77.22 ± 2.45 ^a
	10 s ⁻¹	2.11 ± 0.10 ^c	3.32 ± 0.16 ^b	10.53 ± 0.78 ^a
	100 s ⁻¹	0.52 ± 0.02 ^c	1.045 ± 0.001 ^b	2.12 ± 0.01 ^a

Table 6. Texture and rheological properties of the control and yogurt dressings. Superscripts denoting distinct letters within a row indicate significant differences ($p < 0.05$).

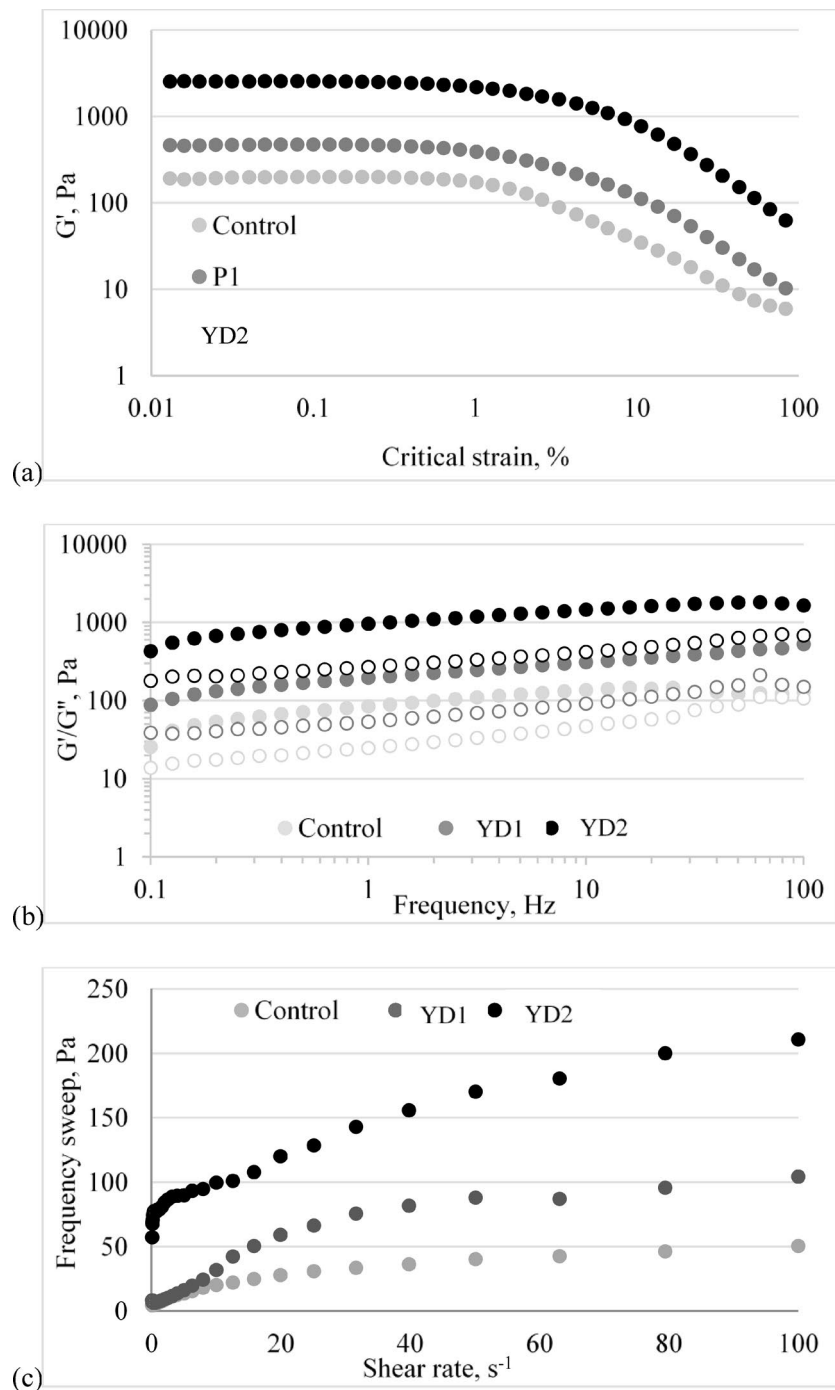


Fig. 2. Rheological properties of yogurt-based sauces prepared with different amounts of microcapsule powder (0%—Control, 1%—YD1, 3%—YD2). Results of the strain scanning test (a) and frequency domain (b). The storage mode (G') is represented by filled symbols and the relaxation mode (G'') by empty symbols. Variation of shear stress (c) and apparent viscosity (d) as a function of shear rate of yogurt-based sauces with different amounts of microcapsule powder.

and soy protein, as indicated by Bandyopadhyay et al.⁶³. The yogurt dressings containing G1 powder (Fig. 3b, c, d) exhibited a microstructure distinctly different from that of the control yogurt dressing. The control yogurt dressing displayed numerous gaps and pores, an uneven surface, and irregular protein connections. In contrast, adding G1 powder significantly reduced the pore spaces and channels in the yogurt dressing samples, resulting in denser and more uniform protein aggregation as well as an improved microstructure.

Incorporating G1 powder into yogurt dressings resulted in a more uniform and evenly distributed protein network, leading to a smoother texture with fewer gaps. However, the overall structure of the yogurt dressings

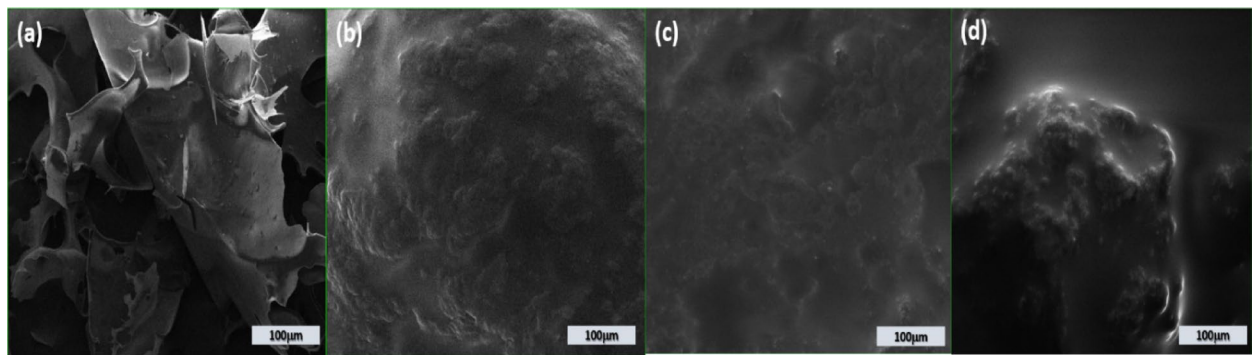


Fig. 3. SEM micrographs of yogurt enriched with G1 powder: (a) G1 powder, (b) C yogurt dressing without powder addition; (c) YD1 and (d) YD2 yogurt with 1 and 2% of G1 powder, respectively.

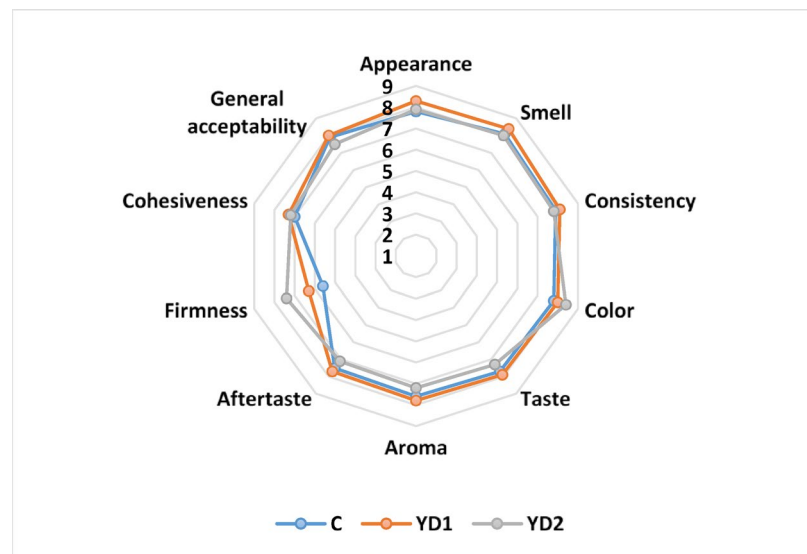


Fig. 4. Comparative diagram of the sensory attributes specific to supplemented yogurts. YC—yogurt without powder addition; YD1 and YD2—yogurt with 1 and 3% G1 powder.

appeared slightly coarser. This effect is likely due to the interaction between G1 powder and proteins, supported by hydrocolloids and the emulsion's stability. These findings align with those reported by Ibrahim and Khalifa⁶⁴.

Sensorial analysis

Figure 4 presents the average results derived from the sensory evaluation. YD1 and YD2 demonstrated superior scores for sensory qualities relative to the control. Adding G1 powder conferred a reddish hue (Fig. 5) to the yogurt dressings, which the panellists highly favoured. YD2 received the highest preference ratings for color, indicating that including G1 powder significantly influenced the acceptability and desirability of the samples' color. The outcomes of the taste sensory evaluation revealed that the enriched yogurt dressings have a markedly superior taste compared to the control. A noticeable difference was observed in smell and aroma scores, with ratings consistently exceeding 8.

Also, a higher score was observed for the consistency of YD1. The yogurt dressings containing G1 powder were assessed as possessing a harmonious taste, aroma, and smell. Sensory analysis revealed that the dressing formulated with the addition of 1% G1 powder (YD1) received higher scores for most of the analyzed attributes (external appearance, smell, consistency, taste, aroma, aftertaste, cohesiveness, and general acceptability) compared to the control. All sensory properties achieved the highest degree of acceptance at this percentage.

The panelists evaluated all the proposed samples positively, with no red OS encapsulated powder flavor being perceived. Generally, enriched yogurt dressing was described as a delicious, creamy yogurt dressing with a garlic flavor. It is ready for salads, but can also be poured on wraps and/or bread or used as a dip. It is a refreshing aromatic sour sauce. The resulting sauce had a soft consistency with a reddish color, a pleasant sour taste, and a smooth creamy texture typical of the conventional product. Sensory evaluations were conducted to determine the overall acceptability of mayonnaise and jelly with encapsulated anthocyanin powder formulations. The mayonnaise and jelly enriched by encapsulation with bioactive compounds achieved superior scores compared



Fig. 5. Yogurt dressing samples with different percentages of G1 powder: C (control), 1% (YD1), and 3% (YD2).

to the control samples^{36,55}. In a study by Karimi Sani et al.⁶⁵, the addition of microcapsules of *Melissa officinalis* essential oil to yogurt did not result in a significant difference in overall acceptability when compared to the plain (control) samples. Overall, analyzing the sensory evaluation results, it is noted that the dressing variants with the addition of G1 powder were evaluated as having a balanced, pleasant taste, smell, and color corresponding to red onion, with a fine and creamy consistency.

Conclusions

The findings indicated that the microencapsulated red OS extract is a significant source of bioactive components exhibiting remarkable AA. This study successfully encapsulated red OS extract within an IPS–MD–P matrix using gelation and freeze-drying techniques, achieving an EE of $87.18 \pm 0.92\%$ for G1 and $84.30 \pm 1.02\%$ for G2. The biopolymer combinations with the highest polysaccharide concentration (G1) as carrier agents demonstrated superior preservation of anthocyanins and antioxidant capacity in red OS powder throughout 28 days of storage. The simulated digestion demonstrated that anthocyanins were effectively protected by the chosen matrices against in vitro stomach digestion and were released during the simulated intestinal phase. Due to their anthocyanin content, the microcapsules exhibited a lower L^* value and a higher a^* value, demonstrating their distinctive potential as colorants.

This study showed that using G1 powder enhances the bioactive content and antioxidant capability of yogurt dressing, improving its nutritional profile. The sensory analysis indicated that panellists valued the enhanced color of the yogurt dressings. An overall valuation of the enhanced yogurt dressing indicated that the YD1 with 1% G1 powder exhibited the optimal composition.

The findings indicate that red OS powder may be an effective substitute for the food industry in producing anthocyanin-enriched yogurt dressings. Further research is needed to evaluate the shelf-life extension, microbiological stability, and safety of yogurt dressings during storage, as well as to conduct clinical trials to confirm their safety and assess the potential health benefits for human consumption. This study acknowledges the potential of utilizing encapsulated anthocyanins from red OS as a novel functional ingredient, serving as a natural red colorant, and presents new opportunities for their application in anthocyanin-enriched food systems such as beverages, dairy products, and sauces, with possible health advantages.

Data availability

The data that support the findings of this study will be available on request from the authors (Florina Stoica; Gabriela Răpeanu).

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Author contributions

Florina Stoica; Gabriela Răpeanu: Conceptualization, Investigation, Supervision, Writing—original draft, Writing—review & editing. Roxana Nicoleta Rațu; Iuliana Aprodu: Data curation, Resources, Visualization. Nicoleta Stănciuc; Doina Georgeta Andronoiu: Supervision, Visualization. Gerard Jitareanu: Methodology, Investigation.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the Faculty of Agriculture, University of Life Sciences in Iasi, Romania (protocol code 3738/03.02.2025 and 03 March 2025 of approval). All participants provided a written informed consent form and received no financial compensation.

Additional information

Correspondence and requests for materials should be addressed to G.R.

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