LWT - Food Science and Technology 250 (2026) 119497

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Microencapsulation of myrtle berry anthocyanins: spray-dried maltodextrin-gum Arabic microcapsules with enhanced antioxidant stability and controlled release

Azita Shafiei [a], Javad Safaei-Ghomi [a,*], Mehdi Mehran [b]

[a] Department of Organic Chemistry, Faculty of Chemistry, University of Kashan, Kashan, I.R., Iran
[b] Barij Medicinal Plants Research Centre, Kashan, I.R., Iran

ARTICLE INFO

Keywords:
Anthocyanin
Encapsulation efficacy
Wall material
Spray dryer
Inulin

ABSTRACT

Myrtle berries contain phytochemicals and natural anthocyanins. However, despite their many health benefits, anthocyanins face stability challenges in food applications due to their sensitivity to environmental factors. The objective of this study was to determine the most effective wall material for microencapsulation myrtle berry extract (MBE) with combinations of gum Arabic (GA) and Inulin (IN) at five different ratios (GA/IN: 1/5, 1/2, 1/1, 2/1, 5/1). The microcapsules formulated with GA/IN (2/1) (F4) showed the highest encapsulation efficiency (97.8%). Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) confirmed the successful encapsulation of the extract. HPLC analysis results showed that delphinidin-3-glucoside and other anthocyanins were not degraded after encapsulation. Among all formulations, F4 demonstrated the smallest decline in antioxidant activity compared to the other treatments after 60 days of storage. The retention of anthocyanins in five formulations storage at 40 °C ranged from 87.1% to 95.9%. The in vitro release profile further demonstrated that the encapsulated anthocyanins had a more controlled release compared with the crude extract. Overall, the findings support the concept that microencapsulation can enhance the stability of anthocyanins.

1. Introduction

Myrtle (*Myrtus communis* L.) is an evergreen shrub that grows in the Mediterranean area, particularly southern European countries (Alipour et al., 2014). Leaves of myrtle have been used for gastrointestinal disorders, healing wounds and urinary systems due to their antiseptic and astringent properties (Alipour et al., 2014). Myrtle leaves contain flavonoids, phenolic compounds, and essential oils. (D'Urso et al., 2019; Messaoud & Boussaid, 2011; Pereira et al., 2017). Its berries are particularly rich in anthocyanins, flavonoids, fatty acids, and various organic acids including ascorbic, tartaric, citric, tannic, and malic acids (Giampieri et al., 2020). The high polyphenol content of myrtle berries is closely associated with significant health benefits, including potential applications in managing cardiovascular diseases and neoplastic disorders (Correddu et al., 2019; Hacıseferoğulları et al., 2012; Çakmak et al., 2021). Also, it has been shown that myrtle berries could be a good source of antioxidants compound and anthocyanins (Giampieri et al., 2020; Jabri et al., 2016; Wannes & Marzouk, 2016). Supporting this, research by Jaberi et al. demonstrated the efficacy of myrtle berry extract in mitigating obesity-related issues. The study showed that the extract effectively restored lipid profiles and reduced inflammation in rats fed a high-fat diet, suggesting its protective potential against diet-induced metabolic disturbances (Jabri et al., 2023).

Anthocyanins, natural coloring compounds (blue, purple, red) found in plants, are a suitable alternative to artificial colors in the food industry (Sganzerla et al., 2021,Li et al., 2022; Liu et al., 2025). These compounds also possess significant antioxidant, antimicrobial, and anti-inflammatory properties (L. Li et al., 2022; Liu et al., 2025; Zhang et al., 2020), offering numerous health benefits including neuroprotective, cardioprotective, and anticancer effects (Shu et al., 2023). Human studies have also confirmed their role in preventing metabolic diseases, mainly due to their anti-inflammatory and antioxidant activities (Kolehmainen et al., 2012; Zafra-Stone et al., 2007). Despite these advantages, the practical application of anthocyanins is limited due to their inherent instability and low bioavailability (Bustamante-Bernedo et al., 2024; Jaouhari et al., 2025). They are highly sensitive to factors

* Corresponding author.
E-mail address: safaei@kashanu.ac.ir (J. Safaei-Ghomi).

https://doi.org/10.1016/j.lwt.2026.119497
Received 14 February 2026; Received in revised form 24 April 2026; Accepted 10 May 2026
Available online 12 May 2026
0023-6438/© 2026 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

such as temperature, light, pH, oxygen, and metal ions, which can lead to rapid degradation. (Qi et al., 2023; Zhao et al., 2021).

To address the instability of anthocyanins, microencapsulation is a promising technique (Gan et al., 2026). Among the hydrocolloids used for encapsulation, GA and IN are commonly applied to entrap bioactive compounds due to their hydrophilic nature. A combination of the two hydrocolloids can be used as a stabilizing agent and texture enhancer. GA, due to its emulsifying properties and its ability to form protective layers around particles, plays a key role in system stability (Osman et al., 1994). IN, on the other hand, is a soluble prebiotic fiber that not only improves the sensory and textural properties of the product but also enhances its nutritional value by increasing its fiber content. Previous studies have shown that the combination of these two substances can lead to synergistic effects in emulsion stability and improvements in the rheological properties of the formulation compared to individual use (Mehran et al., 2020; Pereira Souza et al., 2017), making it an ideal choice for encapsulating the sensitive myrtle berry extract.

Although anthocyanin instability and the application of various wall materials have been extensively investigated, limited attention has been given to the functional performance of a GA/IN system in the microencapsulation of myrtle berry extract. In particular, the effects of this binary mixture on encapsulation efficiency, anthocyanin protection during processing, and bioaccessibility during gastrointestinal conditions remain insufficiently understood. This research gap is especially important because the interactions between GA and IN may result in synergistic functional properties that have not been fully evaluated for this extract. The main hypothesis was that combining GA and IN would provide superior encapsulation performance compared with using either biopolymer alone, leading to enhanced anthocyanin retention and greater stability. Thus, this study aimed to evaluate the effect of GA and IN mixture on encapsulation efficiency, morphology, stability of anthocyanin content and antioxidant activity of the encapsulations. The physicochemical and technological properties of the microcapsules were also assessed, together with anthocyanin release kinetics and stability during in vitro gastrointestinal digestion.

2. Material and method

2.1. Chemicals

Food-grade gum Arabic (GA) and inulin (IN) were sourced from Samchon Chemical (Korea). Other chemicals and reagents such as 2,2-diphenyl-1-picrylhydrazyl (DPPH), citric acid, acetonitrile, pepsin, and pancreatin were of analytical grade and obtained from sigma-aldrich company.

2.2. Anthocyanin extraction

Myrtle berries were collected in October 2023 from the Noorabad area in Fars province. Subsequently, the berries were steeped in 250 ml 70% ethanol containing 1% citric acid for 24 h. The obtained extract was vacuum-filtered to separate the supernatant and solid residues. The supernatant was then evaporated under reduced pressure at 40 °C using a rotary evaporator to remove the solvent. The concentrated myrtle berries extract (MBE) stored at 5 °C until further analysis.

2.3. Preparation of microcapsules by spray dryer

Inulin and gum Arabic with different ratio including F1:5% GA and 25% IN; F2: 10% GA and 20% IN; F3: 15% GA and 15% IN; F4: 20% GA and 10% IN; and F5: 25% GA and 5% IN w/w% of total solution; were added to 60 ml distilled water. The mixture was stirred at 1000 rpm for 30 min to ensure complete dissolution and the absence of lumps. Subsequently, the mixture was stored overnight at 4 °C for full hydration. Following hydration, 10 ml of MBE was gradually incorporated into the slurry while homogenizing at 15000 rpm for 5 min using an Ultra-turrax homogenizer (IKA T18 Staufen, Germany). (Robert & Fredes, 2015).

A laboratory scale spray dryer (DSD02, Dorsa, Iran) was used in this study. The homogenized mixtures were fed using a peristaltic pump at the rate of 0.8 L/min, and dried at an inlet temperature of 120 °C and an outlet temperature 68 °C. The concentrated myrtle berries extract was continuously stirred with a magnetic stirrer at ambient temperature during the spray drying process. Dried red powder samples were kept them in amber glass at 5 °C for further analyses. It is noteworthy that the single-temperature approach inherently limits the generalizability of the obtained results regarding process optimization.

2.4. Moisture content

Moisture content of the microcapsules was measured by the gravimetric method. To determine moisture content, 0.2 g of each sample was weighed in triplicate and dried at 105 °C by Wisd oven until constant weight was achieved. The moisture content was then calculated based on the weight difference.

2.5. Powder yield

Powder yield was determined by calculating the ratio of the total dry weight of the powder—obtained after subtracting the moisture content from the total powder weight post-spray drying—to the initial weight of solids used to make the suspension, as showing in following equation:

$$Yield\ (\%) = \frac{total\ weight\ of\ powder\ after\ spray\ drying}{total\ theoretical\ dry\ weight\ of\ powder} \quad (1)$$

2.6. Total monomeric anthocyanin content (ACY)

Total monomeric anthocyanins (ACY) determination Total monomeric anthocyanins were calculated using the pH differential method. Absorption of ANY extracted from microparticles in two buffers, pH = 1.0 at 520 nm and pH = 4.5 at 700 nm was read using a Lambda EZ210 spectrophotometer. The results after three replicates in the measurement were calculated using the equation:

$$ACY\ (mg/L) = ((A_1\text{-}A_2)\ x\ MW\ x\ 1000 \times D)/(\varepsilon\ x\ L) \quad (2)$$

Where A_1 and A_2 are absorption in pH 1.0 and pH 4.5, respectively; D is the dilution factor; Mw is the molecular weight (449.2166 g mol $^{-1}$); ε is the extinction coefficient (26,900 cm^{-1} mol^{-1} L) and L is the cell length (cm).

2.7. HPLC/DAD (HPLC coupled with a diode array detector) for anthocyanin analysis

An Azura system equipped with DAD detector (Knauer, Germany) was used to analyze the samples. Chromatographic separation was performed on a Nucleodur (250 × 4 mm, C18, 5 μm) controlled at 25 °C with a special column. The solvent flow rate and injection volume were 1.0 ml/min and 10 μL, respectively. Solvent consisted of water 87%, acetonitrile 3% formic acid 10% and solvent B includes water 40%, acetonitrile 50% and formic acid 10%. The applied gradient program was: from 90% to 75% A in 20 min, from 75% to 50% A in 35 min. Absorbance spectra were collected for all peaks from 200 to 700 nm. The identification and quantification were done by the pure standard.

2.8. Encapsulation efficiency (EE%)

The encapsulation efficiency is calculated to evaluate the ability of walls to encapsulate anthocyanins and determines how much anthocyanin is trapped in the walls. To isolate the total anthocyanin content, 1 mL distilled water was poured to 200 mg of microparticles and put in an ultrasonic bath for 10 min. Then, it was made up to 20 mL with ethanol and the mixture was filtered by Whatman paper (A). To determine the

surface anthocyanins, a mixture containing 250 mg powder and 10 ml ethanol was agitated in glass tube for 10 s at room temperature. Following this, the slurry was centrifuged at 5000 rpm for 3 min to separate undissolved particles (B). The absorbance of clear supernatants of solution A and B was read at 520 nm. EE% of anthocyanin compounds are computed utilizing the subsequent equation:

$$EE = \frac{(A_{solution\ A} - A_{solution\ B})}{A_{solution\ A}} \times 100 \quad (3)$$

2.9. Fourier transform infrared spectroscopy (FTIR) analysis

The Fourier transform infrared (FTIR) spectroscopic analysis was performed using the Nicolet (Magna 550, USA). For this purpose, the samples were compressed into disk-shaped tablet by mixing with anhydrous potassium bromide. Each spectrum was recorded by 16 scans across a spectral range of 4000 to 400 cm^{-1}, with a resolution of 4 cm^{-1}.

2.10. Antioxidant activity determination

The antioxidant activities of the MBE and encapsulated powders stored at 40 °C for 0, 15, 30 and 60 days were determined using DPPH method. The DPPH assay was carried out according to the procedure of Bolling et al. (Bolling et al., 2015), and the absorbance was recorded at 517 nm. In the method, anthocyanins were combined with 2 mL of DPPH methanolic solution (60 μL/mL). After 70 min in darkness, absorbance was read at mentioned wavelength. The percentage of radical scavenging activity (%SA) is calculated using Equation (4):

$$\%SA = \frac{A_c - A_s}{A_c} \times 100 \quad (4)$$

Where As represents the absorbance of the sample and Ac represents the absorbance of the control sample. To prepare the control sample, methanol is used instead of anthocyanin. The sample concentration yielding 50% inhibition (IC50) was determined by plotting the inhibition percentages against the sample concentrations. The samples were analyzed in triplicate.

2.11. Scanning electron microscopy (SEM)

The microscopic morphology of the microcapsules was recorded with a scanning electron microscope (MIRA3, TESCAN, Czech Republic). For this purpose, a layer of conductive tape was applied to a sample holder. The samples were evenly distributed on the conductive tape, and a thin layer of gold was sprayed onto them. Measurement conditions included a voltage of 3 kV.

2.12. Storage stability of microcapsules

To evaluate degradation of encapsulated anthocyanins, they were put in an amber glass bottles (30 ml) provided with a self-sealing rubber cap and aluminium seals and was stored at 5 °C and at 40 °C. After extraction of anthocyanins, the absorbance of the samples at 520 nm was read for analysis of total anthocyanin contents at 0, 15, 30 and 60 days intervals (Mehran et al., 2020).

2.13. In vitro study of release profile

The release profile of anthocyanins under simulated gastric and intestinal conditions was evaluated following the methodology described by de moura et al., with minor modifications (de Moura et al., 2019). For the release profile study, 0.3 g of microcapsules were suspended in 100 mL of simulated gastric fluid (pH 1.2) containing pepsin and maintained in an Erlenmeyer flask at 37 °C for 240 min in a thermostatic bath, with intermittent stirring. The study was also conducted in simulated intestinal fluid (pH 7.4) containing pancreatin with the same amount of sample. The in vitro release of total anthocyanins from MBE and microparticles in the two specified media was monitored at predetermined time intervals (15, 30, 60, and 120 min).

2.14. Statistical analyses

The data were calculated from at least three replicates and reported as mean ± standard deviation. A p-value <0.05 was considered significant, determined using Duncan's multiple range tests in Minitab v22.4.0. Graphs of mean values with error bars were created using Microsoft Excel 2019.

3. Results

3.1. Moisture

Moisture content is an important property because powder quality, flowability, stickiness, and product stability depend on its moisture content. The ideal moisture content for powders is 3 to 4%. Exceeding this threshold may not only alter the physical characteristics of the product but also increase the risk of microbial proliferation.

In the present work, the moisture values found for five formulations ranged from 2.31% to 4.52%. A progressive increase in moisture was observed with higher concentrations of IN. This trend can be attributed to the intrinsic chemical structure of IN, which contains numerous hydroxyl groups capable of readily interacting with and absorbing water molecules from the surrounding environment. Oliveira et al. observed a similar behaviour, studying the freeze-dried of buriti oil with GA and IN (de Oliveira et al., 2022).

3.2. Encapsulation efficiency

The significant difference ($p \leq 0.05$) observed between treatments highlighted that microencapsulation efficiency is largely dependent on the type and ratio of wall materials. Treatment F4 exhibited the highest encapsulation efficiency, which can be attributed to the excellent emulsification capacity and film-forming properties of GA. GA's protein and polysaccharide compounds effectively entrap active ingredients, thereby significantly enhancing the protection of anthocyanins from degradation. This superior protection is attributed to the wall's ability to shield the flavylium cation in anthocyanins from water molecules.

Conversely, an excess of GA in formulation F5 led to a reduction in efficiency, indicating that an optimal ratio of wall materials is necessary. Formulation F1, with a higher proportion of IN, displayed lower encapsulation efficiency, likely due to IN's limited film-forming capacity and emulsification properties. This finding is consistent with the principle that a combination of proteins and polysaccharides can achieve higher efficiency than single encapsulating materials (Dagni et al., 2025; Mahdavi et al., 2016). Since encapsulation efficiency directly affects the retention and stability of anthocyanins, the total and individual anthocyanin contents of the formulations were subsequently evaluated.

3.3. Powder yield analysis

Powder yield is a key parameter in spray-drying processes, reflecting the efficiency with which the liquid extract is converted into a dry powder. High yield indicates minimal material loss during drying and collection, while low yield often results from sticking, incomplete drying, or deposition of material on the dryer walls. Evaluating powder yield is essential for optimizing processing parameters and ensuring the scalability of spray-dried extract production. The lowest powder yield was obtained from the crude extract, likely due to its sticky nature. Encapsulation markedly improved the powder yield; however, differences among the various formulations were not statistically significant. For instance, Guldiken et al. reported spray-dried black carrot extract

yields ranging from 36.9% to 52.1% (Guldiken et al., 2019).

3.4. Evaluation of total anthocyanins

Table 1 shows that formulation F4 achieved the highest total anthocyanin content (2.57 mg/g), with F3 closely following (2.56 mg/g). This indicates minimal anthocyanin degradation during the spray-drying process for these formulations, suggesting that the combination of GA and IN at a 20:10 ratio provided superior encapsulation efficiency compared to using either GA or IN alone. The overall anthocyanin degradation across all formulations ranged from 11.76% to 27.55%, based on initial anthocyanin content. The higher efficiency observed in formulation F4 can be explained by the synergistic mechanism of the wall materials. GA, due to its proteinaceous fractions, establishes strong interactions with anthocyanins and prevents their thermal instability. IN, by forming a dense carbohydrate matrix, limits oxygen penetration and heat transfer. The combination of these two polymers creates a stable and protective structure that reduces anthocyanin degradation during the process. This finding aligns with Gonzalez et al., who reported that a maltodextrin-IN blend maximized total anthocyanin and phenolic content retention (Romero-González et al., 2020). Also, in a study by Farahani et al., the amount of degradation of anthocyanins in malva was reported to be between 15.66% and 26.52% was reported, which is consistent with the results of this study (Farahani et al., 2024).

3.5. Evaluation of anthocyanins by HPLC

To better understand the types of anthocyanins, present in MBE and all treatments, a detailed HPLC analysis was performed. The HPLC–DAD approach enabled a rapid analysis of the anthocyanin fractions. As depicted in the chromatogram (Fig. 1), six major peaks were resolved within a 50-min analysis. Peak 1 was identified as delphinidin-3-O-glucoside by comparison with a reference standard. This compound was found in the highest concentration in the fourth treatment, measuring 0.492 mg/g. Subsequent analysis of peak spectral characteristics and comparison with established HPLC conditions for anthocyanins, supported by existing literature, allowed for the tentative identification of peaks 2 through 6. These peaks correspond to cyanidin-3-glucoside, petunidin-3-O-glucoside, peonidin-3-O-glucoside, malvidin-3-O-glucoside, and petunidin-3-arabinoside, respectively, constituting approximately 5.9%, 19.1%, 7.2%, 39.4%, and 8.2% of the total identified anthocyanins. Notably, similar anthocyanin profiles have been reported in other studies analyzing myrtle berry (Maldini et al., 2016; Tuberoso et al., 2010).

3.6. Fourier transform infrared spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy is a technique used to identify chemical bonds within molecules by analyzing their infrared absorption spectra. In this study, FTIR was employed to detect chemical bonds characteristic of phenolic compounds. The FT- IR spectra for MBE extract, wall material and F4 formulation are shown in Fig. 2.

The major broad peak band that occurred around at 3400 cm^{-1} in F4 and wall corresponds to the O-H functional group stretching vibration in carbohydrates and residual water. This peak appears broader in the infrared spectrum of the extract, which is related to the hydroxyl group of phenolic compounds. The MBE spectra showed a band 2930 cm^{-1} was assigned to CH stretching vibration. The band at 1725 cm^{-1} corresponding to the bending vibration of C-O-C groups, at 1640 cm^{-1} attributed to the vibration of the (C=C) bond in the benzopyran ring, at 1408 cm^{-1} associated with the (C=C) stretching vibration in the aromatic ring, at 1252 cm^{-1} linked to the stretching of pyran rings in the anthocyanin structure, and a peak at 1078 cm^{-1} assigned to the aromatic C-H in the aromatic ring.

Most peaks associated with MBE disappeared in the F4 microcapsule spectra. This phenomenon can be attributed to the MBE peaks being masked by the matrix spectra due to the low MBE content in the prepared microcapsule. The spectrum of the F4 powder closely resembles that of the matrix, confirming successful encapsulation of MBE. These

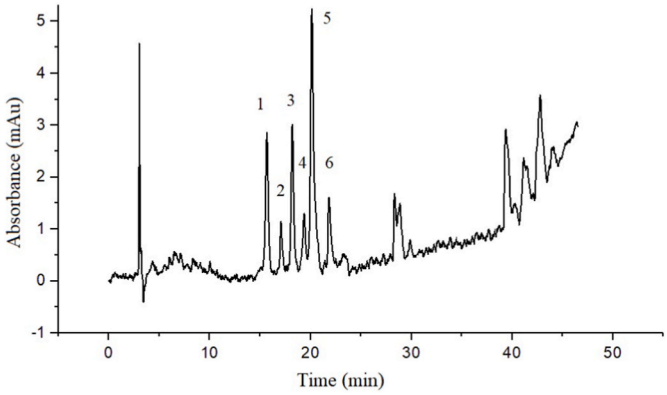


Fig. 1. HPLC chromatogram of anthocyanin extracted of MBE.

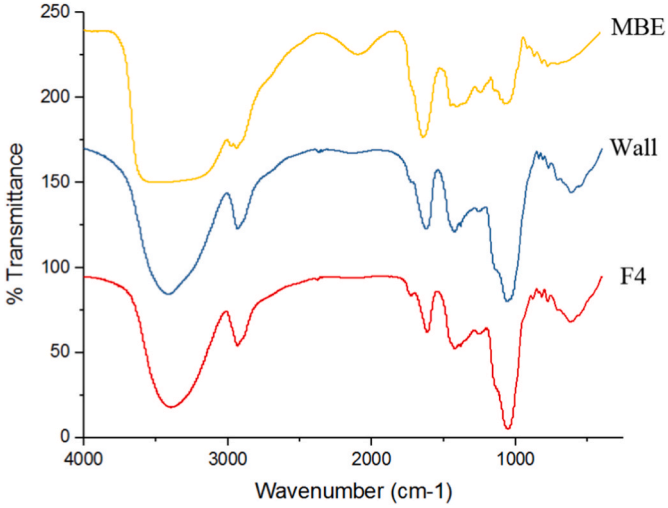


Fig. 2. FTIR spectra of MSE, MD, IN and F4.

Table 1
Characterization of myrtle berries extract and microparticles with different formulation.

Formulation	Moisture content w/w%	Total anthocyanins (mg/g)	Delphinidin-3-glucoside (mg/g)	EE%	Yield w/w%
F1	4.52 ± 0.04^{a}	2.11 ± 0.03^{a}	0.401 ± 0.008^{a}	94.3 ± 0.2^{a}	76.11 ± 0.52^{a}
F2	4.23 ± 0.05^{a}	2.31 ± 0.02^{a}	0.439 ± 0.005^{a}	95.4 ± 0.3^{b}	74.78 ± 0.61^{a}
F3	3.36 ± 0.05^{b}	2.56 ± 0.02^{b}	0.480 ± 0.004^{b}	96.1 ± 0.3^{c}	76.15 ± 0.84^{a}
F4	3.01 ± 0.04^{b}	2.57 ± 0.04^{c}	0.492 ± 0.006^{c}	97.8 ± 0.2^{d}	75.31 ± 0.96^{a}
F5	2.31 ± 0.05^{c}	2.45 ± 0.01^{b}	0.474 ± 0.009^{b}	96.5 ± 0.4^{c}	74.96 ± 0.72^{a}
MBE	5.27 ± 0.03	11.65 ± 0.03	2.24 ± 0.008	–	63.47 ± 0.96^{b}

Results show the mean value ± standard deviation from three samples.
There are no significant differences among the samples with the same letters in the same column ($p < 0.05$)

results are in agreement with those reported by Mehran et al. (Mehran et al., 2020) and Karunrat et al. (Sakulnarmrat et al., 2022) for *echium amoenum* petal and mangosteen pericarp encapsulates, respectively.

3.7. Antioxidant activity assays

An excess of free radicals in the body can engage in chemical reactions with other substances, leading to damage in organs and tissues. Numerous conditions, including cardiovascular, degenerative diseases, cerebrovascular disorders, and inflammation, are associated with free radicals. Anthocyanins, due to their efficient electron-donating properties, act as potent antioxidants by scavenging free radicals through electron donation, thereby preventing oxidative harm (Kalisz et al., 2013). Therefore, assessing the antioxidant capacity of both crude and encapsulated anthocyanin extracts is crucial.

In this study, the DPPH test, which is a simple and reproducible method, was used to determine antioxidant activity. As depicted in Fig. 3, the IC_{50} value of the crude MBE extract exhibited a five-fold increase after one month of storage at 40 °C, signifying a commensurate decrease in its antioxidant efficacy. In contrast, the prepared microcapsules demonstrated no significant elevation in their IC_{50} values. These findings underscore the protective effect of the encapsulation process on antioxidant activity, suggesting that the anthocyanins, when entrapped within the matrix, effectively retain their radical-scavenging capabilities.

The IC_{50} values for F1, F2, F3, F4, and F5 increased by 2.30, 1.90, 1.82, 1.33 and 1.68 times, respectively, over 60 days. Notably, formulation F4 displayed the least reduction in antioxidant activity after 60 days compared to the other treatments. This improved performance of formulation F4 under the tested conditions may be attributed to its more suitable matrix structure. This structure likely contributed to its higher encapsulation efficiency, enabling it to protect anthocyanins from oxygen and temperature.

This result is consistent with the study by Jéssica Righi da Rosa et al. on the encapsulation of blueberry anthocyanins by xanthan gum and maltodextrin (da Rosa et al., 2019). Also, Lacerda et al. demonstrated that the combination of IN, starch, and maltodextrin significantly enhances the antioxidant activity of jussara pulp (Lacerda et al., 2016).

3.8. Particle morphology

The morphologic characteristics, influenced by the formulation components, provide insights into the physical integrity and potential behavior of the encapsulated anthocyanins. SEM images of the five-formulation encapsulated of MBE are presented in Fig. 4. The morphological analysis revealed that the particles generally presented a spherical shape with a notably wrinkled surface texture, devoid of any visible cracks (see Fig. 5).

Formulation F1, characterized by the highest IN content in the wall material, yielded particles that appeared more spherical and possessed smoother surfaces. An increase in the GA content, however, resulted in more pronounced surface wrinkling. This effect was most evident in formulations F4 and F5, which displayed the most wrinkled particle surfaces. In this regard, Farahani et al. showed smooth surface formation with IN whereas maltodextrin resulted in wrinkled surfaces (Farahani et al., 2024). The same results were recorded according to the formation of smoother surfaces in spray-dried *Hibiscus sabdariffa* extract, where maltodextrin, IN, and quince seed mucilage were used as the wall material (Kalajahi et al., 2025).

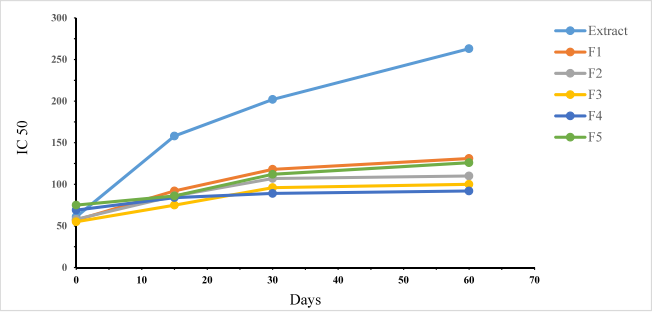


Fig. 3. The trend of antioxidant activity during 60 days.

3.9. Stability

Thermal stability is a critical parameter for evaluating the preservation of anthocyanins over time (Govaichelvan et al., 2024). As illustrated in Figs. 3 and 4, the total anthocyanin content of both the MBE and the five microencapsulated treatments progressively decreased with prolonged storage. At both evaluated temperatures, the unencapsulated MBE exhibited the most pronounced loss, confirming that the microcapsule wall materials effectively shielded anthocyanins from thermal stress and reduced their degradation rate.

The retention rate of anthocyanins in five encapsulated samples at 5 °C ranged from 92.8% to 95.9 %, while at 40 °C these values reached 87.1% to 95.5%. This finding indicated that anthocyanins undergo greater degradation at elevated temperatures. Among all formulations, treatment F4 exhibited the highest stability at both temperatures, with only 4.1–5.8% degradation. These results may be attributed to the ideal proportions of GA and IN, which serve as an effective wall material to safeguard anthocyanins.

The enhanced stability of anthocyanins in treatment F4 is hypothesized to stem from a combination of specific molecular interactions and the synergistic behavior of the wall material blend, primarily GA and IN in a specific ratio. Firstly, the glycoprotein structure of GA is believed to engage in protective interactions with anthocyanins. This likely involves hydrophobic interactions between the non-polar regions of GA and the aromatic benzene rings of anthocyanins, which are crucial structural components responsible for their color and susceptibility to degradation. Simultaneously, the abundant carbohydrate hydroxyl groups present in both GA and IN can form multiple hydrogen bonds with the polar, hydrophilic regions of anthocyanins. These hydrogen bonds effectively anchor the anthocyanin molecules within the matrix, limiting their conformational flexibility and shielding them from external destabilizing agents.

The observed synergistic behavior of the GA-IN blend further contributes to superior encapsulation. GA's role as an effective emulsifier ensures the initial formation of a stable emulsion with finely dispersed anthocyanin-loaded droplets. IN likely acts as a structural co-matrix, potentially forming a more rigid and continuous network during the drying process, thus reinforcing the protective film formed by GA. This combined matrix significantly improves the overall encapsulation efficiency by minimizing anthocyanin loss during processing. Crucially, By effectively entrapping anthocyanins within the core of the microcapsule, the wall material blend provides a robust barrier, directly leading to the enhanced stability observed in this study (Song et al., 2022). The enhanced stability observed in the present study may also be attributed to the synergistic behavior of the wall-material blends, which improve encapsulation efficiency and limit the exposure of anthocyanins at the microcapsule surface. These results consistent with the study of Wei deng et al., who showed the stability of purple corn anthocyanin improve with blending of maltodextrin/GA and maltodextrin/whey protein (Deng et al., 2023). Coyotecat et al. also reported high encapsulation efficiency and increased stability of red cabbage extract by combining GA, IN and pea protein (Muñoz-Coyotecatl et al., 2025). The hygroscopicity of IN is a well-documented characteristic. However, this study did not include an evaluation of storage humidity's effects on the microcapsules. Future research should address this by investigating product stability under various controlled humidity conditions.

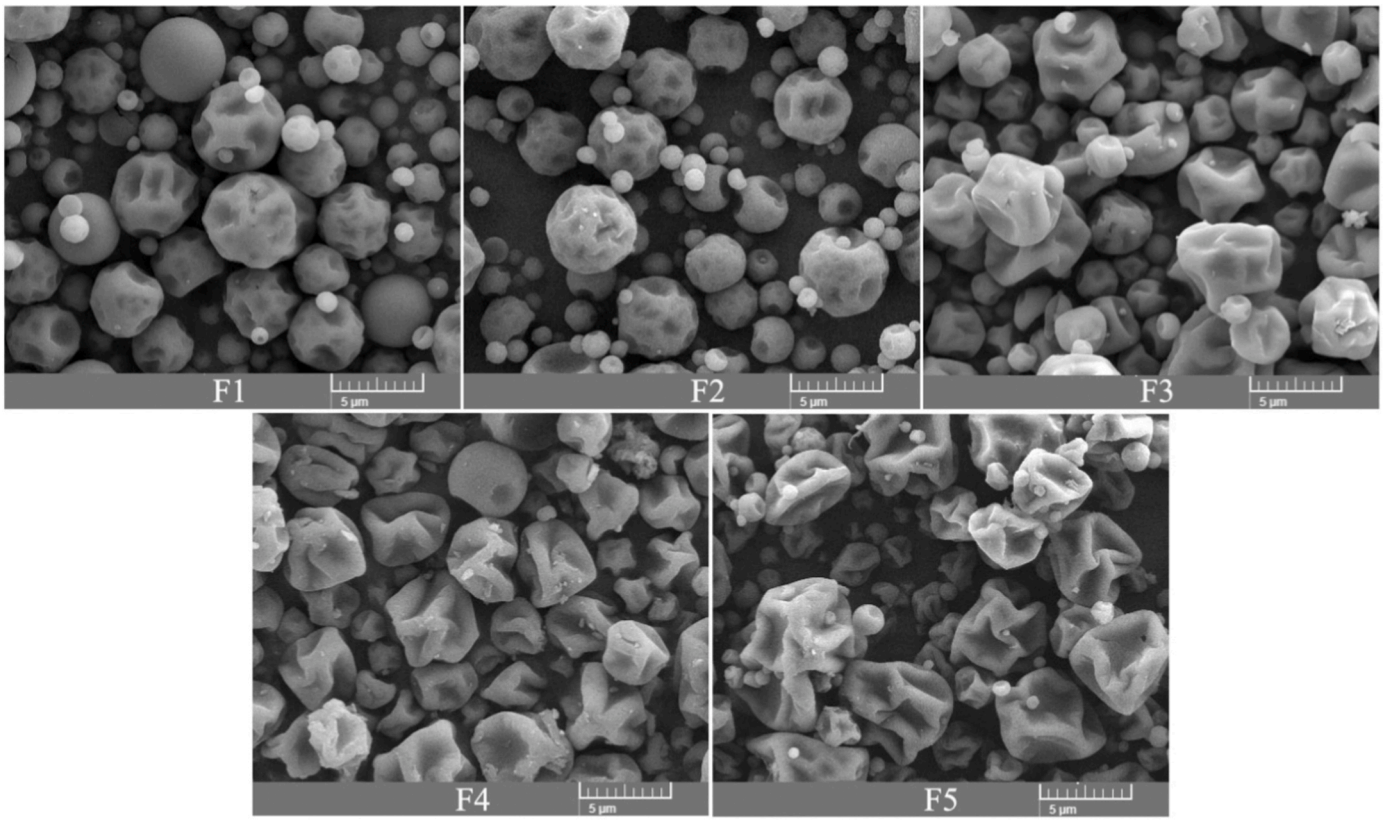


Fig. 4. Scanning electron photomicrographs of spray-dried products (F1, F2, F3, F4, F5).

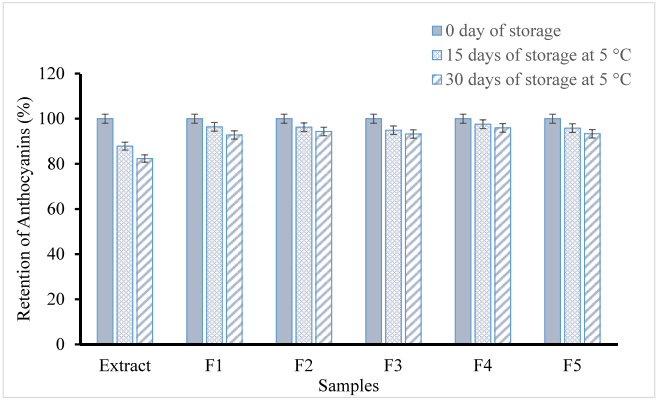


Fig. 5. Storage stability of MBE and encapsulated powders during storage at 5 °C for 15 days and 30 days.

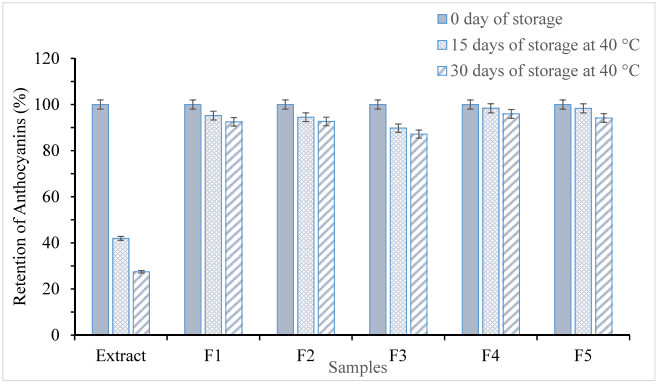


Fig. 6. Storage stability of MBE and encapsulated powders during storage at 40 °C for 15 days and 30 days.

3.10. Release

Investigating the release profile of an active ingredient is crucial for understanding its behavior and the mechanism governing its release (see Fig. 6). Experiments conducted under defined conditions can yield valuable insights, particularly concerning the food matrices suitable for incorporating this active material. Fig. 7 illustrates the percentage of anthocyanins released from MBE and the encapsulated extract F4 during simulated gastrointestinal digestion over 2 h. The unencapsulated anthocyanins (MBE) exhibited a rapid release, with 63%, 89%, and 96% released within the first 15, 30, and 60 min, respectively. In contrast, the encapsulated powder (F4) demonstrated a sustained and controlled release, with only 79% released after 60 min. This controlled release is critical for ensuring a more consistent and prolonged delivery of anthocyanins throughout the gastrointestinal tract, thereby maximizing their potential therapeutic benefits.

The release kinetics of anthocyanins differed significantly between the unencapsulated and encapsulated extracts in this medium. The F4 formula achieved a release of 89% after 120 min. Conversely, the anthocyanin content in the MBE began to decline after 30 min, dropping to 64% by the end of the 2-h period.

Anthocyanins exhibit greater stability in acidic conditions due to the formation of the flavylium cation; however, in neutral media, they transform into a colorless carbinol-like form. The slight decrease in anthocyanin release at pH = 6.8 from 30 min onwards in the crude extract may be related to the faster deprotonation of the flavylium cation in anthocyanins, leading to reduced color stability. As documented in the literature (Jiang et al., 2019; Xue et al., 2024), this deprotonation at near-neutral pH shifts the anthocyanin equilibrium towards less stable

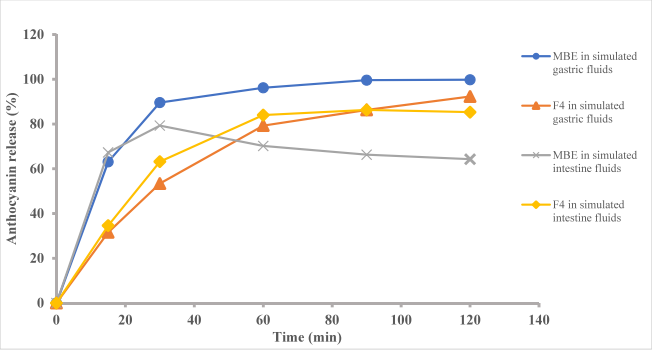


Fig. 7. Percentage of release of anthocyanins from MBE and microcapsules in simulated gastric and simulated intestine fluids.

quinoidal and ring-opened species. This degradation process directly leads to reduced color stability. This finding aligns with the research by Yue Wu et al. who reported that encapsulation of anthocyanins significantly enhanced the colonic accessibility (Wu et al., 2020). A comparable trend was observed in a study by Li et al., in which the encapsulating anthocyanins within a gel network enhances their stability and enables a safe, regulated release of anthocyanins in simulated intestinal fluid (W. Li et al., 2025). Release profiles show potential in lab conditions, but performance in real food matrices requires further study.

4. Conclusion

This comparative investigation into the microencapsulation of myrtle berry anthocyanins using various ratios of GA and IN has elucidated the critical role of wall material synergy in stabilizing these sensitive bioactives. The high encapsulation efficiencies achieved, ranging from 94.3% to 98.7%, demonstrate the potential of these natural polymers for effective protection. Notably, the GA:IN ratio of 2:1 emerged as optimal, achieving an encapsulation efficiency of 98.7% and exhibiting superior anthocyanin retention. Therefore, the combination of high performance (high efficiency and controlled release) with the use of readily available, low-cost, and safe GA/IN carriers firmly establishes a pathway for the large-scale application of this encapsulation technology. The in vitro release profiles in simulated gastric and intestinal fluids further suggest that this optimized microenvironment not only preserves anthocyanins during processing but also influences their subsequent release dynamics. While this study provides robust evidence for enhanced in vitro thermal stability and protective encapsulation, future *in vivo* investigations are essential to ascertain the potential improvements in anthocyanin bioavailability. This research provides the necessary scientific principles for the food and pharmaceutical industries to develop innovative products with enhanced shelf life and performance.

CRediT authorship contribution statement

Azita Shafiei: Writing – original draft, Data curation, Conceptualization. **Javad Safaei-Ghomi:** Writing – review & editing, Supervision, Project administration. **Mehdi Mehran:** Writing – review & editing, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the University of Kashan and Barij Essence pharmaceutical company for supporting this work.

Data availability

No data was used for the research described in the article.

References

Alipour, G., Dashti, S., & Hosseinzadeh, H. (2014). Review of pharmacological effects of Myrtus communis L. and its active constituents. *Phytotherapy Research, 28*(8), 1125–1136. https://doi.org/10.1002/ptr.5122

Bolling, B. W., Taheri, R., Pei, R., Kranz, S., Yu, M., Durocher, S. N., & Brand, M. H. (2015). Harvest date affects aronia juice polyphenols, sugars, and antioxidant activity, but not anthocyanin stability. *Food Chemistry, 187*, 189–196. https://doi.org/10.1016/j.foodchem.2015.04.106

Bustamante-Bernedo, M. S., Félix, L. L., Gutiérrez-Pineda, E., Huamán-Castilla, N. L., Solis, J. L., León, M. M. G., … Pacheco-Salazar, D. G. (2024). Development of antioxidant films based on anthocyanin microcapsules extracted from purple corn cob and incorporated into a chitosan matrix. *International Journal of Biological Macromolecules.* , Article 137658. https://doi.org/10.1016/j.ijbiomac.2024.137658

Çakmak, M., Bakar, B., Özer, D., Geckil, H., Karatas, F., & Saydam, S. (2021). Investigation of some biochemical parameters of wild and cultured Myrtus communis L. fruits subjected to different conservation methods. *Journal of Food Measurement and Characterization, 15*, 983–993. https://doi.org/10.1007/s11694-020-00692-x

Correddu, F., Fancello, F., Chessa, L., Atzori, A. S., Pulina, G., & Nudda, A. (2019). Effects of supplementation with exhausted myrtle berries on rumen function of dairy sheep. *Small Ruminant Research, 170*, 51–61. https://doi.org/10.1016/j.smallrumres.2018.11.003

da Rosa, J. R., Nunes, G. L., Motta, M. H., Fortes, J. P., Weis, G. C. C., Hecktheuer, L. H. R., … da Rosa, C. S. (2019). Microencapsulation of anthocyanin compounds extracted from blueberry (vaccinium spp.) by spray drying: Characterization, stability and simulated gastrointestinal conditions. *Food Hydrocolloids, 89*, 742–748. https://doi.org/10.1016/j.foodhyd.2018.11.042

Dagni, A., Jarjini, S., Sakoui, S., Elmakssoudi, A., Elemer, S., Vodnar, D. C., … Suharoschi, R. (2025). Innovative encapsulation of Dysphania ambrosioides essential oil and α-terpinene with gum arabic and inulin: Enhancing antibacterial activity, stability, and bioavailability. *International Journal of Biological Macromolecules.* , Article 140643. https://doi.org/10.1016/j.ijbiomac.2025.140643

de Moura, S. C., Berling, C. L., Garcia, A. O., Queiroz, M. B., Alvim, I. D., & Hubinger, M. D. (2019). Release of anthocyanins from the hibiscus extract encapsulated by ionic gelation and application of microparticles in jelly candy. *Food Research International, 121*, 542–552. https://doi.org/10.1016/j.foodres.2018.12.010

de Oliveira, J. P., Almeida, O. P., Campelo, P. H., Carneiro, G., Rocha, L.d. O. F., Santos, J. H., & da Costa, J. M. G. (2022). Tailoring the physicochemical properties of freeze-dried buriti oil microparticles by combining inulin and gum Arabic as encapsulation agents. *Lwt, 161*, Article 113372.

Deng, W., Li, X., Ren, G., Bu, Q., Ruan, Y., Feng, Y., & Li, B. (2023). Stability of purple corn anthocyanin encapsulated by maltodextrin, and its combinations with gum arabic and whey protein isolate. *Foods, 12*(12), 2393. https://doi.org/10.1016/j.lwt.2022.113372

D'Urso, G., Montoro, P., Lai, C., Piacente, S., & Sarais, G. (2019). LC-ESI/LTQOrbitrap/MS based metabolomics in analysis of Myrtus communis leaves from sardinia (italy). *Industrial crops and products, 128*, 354–362. https://doi.org/10.1016/j.indcrop.2018.11.022

Farahani, B., Behpour, M., & Memarzadeh, M. (2024). Microencapsulation of Malva sylvestris anthocyanins using maltodextrin and inulin as two alternative coating materials: Characterization, stability and release. *Journal of Food Measurement and Characterization, 18*(9), 7247–7259. https://doi.org/10.1007/s11694-024-02605-8

Gan, W., Li, X., Zhang, Y., Wang, Y., Liu, X., & Fan, L. (2026). Tailoring liposome composition for enhanced anthocyanin loading: Characterization, release kinetics, and interaction mechanisms. *LWT, 241*, Article 119092. https://doi.org/10.1016/j.lwt.2026.119092

Giampieri, F., Cianciosi, D., & Forbes-Hernández, T. Y. (2020). Myrtle (Myrtus communis L.) berries, seeds, leaves, and essential oils: New undiscovered sources of natural compounds with promising health benefits. *Food Frontiers, 1*(3), 276–295. https://doi.org/10.1002/fft2.37

Govaichelvan, K. N., Hamid, N., Kantono, K., Simarani, K., & Yaacob, J. S. (2024). Unleashing the power of nature: Investigating the effects of storage on plant-based pigments and bioactivities in tropical ficus spp. extracts. *Journal of Applied Research on Medicinal and Aromatic Plants, 39*, Article 100528. https://doi.org/10.1016/j.jarmap.2024.100528

Guldiken, B., Linke, A., Capanoglu, E., Boyacioglu, D., Kohlus, R., Weiss, J., & Gibis, M. (2019). Formation and characterization of spray dried coated and uncoated liposomes with encapsulated Black carrot extract. *Journal of Food Engineering, 246*, 42–50. https://doi.org/10.1016/j.jfoodeng.2018.10.025

Hacıseferoğulları, H., Özcan, M. M., Arslan, D., & Ünver, A. (2012). Biochemical compositional and technological characterizations of black and white myrtle (Myrtus communis L.) fruits. *Journal of Food Science and Technology, 49*(1), 82–88. https://doi.org/10.1007/s13197-011-0253-z

Jabri, M.-A., Hajaji, S., Omrani, A., Ben Youssef, M., & Sebai, H. (2023). Myrtle berries seeds prevent dyslipidemia, inflammation, and excessive cardiac reactive oxygen

species production in response to high-fat diet–induced obesity. *Journal of Medicinal Food, 26*(9), 631–640. https://doi.org/10.1089/jmf.2021.0199

Jabri, M.-A., Rtibi, K., Ben-Said, A., Aouadhi, C., Hosni, K., Sakly, M., & Sebai, H. (2016). Antidiarrhoeal, antimicrobial and antioxidant effects of myrtle berries (Myrtus communis L.) seeds extract. *Journal of Pharmacy and Pharmacology, 68*(2), 264–274. https://doi.org/10.1111/jphp.12505

Jaouhari, Y., Tao, W., Disca, V., Fernandes, A., Mateus, N., De Freitas, V., … Bordiga, M. (2025). Encapsulation of anthocyanins: A key for improvement of the gut-metabolism health axis? *Food Research International.* , Article 117380. https://doi.org/10.1016/j.foodres.2025.117380

Jiang, T., Mao, Y., Sui, L., Yang, N., Li, S., Zhu, Z., … He, Y. (2019). Degradation of anthocyanins and polymeric color formation during heat treatment of purple sweet potato extract at different pH. *Food Chemistry, 274*, 460–470.

Kalajahi, S. E. M., Mohammadi, M., Soofi, M., Ghandiha, S., Sabzichi, M., & Hamishehkar, H. (2025). Application of encapsulated phenolic compounds from Hibiscus sabdariffa L. extract using maltodextrin, inulin, and quince seed mucilage to enhance stability and bioavailability in sponge cake. *Carbohydrate Polymer Technologies and Applications.* , Article 100897. https://doi.org/10.1016/j.carpta.2025.100897

Kalisz, S., Oszmiański, J., Hładyszowski, J., & Mitek, M. (2013). Stabilization of anthocyanin and skullcap flavone complexes–investigations with computer simulation and experimental methods. *Food Chemistry, 138*(1), 491–500. https://doi.org/10.1016/j.foodchem.2012.10.146

Kolehmainen, M., Mykkänen, O., Kirjavainen, P. V., Leppänen, T., Moilanen, E., Adriaens, M., … Pulkkinen, L. (2012). Bilberries reduce low-grade inflammation in individuals with features of metabolic syndrome. *Molecular Nutrition & Food Research, 56*(10), 1501–1510. https://doi.org/10.1002/mnfr.201200195

Lacerda, E. C. Q., de Araújo Calado, V. M., Monteiro, M., Finotelli, P. V., Torres, A. G., & Perrone, D. (2016). Starch, inulin and maltodextrin as encapsulating agents affect the quality and stability of jussara pulp microparticles. *Carbohydrate polymers, 151*, 500–510. https://doi.org/10.1016/j.carbpol.2016.05.093

Li, W., Qi, Q., Yang, Y., Chen, X., Huang, Y., & Chen, P. (2025). Regulated release of anthocyanins via gelatin/pectin composite gels in simulated digestion. *Food Hydrocolloids, 166*, Article 111390. https://doi.org/10.1016/j.foodhyd.2025.111390

Li, L., Zhou, P., Wang, Y., Pan, Y., Chen, M., Tian, Y., … Zheng, J. (2022). Antimicrobial activity of cyanidin-3-O-glucoside–lauric acid ester against Staphylococcus aureus and Escherichia coli. *Food Chemistry, 383*, Article 132410. https://doi.org/10.1016/j.foodchem.2022.132410

Liu, X., Yuan, Y., Yu, B., Shen, L., Wang, H., Shen, H., … Zhang, Y. (2025). Potato protein/sugar beet pectin glycation conjugates: Ultrasound-assisted preparation and their applications as carriers of anthocyanins. *Food and Bioproducts Processing, 154*, 603–612. https://doi.org/10.1016/j.fbp.2025.10.016

Mahdavi, S. A., Jafari, S. M., Assadpoor, E., & Dehnad, D. (2016). Microencapsulation optimization of natural anthocyanins with maltodextrin, gum Arabic and gelatin. *International Journal of Biological Macromolecules, 85*, 379–385. https://doi.org/10.1016/j.ijbiomac.2016.01.011

Maldini, M., Chessa, M., Petretto, G. L., Montoro, P., Rourke, J. P., Foddai, M., … Pintore, G. (2016). Profiling and simultaneous quantitative determination of anthocyanins in wild Myrtus communis L. berries from different geographical areas in sardinia and their comparative evaluation. *Phytochemical Analysis, 27*(5), 249–256. https://doi.org/10.1002/pca.2623

Mehran, M., Masoum, S., & Memarzadeh, M. (2020). Improvement of thermal stability and antioxidant activity of anthocyanins of Echium amoenum petal using maltodextrin/modified starch combination as wall material. *International Journal of Biological Macromolecules, 148*, 768–776. https://doi.org/10.1016/j.ijbiomac.2020.01.197

Messaoud, C., & Boussaid, M. (2011). Myrtus communis berry color morphs: A comparative analysis of essential oils, fatty acids, phenolic compounds, and antioxidant activities. *Chemistry and Biodiversity, 8*(2), 300–310. https://doi.org/10.1002/cbdv.201000088

Muñoz-Coyotecatl, S., Domínguez-Uscanga, A., Ortiz-Castro, R., Rosas-Saito, G. H., Romero-De la Vega, G., Amador-Espejo, G., & Luna-Vital, D. A. (2025). Complex coacervation of anthocyanin-rich pigments from red cabbage (Brassica oleracea) with inulin, gum Arabic and pea protein. *Frontiers in Nutrition, 12*, Article 1523365. https://doi.org/10.3389/fnut.2025.1523365

Osman, M. E., Menzies, A. R., Williams, P. A., & Phillips, G. O. (1994). Fractionation and characterization of gum arabic samples from various African countries. *Food Hydrocolloids, 8*(3–4), 233–242. https://doi.org/10.1016/S0268-005X(09)80335-4

Pereira, P., Cebola, M.-J., Oliveira, M. C., & Bernardo Gil, M. G. (2017). Antioxidant capacity and identification of bioactive compounds of Myrtus communis L. extract obtained by ultrasound-assisted extraction. *Journal of food science and technology, 54*, 4362–4369. https://doi.org/10.1007/s13197-017-2907-y

Pereira Souza, A. C., Deyse Gurak, P., & Damasceno Ferreira Marczak, L. (2017). Maltodextrin, pectin and soy protein isolate as carrier agents in the encapsulation of anthocyanins-rich extract from jaboticaba pomace. *Food and Bioproducts Processing, 102*, 186–194. https://doi.org/10.1016/j.fbp.2016.12.012

Qi, Q., Chu, M., Yu, X., Xie, Y., Li, Y., Du, Y., … Yan, N. (2023). Anthocyanins and proanthocyanidins: Chemical structures, food sources, bioactivities, and product development. *Food Reviews International, 39*(7), 4581–4609. https://doi.org/10.1080/87559129.2022.2029479

Robert, P., & Fredes, C. (2015). The encapsulation of anthocyanins from berry-type fruits. Trends in foods. *Molecules, 20*, 5875–5888.

Romero-González, J., Ah-Hen, K. S., Lemus-Mondaca, R., & Muñoz-Fariña, O. (2020). Total phenolics, anthocyanin profile and antioxidant activity of maqui, Aristotelia chilensis (Mol.) Stuntz, berries extract in freeze-dried polysaccharides microcapsules. *Food Chemistry, 313*, Article 126115. https://doi.org/10.1016/j.foodchem.2019.126115

Sakulnarmrat, K., Sittiwong, W., & Konczak, I. (2022). Encapsulation of mangosteen pericarp anthocyanin-rich extract by spray drying. *International Journal of Food Science and Technology, 57*(2), 1237–1247. https://doi.org/10.1111/ijfs.15508

Shu, C., Wu, S., Li, H., & Tian, J. (2023). Health benefits of anthocyanin-containing foods, beverages, and supplements have unpredictable relation to gastrointestinal microbiota: A systematic review and meta-analysis of random clinical trials. *Nutrition Research, 116*, 48–59. https://doi.org/10.1016/j.nutres.2023.04.002

Song, J., Yu, Y., Chen, M., Ren, Z., Chen, L., Fu, C., … Li, Z. (2022). Advancement of protein-and polysaccharide-based biopolymers for anthocyanin encapsulation. *Frontiers in Nutrition, 9*, Article 938829. https://doi.org/10.3389/fnut.2022.938829

Tuberoso, C. I. G., Rosa, A., Bifulco, E., Melis, M. P., Atzeri, A., Pirisi, F. M., & Dessì, M. A. (2010). Chemical composition and antioxidant activities of Myrtus communis L. berries extracts. *Food Chemistry, 123*(4), 1242–1251. https://doi.org/10.1016/j.foodchem.2010.05.094

Wannes, W. A., & Marzouk, B. (2016). Characterization of myrtle seed (Myrtus communis var. baetica) as a source of lipids, phenolics, and antioxidant activities. *Journal of Food and Drug Analysis, 24*(2), 316–323. https://doi.org/10.1016/j.jfda.2015.11.001

Wu, Y., Han, Y., Tao, Y., Li, D., Xie, G., Show, P. L., & Lee, S. Y. (2020). In vitro gastrointestinal digestion and fecal fermentation reveal the effect of different encapsulation materials on the release, degradation and modulation of gut microbiota of blueberry anthocyanin extract. *Food Research International, 132*, Article 109098. https://doi.org/10.1016/j.foodres.2020.109098

Xue, H., Zhao, J., Wang, Y., Shi, Z., Xie, K., Liao, X., & Tan, J. (2024). Factors affecting the stability of anthocyanins and strategies for improving their stability: A review. *Food Chemistry, 24*, Article 101883. https://doi.org/10.1016/j.fochx.2024.101883

Zafra-Stone, S., Yasmin, T., Bagchi, M., Chatterjee, A., Vinson, J. A., & Bagchi, D. (2007). Berry anthocyanins as novel antioxidants in human health and disease prevention. *Molecular Nutrition & Food Research, 51*(6), 675–683. https://doi.org/10.1002/mnfr.200700002

Zhang, H., Xu, Z., Zhao, H., Wang, X., Pang, J., Li, Q., … Ling, W. (2020). Anthocyanin supplementation improves anti-oxidative and anti-inflammatory capacity in a dose–response manner in subjects with dyslipidemia. *Redox Biology, 32*, Article 101474. https://doi.org/10.1016/j.redox.2020.101474

Zhao, Y.-W., Wang, C.-K., Huang, X.-Y., & Hu, D.-G. (2021). Anthocyanin stability and degradation in plants. *Plant Signaling & Behavior, 16*(12), Article 1987767. https://doi.org/10.1080/15592324.2021.1987767