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Microencapsulation of Betacyanin from Dragon Fruit (*Hylocereus polyrhizus*) Peel by Foam-Mat Drying for Natural Food Colorant Application

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ABSTRACT

The growing demand for natural food colorants highlights the potential of betacyanin, a red-violet pigment from dragon fruit (*Hylocereus polyrhizus*) peel, valued for its antioxidant, anti-inflammatory, and anticancer properties. However, its application is limited by sensitivity to heat, light, and pH variations. This study aimed to enhance the stability and usability of betacyanin as a natural food coloring agent through microencapsulation using the foam-mat drying method. The extraction process was optimized using ultrasound-assisted extraction with a Box-Behnken Design (BBD) 3 levels (X_1: temperature; X_2: solvent concentration; X_3: solid to solvent ratio) and a total of 15 experiments to maximize total betacyanin content and color intensity. Foaming agents were screened, with SP exhibiting the highest foam expansion and stability among commercial foaming agents. The foam was subsequently dried at 60°C under vacuum to produce a stable, bioactive powder. The foam-mat drying resulted in encapsulated betacyanin with favorable properties, including high solubility of around 80% and encapsulation efficiency of up to 85%, making it suitable for applications in the food industry as a natural coloring agent. Moreover, foam-mat microencapsulation is more cost-effective and easier to implement than microencapsulation using spray drying.

1. INTRODUCTION

The use of food coloring dates back to prehistoric times, reflecting its integral role in enhancing the visual appeal and sensory attributes of food. Food colors are strictly regulated by various regulatory bodies worldwide, including the Food and Drug Administration (FDA) in the United States, the European Commission (EC) in the European Union, Food Standards Australia New Zealand (FSANZ), the Ministry of Health, Labor, and Welfare (MHLW) in Japan, the Food Safety Act in China, the Food Safety and Standard Authority of India (FSSAI), the Ministry of Health Regulation No. 33 of 2012 in Indonesia and the Ministry of Food and Drug Safety (MFDS) in South Korea. In Chile, the Ministry of Health established the Technical Standard for Food Additives in November 2021, aligning its colorant regulations with the Codex Alimentarius and the European Union's Regulation of Food Additives. The differences in food colorant regulations across countries highlight the urgent need for monitoring plans that assess the types and levels of colorants used in the food industry [1, 2].

Food colorants are classified into two categories: natural and synthetic. Among these, natural food colorings are increasingly preferred due to their association with health benefits, attributed to bioactive compounds such as carotene, betacyanin, and chlorophyll. These compounds not only impart vibrant hues but also exhibit antioxidant properties that contribute to improved health outcomes. Furthermore, natural colorings have undergone implicit long-term "clinical trials," evidenced by their safety across generations with no reported adverse health effects. In addition to their safety profile, natural food colorings are valued for their distinct aromatic properties and nuanced coloration, distinguishing them from synthetic alternatives. These natural pigments are derived from various plant parts, including flowers, roots, seeds, peels, stems, leaves, and fruits, and serve to enhance both the appearance and functional properties of food products [3].

The increasing demand for natural food colorants in the food industry is driven by rising consumer awareness of the potential health risks posed by synthetic additives. A notable concern is the presence of azo compounds (aromatic amines) in synthetic dyes, many of which are recognized as carcinogenic [4]. For instance, research by Al-Radadi [5]

demonstrated that even low doses of allura red dye could result in adverse health effects, such as skin irritation and kidney and liver disorders. Consequently, the demand for natural colorants that offer both safety and additional health benefits is on the rise.

Among the natural pigments, betacyanin—a red-violet pigment found in dragon fruit (*Hylocereus polyrhizus*) peel—has garnered significant attention. Betacyanin is highly valued not only for its vivid coloration but also for its bioactive properties, including antioxidant, anti-inflammatory, and anticancer effects [5, 6]. These attributes make betacyanin a compound of interest in the food and nutraceutical industries. However, its practical application as a food coloring agent is limited by its instability under heat, light, and pH variations, which can compromise its color intensity and bioactivity during food processing and storage [7]. The stability of betacyanin is influenced by factors such as temperature, pH, water activity, oxygen, light, storage, and processing. Being heat-sensitive, betacyanin degrades with higher temperatures and longer heating times. An optimal pH condition can help minimize thermal degradation and color loss. Water activity affects stability due to hydrolytic reactions, and daylight exposure can degrade pigments by up to 15.6% [8]. Additionally, long-term storage of encapsulated betacyanin powder at high temperatures can increase moisture content, leading to caking and microbial growth, which further reduces the pigment's stability [9].

Microencapsulation has emerged as a promising solution to address these challenges. This technique involves creating a protective matrix around sensitive compounds, enhancing their stability, and preserving their functional properties. Microencapsulated bioactive compound products have a relatively long shelf life of over 90 days when stored at temperatures below 23°C and under low relative humidity [10, 11]. Among various encapsulation methods, foam-mat drying presents a cost-effective and scalable approach suited for bioactive compounds. This method stabilizes an extract into foam using foaming agents, followed by moderate temperature drying to produce a powdered form of encapsulated bioactive compounds. Foam-mat drying not only enhances the stability of bioactive compounds but also retains their desirable properties, making it a suitable technique for preserving natural pigments like betacyanin [12]. The addition of maltodextrin in the betacyanin microencapsulation process can enhance stability during encapsulate storage and has demonstrated the highest bioavailability during in vitro gastrointestinal digestion [9].

Extracting betacyanin from dragon fruit peel is an essential step in obtaining this bioactive compound for foam-mat microencapsulation. The use of ultrasound-assisted extraction (UAE), integrated with response surface methodology (RSM), is considered an optimal method, as it efficiently yields betacyanin extracts with properties well-suited for food coloring applications. This integrated approach enhances the extraction process by improving the solubility and stability of the compounds, chosen as a preferred method for obtaining high-quality betacyanin suitable for use as a natural food dye [13].

This study aimed to investigate the microencapsulation of betacyanin extracted from dragon fruit peel using the foam-mat drying method and evaluate its potential as a natural food coloring ingredient. This research focused on optimizing the process parameters and assessing the physicochemical properties of the encapsulated product. By utilizing dragon fruit peel, an often-discarded by-product, this approach not only adds economic and functional value but also aligns with global trends toward sustainable and health-oriented food innovations.

2. MATERIALS AND METHODS

2.1 Materials

Dragon fruits were procured from local farmers in Bantul Regency, Yogyakarta, Indonesia. The peels were carefully separated from the fruit flesh and cleaned to remove any green outer portions. The cleaned peels were thoroughly washed and gently dried using paper towels to remove surface moisture. The cleaned dragon fruit peel is shown in Figure 1. The drying process was conducted in two stages: initially, the peels were dehydrated using a food dehydrator at 50°C for 24 hours, followed by a secondary drying phase at 70°C for 4 hours to ensure complete removal of residual moisture. Once dried, the peels were ground into a fine powder using a grinding machine. The ground powder was subsequently sieved through a 40-mesh sieve to achieve uniform particle size. The resulting dragon fruit peel powder was stored in sealed aluminium-plastic packaging with silica gel to prevent moisture absorption. Storage of the powder in an aluminum plastic bag can preserve its quality, thereby extending its shelf life [14]. The packaged powder was refrigerated at 8 - 10°C to preserve its stability and quality until further use. Storage of the powder at temperatures between 8 - 10°C can inhibit the degradation of bioactive compounds [11].

Figure 1. Cleaned dragon fruit peel (a) outer fruit peel and (b) inner fruit peel

2.2 Optimization of ultrasound-assisted extraction

The extraction of dragon fruit peel powder was performed using an ultrasound-assisted extraction (UAE) method. The powder was extracted with ethanol at varying concentrations, solid-to-solvent ratios, and temperatures, as determined by the experimental design. The extraction process was performed for 10 minutes at 80% amplitude with a duty cycle of 1/s. After extraction, the mixture was centrifuged at 4000 rpm for 15 minutes to separate the supernatant. The supernatant was filtered through Whatman No.1 filter paper to remove residual solids. The resulting extract was transferred to glass bottles, covered with aluminum foil to prevent light-induced degradation, and stored at 8-10°C in a refrigerator until further analysis.

A Box-Behnken Design (BBD) was employed to optimize the UAE process. This design used three levels (-1: low, 0: medium, 1: high) and three independent variables: temperature (X_1), solvent concentration (X_2), solid-to-solvent ratio (X_3), with total betacyanin content and color intensity as the response variables (Table 1). The experimental setup consisted of 15 runs, including three replicates at the central point to

estimate experimental variability. Data analysis was conducted using Minitab software (Minitab Ltd, Brandon Curt, UK). The significance of the variables and their interactions, as well as the model's goodness of fit, were evaluated using analysis of variance (ANOVA). A second-order polynomial (Eq. (1)) was applied to predict the responses as a function of the independent variables.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k} \sum_{j=1, j \neq i}^{k} \beta_{ij} X_i X_j \quad (1)$$

The response variable y represents the response variable (e.g., total betacyanin or color intensity), β_0 is the intercept, β_i are linear coefficients, β_{ii} are quadratic coefficients, and β_{ij} are interaction coefficients. Xi and Xj are the independent variables, k is the number of factors (in this case, 3), and ε accounts for random error. The coefficients were estimated using the least squares regression method.

The response surface equation generated from the model was used to perform multi-response optimization (MRO) to identify the optimal extraction conditions for the two responses: total betacyanin content and color intensity. This approach allowed the simultaneous optimization of multiple factors and responses, leveraging methodologies successfully demonstrated in prior studies [15].

Table 1. Selected factors and their level

Factor	-1	0	+1	Unit
X_1: Temperature	5	20	35	°C
X_2: Solvent concentration	30	50	70	% ethanol in water
X_3: Solid to solvent ratio	1:15	1:10	1:5	-

2.3 Foaming agent screening

A total of 100 mL of dragon fruit peel extract was mixed with 5% w/v maltodextrin and homogenized using an Ultra-Turrax T50 homogenizer (IKA, Staufen, Germany) for 3.5 minutes at 10,000 rpm. Subsequently, 1% w/v of a commercial foaming agent was added to the solution. The foaming agents evaluated included: a mixture of monoglyceride, diglyceride, and polyglycerol ester of fatty acid (SP); a combination of monoglyceride, polyglycerol ester, and sorbitan monostearate (TBM); and mono- and diglycerides derived from animal and vegetable fats and fatty acids (Ovalet) (PT. Gunacipta Multirasa, Banten, Indonesia). The solution was then further homogenized at 14,000 rpm for 15 minutes. The resulting foam was analyzed for its foaming properties, including foam expansion, density, and stability. The addition of maltodextrin in the range of 2–10% can provide good foam stability [16]. Meanwhile, the use of a 1% foaming agent is capable of producing optimal foam [17].

2.4 Microencapsulated with foam-mat drying

Dragon fruit peel extract was combined with 5% w/v maltodextrin, which served as a foam stabilizer, and homogenized using an Ultra-Turrax T50 homogenizer (IKA, Staufen, Germany) for 3.5 minutes at 10,000 rpm. Subsequently, 1% w/v of a foaming agent was added, and the mixture was homogenized again at 14,000 rpm for 15 minutes. The resulting foam was evenly spread onto trays and dried in a vacuum dryer (Memmert, Eagle, USA) at 60°C for six hours. A temperature of 60°C is considered safe for prolonged drying without compromising the bioactive components of the material [18]. Once dried, the foam sheet was ground into a fine powder, referred to as foam-mat dried powder. The powder was then sealed in airtight bags and stored in a refrigerator at 8-10°C to maintain stability.

2.5 Microencapsulated with spray drying

Spray drying was performed following a reference method with modifications [19]. Dragon fruit peel extract was mixed with 5% w/v maltodextrin as a foam stabilizer and homogenized for 3.5 minutes at 10,000 rpm. Subsequently, 1% w/v of a foaming agent was added, and the solution was homogenized again at 14,000 rpm for 15 minutes. The prepared solution was then processed using a lab-scale spray dryer (BUCHI Labortechnik AG 9230 B-290, Switzerland). During spray drying, the airflow rate was maintained at 5 m^3/min, the feed rate at 1 mL/min, and the inlet temperature at 100°C. A temperature of 100°C is considered optimal for spray dryer treatment to preserve bioactive components [19]. The resulting microencapsulated powder was collected and stored in airtight containers at 8-10°C until further analysis.

2.6 Moisture analysis

The moisture content of the samples was determined using a moisture analyzer [20]. Approximately 1-2 g of each sample was placed on the analyzer's plate, and the moisture content was measured by heating the sample at 105°C for 8 hours until a constant weight was achieved. The sample was then reweighed, and the moisture content was calculated as the percentage difference between the initial and final weights.

2.7 Color analysis

Color analysis was performed using a Chroma meter (Model CR-310, Konica Minolta, Inc., Tokyo, Japan) [21]. The analysis measured three color parameters: L^*, representing lightness, a^*, indicating the green-to-red spectrum, and b^*, representing the blue-to-yellow spectrum. Chroma, which specifies the color intensity of the sample, was calculated from the a^* and b^* parameters using Eq. (2).

$$\text{Chroma} = \sqrt{a^2} + b^2 \quad (2)$$

2.8 Foam expansion

Foam expansion (FE) was determined following the reference method [17]. The volume of the solution was measured using a graduated cylinder both before (V_i, cm^3) and immediately after (V_f, cm^3) the foaming process, and foam expansion was calculated using Eq. (3).

$$\text{FE (\%)} = \frac{V_f - V_i}{V_f} \times 100 \quad (3)$$

2.9 Foam density

Foam density (FD) was determined following the reference method [17]. The volume of the solution before the foaming

process (V_i, cm^3) was measured using a graduated cylinder. After the foaming process, the generated foam was collected using a scoop, transferred into a pre-weighed container, and weighed to determine its mass (m, mg). Foam density was calculated using Eq. (4).

$$\text{FD } (\frac{g}{cm^3}) = \frac{m}{V_i} \quad (4)$$

2.10 Foam stability

Foam stability (FS) was determined using a modified reference method [17]. A transparent graduated cylinder containing 50 mL of the foamed solution was maintained at room temperature (28 ± 2°C) for one hour to assess foam stability. The foam volume after a 15-minute interval (V_t, cm^3) was compared to the initial foam volume (V_i, cm^3) to calculate foam stability using Eq. (5).

$$\text{Foam stability } (\%) = \frac{V_t}{V_i} \times 100 \quad (5)$$

2.11 Total betacyanin content

The total betacyanin content was determined following the reference method with modifications [22]. Two grams of dragon fruit peel powder were extracted under the optimized conditions. The extraction results were centrifuged at 4000 rpm for 15 minutes to obtain the supernatant, which was then filtered using Whatman No.1 filter paper. The supernatant was placed into a cuvette, and the absorbance at the maximum wavelength for betacyanin (λ = 538 nm) was measured using a UV-Vis spectrophotometer (Genesys 10, Thermo Scientific Co.). The total betacyanin content was calculated using Eq. (6).

$$\text{Total betacyanin content } (\frac{mg}{g}) = \frac{A(MW)V(DF)}{\varepsilon L} \quad (6)$$

where, A is the absorbance at 538 nm, MW is the molecular weight of betanin (550 g/mol), V is the volume of extract, DF is the dilution factor, ε is the mean molar absorptivity (60,000 mol/L·cm), and L is the path length (1 cm). The results were expressed as mg of betacyanin per gram of dry matter.

2.12 Encapsulation efficiency

Encapsulation efficiency was expressed as the percentage ratio of the betacyanin content within the microcapsules (W_f) to the initial betacyanin content in the extract (W_i) [21]. The encapsulation efficiency was calculated using Eq. (7) and expressed in percentages.

$$\text{Encapsulation efficiency } (\%) = \frac{W_f}{W_i} \times 100 \quad (7)$$

2.13 Solubility of microcapsules

The solubility of microcapsules was determined following a reference study [23] with modifications. One gram of microcapsules was mixed with 25 mL of purified water and stirred for 5 minutes using a mechanical stirrer. The solution was then transferred to a centrifuge tube and centrifuged at 4000 rpm for 10 minutes at 25°C. The supernatant was collected and transferred to pre-weighed Petri dishes, which were dried for 5 hours in an oven at 105°C. The solubility percentage, representing the ratio of the dried supernatant weight ($W_{initial}$) to the initial weight of the supernatant before drying (W_{final}), was calculated using Eq. (8).

$$\text{Solubility } (\%) = \frac{W_{final}}{W_{initial}} \times 100 \quad (8)$$

3. RESULTS AND DISCUSSION

Fresh dragon fruit peels exhibit a high moisture content of 92.79 ± 0.10%, consistent with previous studies that report moisture levels in fresh dragon fruit peels exceeding 90% [24]. This high moisture content primarily consists of water, with minimal structural solids, a characteristic common to many fresh fruit by-products. High water content highlights the importance of appropriate handling and processing to prevent microbial growth and spoilage during storage.

Following the drying process, the moisture content of the dragon fruit peel is significantly reduced to 9.09 ± 0.29%. This reduction is achieved through a drying method specifically designed to remove water. The resulting moisture content falls within the range of 3-10%, as previously reported in the literature [25]. A low moisture content is essential for extending the shelf life of the powder and maintaining its quality during storage, underscoring the effectiveness of the applied drying process.

3.1 Optimization of ultrasound-assisted extraction

A Box-Behnken design (BBD) was utilized to assess the effects of three independent variables (X_1, X_2, and X_3) on two responses: Total betacyanin content (mg/g dry weight) and color intensity (Table 2). Compared to other three-level designs, the BBD minimizes the total number of experimental runs while avoiding extreme factor combinations, thereby reducing the risks associated with impractical or undesirable outcomes [26].

The analysis of variance (ANOVA) for the Box-Behnken Design (BBD) was conducted, and p-values were calculated using the t-test in Minitab software at a 95% confidence level. Variables with p-values below 0.05 were considered statistically significant.

Table 2. Box-Behnken design with measured responses

Run	Factor			Total Betacyanin Content (mg/g Dry Weight)	Color Intensity
	X_1	X_2	X_3		
1	0	-1	-1	2.455	9.955
2	0	0	0	20.411	16.878
3	0	1	-1	3.955	14.903
4	1	-1	0	0.788	4.204
5	0	0	0	21.202	18.097
6	-1	0	1	8.639	9.469
7	1	0	-1	11.652	14.854
8	-1	1	0	9.734	10.491
9	-1	-1	0	0.871	3.764
10	1	0	1	20.557	17.447
11	0	1	1	15.019	14.099
12	1	1	0	10.296	14.020
13	0	-1	1	8.205	5.773
14	-1	0	-1	13.318	12.013
15	0	0	0	21.411	16.425

The influence of each variable was visualized in a Pareto chart (Figure 2), which displayed the absolute values of the standardized effects ranked from largest to smallest. A

reference line at the significance level was included to identify statistically significant effects.

The ANOVA identified solvent concentration (X_2) as the most influential variable affecting total betacyanin content and color intensity. The solid-to-solvent ratio (X_3) had a significant impact on total betacyanin content but did not notably affect color intensity. Conversely, temperature (X_1) significantly influenced color intensity but did not affect total betacyanin content.

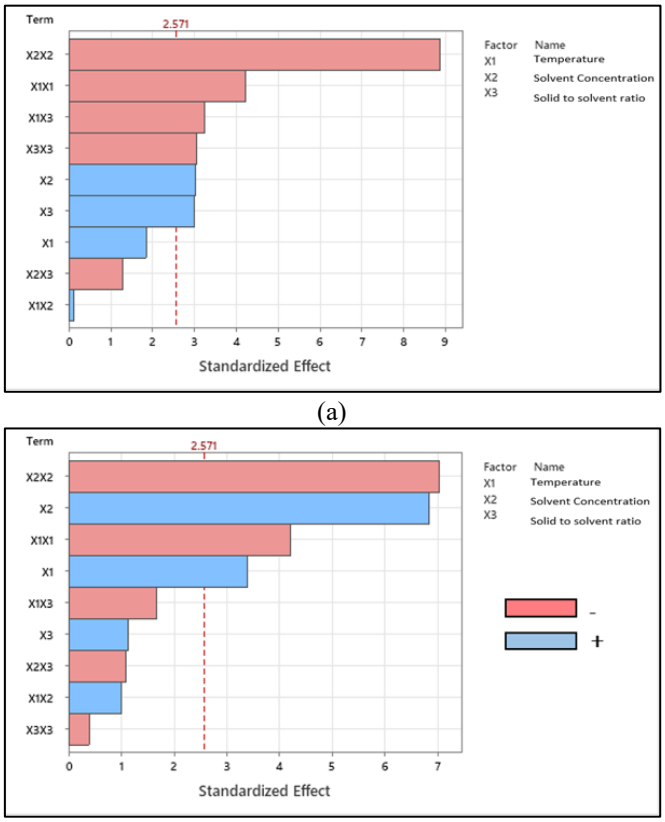


Figure 2. Pareto chart for the standardized effect of the variables on (a) Total betacyanin content and (b) Color intensity

The solid-to-solvent ratio is crucial in determining the total betacyanin content by increasing the contact surface area between the solid material and the solvent. This enhanced interaction facilitates greater solvent penetration into the matrix, allowing for a more efficient release and extraction of betacyanin from the solid material [27]. Temperature is a key factor affecting color intensity due to its impact on the molecular structure of pigments. Higher temperatures can enhance pigment intensity by improving molecular interactions but may also cause degradation at excessively high levels, thereby diminishing color intensity [28].

Solvent concentration positively influenced total betacyanin content and color intensity, indicating that higher solvent concentrations enhanced the extraction efficiency. However, the quadratic effect of solvent concentration negatively impacted these responses, suggesting that excessively high concentrations might reduce compound solubility. This observation highlights the importance of optimizing solvent polarity. Incorporating water into organic solvents, such as ethanol, has been shown to increase solvent polarity [29], which can improve the extraction efficiency of bioactive compounds when the polarity of the solvent aligns with the target compound [30].

Temperature significantly influenced color intensity but did not notably affect total betacyanin content. The quadratic effect of temperature negatively impacted both responses. High temperatures can degrade bioactive compounds [31] and cause solvent evaporation, particularly at temperatures approaching the solvent's boiling point [29]. Therefore, precise temperature control is essential for maintaining pigment integrity during the extraction process.

The UAE optimization was modeled using second-order polynomial equations to predict phytochemical content under varying experimental conditions. The following quadratic equations were developed for total betacyanin content (Eq. (9)) and color intensity (Eq. (10)).

$$Y = -20.26 + 0.3264X_1 + 0.6438X_2 + 69.8X_3 - 0.00497{X_1}^2 - 0.005855{X_2}^2 - 183.3{X_3}^2 + 0.000100X_1X_2 - 0.828X_1X_3 - 0.249X_2X_3 \quad (9)$$

$$Y = -43.49 + 0.766X_1 + 1.629X_2 + 85.6X_3 - 0.01500{X_1}^2 - 0.01410{X_2}^2 - 71{X_3}^2 + 0.00257X_1X_2 - 1.288X_1X_3 - 0.635X_2X_3 \quad (10)$$

In these equations, Y represents the response variable, while X_1, X_2, and X_3 correspond to temperature, solvent concentration, and solid-to-solvent ratio, respectively. The optimization process was conducted by incorporating a multi-response optimization approach. The suggested optimal parameters included 55.05% ethanol in water as the extraction solvent, an extraction temperature of 24.09°C, and a solid-to-solvent ratio of 1:7.69. To confirm the predicted optimal conditions, actual experiments were conducted (Table 3).

Table 3. Predicted and actual response values in the optimum extraction condition

	Solvent Cons. (%)	Solid-to-Solvent Ratio	Temp. (°C)	Total Betacyanin Content (mg/g dry weight)	Color Intensity
Predicted	55.05	0.130	24.09	21.40	18.02
Actual	55.00	0.125	24.00	23.47±0.22	17.13±0.1
% Error	0.10	3.85	0.37	9.52	4.92

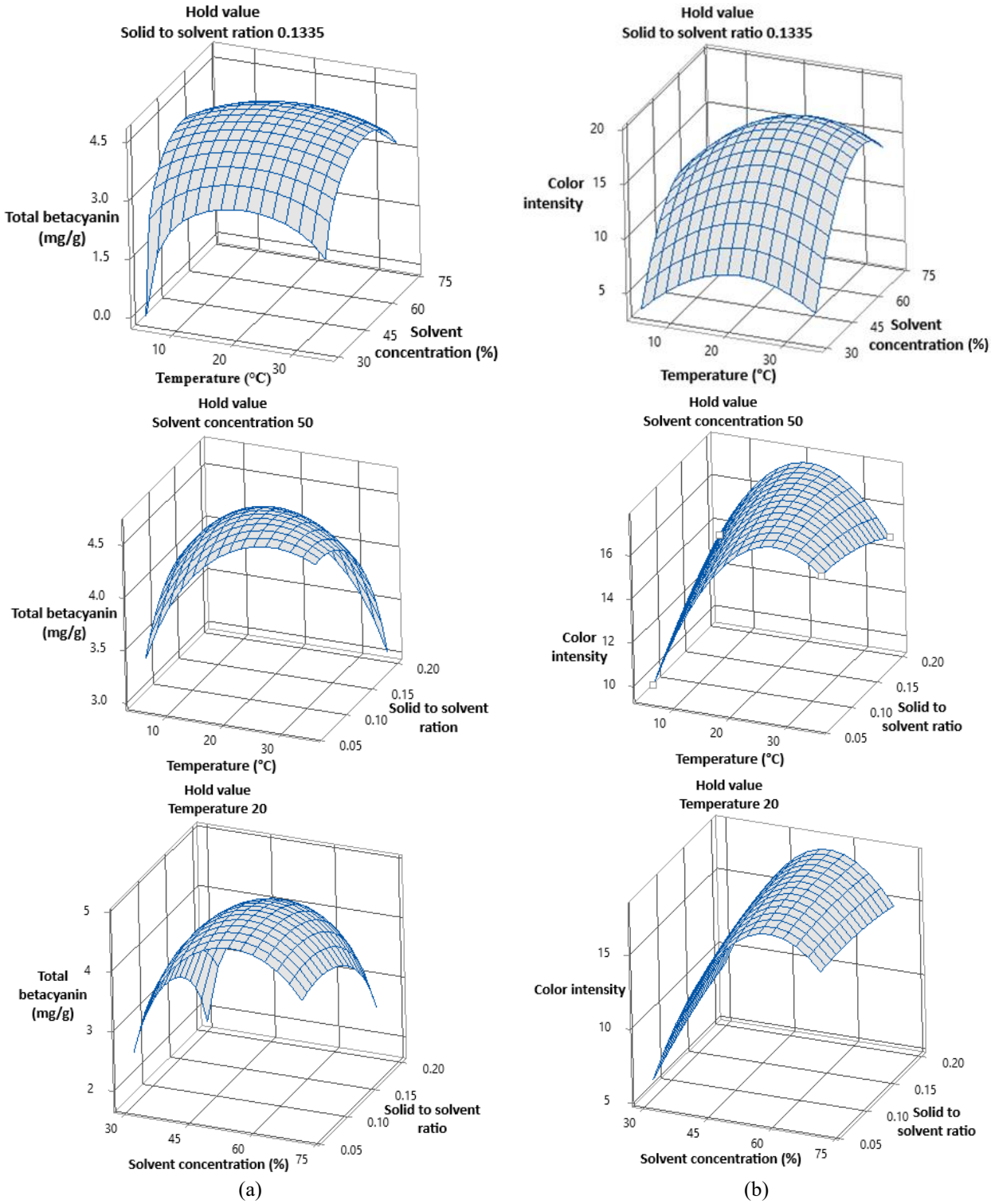
The results confirmed that the optimal conditions closely matched the predicted values. The actual parameters were 55% ethanol in water, an extraction temperature of 24°C, and a solid-to-solvent ratio of 1:8. The response surface methodology (RSM) plots (Figure 3) illustrate the interactions between temperature, solvent concentration, and solid-to-solvent ratio on total betacyanin content and color intensity. These plots reveal that all three factors significantly influence the extraction process.

An increase in temperature enhances betacyanin extraction by disrupting the material's structure and facilitating pigment release into the solvent. However, excessive temperatures can lead to pigment degradation, reducing the overall yield. This underscores the need for precise temperature control during extraction.

Efficient extraction is further supported by the cavitation effect, a phenomenon induced during ultrasound-assisted

extraction where collapsing bubbles generate strong forces, breaking apart the plant matrix and improving solvent penetration.

Optimal solvent concentration and solid-to-solvent ratio also play a critical role, as they enhance the interaction between the solvent and the target compounds, increasing the efficiency of betacyanin extraction [32]. The percentage of solvent concentration in the extraction process significantly affects the amount of betacyanin extracted. The interaction between the target compound and the solvent is key in determining the best solvent mixture. Polar compounds are more effectively extracted with polar solvents, while non-polar compounds require non-polar solvents. Additionally, the extraction of phenolic compounds increases when the solvent-to-solid ratio reaches equilibrium. Using a high volume of solvent for the extraction procedure could negatively impact phytochemical extraction. Additionally, if the solvent is insufficient, it may inhibit the cavitation effect of the ultrasound extraction. At this point, the ratio between the solvent and the solid material is optimized, allowing for the best diffusion of the compounds into the solvent. In other words, once equilibrium is reached, the extraction process is at its most efficient, extracting the maximum amount of bioactive compounds [33, 34].



(a) (b)

Figure 3. Surface plot of the factors on (a) total betacyanin content and (b) color intensity

3.2 Foaming agent screening

Screening foaming agents is a crucial step in identifying the most effective option for foam-mat drying, particularly in microencapsulation processes. The selection of a foaming agent directly impacts the quality and efficiency of the drying process. Key performance indicators for evaluating foaming agents include foam expansion, density, and stability. An effective foaming agent can produce foam properties with a minimum foam expansion of 35%, foam density ranging from 0.22 to 0.56 g/cm^3, and foam stability greater than 80% [17, 35]. The data in Table 4 show that SP (Surface-Active Agent or Sponge Improver) emerged as the most effective foaming agent, demonstrating superior foam expansion and stability. It is highly suitable for applications requiring efficient and stable foam-mat drying.

Table 4. Analysis of foaming properties

Foaming Agent	Foaming Properties Analysis		
	Foam Expansion (%)	Foam Density (g/cm^3)	Foam Stability (%)
SP	57.773±3.832^{a}	0.251±0.029^{ab}	83.423±2.337^{aa}
TBM	45.848±4.498^{b}	0.298±0.024^{aa}	73.726±0.285^{ba}
Ovalet	38.265±0.622^{b}	0.234±0.009^{ba}	75.145±6.134^{ab}

Notes: A different letter in a different row means significant differences based on Fisher LSD ($p < 0.05$).

SP demonstrated the highest foam expansion and stability among the evaluated foaming agents, attributed to its composition of monoglycerides, diglycerides, and polyglycerol esters of fatty acids. These surface-active compounds effectively reduce surface tension at the air-liquid interface, facilitating the incorporation and uniform distribution of air bubbles during the foaming process. This stabilization results in a foam with a high expansion rate, capable of retaining a substantial volume of air and forming a light, voluminous, and aerated structure. High foam expansion is critical in foam-mat drying, as it increases surface area and porosity, thereby enhancing drying efficiency and product quality.

SP also exhibited excellent foam stability, a key parameter for the success of foam-based drying methods. Its ability to maintain foam integrity over time prevents bubble coalescence and delays foam collapse, ensuring consistent performance throughout the drying process. These properties make SP an ideal foaming agent for applications requiring both high foam expansion and stability [17].

3.3 Microencapsulation with foam-mat drying

The microencapsulation process in this study was conducted using two treatments: foam-mat drying and spray drying (as a reference). These methods were chosen to compare the microencapsulated products based on key parameters, including total betacyanin content, encapsulation efficiency, solubility, and moisture content (Table 5). Foam-mat drying is a simple and cost-effective technique that utilizes foaming agents to create stable foam, which is then dried to produce the encapsulated product.

Table 5. Analysis of microencapsulating properties

Drying	Microencapsulating Properties Analysis			
	Total Betacyanin (mg/g Dry Weight)	Encapsulation Efficiency (%)	Solubility (%)	Moisture Content (%)
Foam-mat	20.29±0.02^{a}	86.42±0.08^{a}	80.23±0.27^{a}	21.54±0.19^{a}
Spray	22.12±0.02^{b}	94.24±0.08^{b}	85.85±0.06^{b}	16.42±0.62^{b}

Notes: A different letter in a different row means significant differences based on Fisher LSD ($p < 0.05$).

Foam-mat drying demonstrated slightly lower encapsulation efficiency (86.42 ± 0.08%) and total betacyanin content (20.29 ± 0.02 mg/g dry weight) than spray drying. Despite this, the encapsulation efficiency of foam-mat drying remains within the reported range for dragon fruit peel (80-92%) [21], indicating its effectiveness in retaining bioactive compounds. Furthermore, the microencapsulated products from foam-mat drying exhibited high solubility (80.23 ± 0.27%), a critical parameter for assessing the performance of encapsulated products and their ability to dissolve in various food formulations. The use of maltodextrin (MD) as a wall material contributed to the high solubility of the encapsulated bioactive compounds. MD's hydrophilic nature enhances its interaction with water, facilitating the dissolution process. Additionally, MD synergizes with other wall materials, improving the structural integrity and dispersion of encapsulated compounds [9].

Foam-mat drying resulted in a higher moisture content (21.54 ± 0.19%) than spray drying. This elevated moisture level may be attributed to the relatively lower drying temperatures in foam-mat drying, which are less efficient at removing water. Higher drying temperatures typically improve the evaporation rate of water molecules from the material [36]. Nonetheless, excessively high temperatures can degrade betacyanin content and negatively affect the color quality of the product, underscoring the need to balance drying temperature and product quality.

4. CONCLUSIONS

This study demonstrated the effectiveness of foam-mat drying as a method for microencapsulating betacyanin from dragon fruit peel. The optimized extraction conditions—55% ethanol in water, an extraction temperature of 24°C, and a solid-to-solvent ratio of 1:8—produced the highest total betacyanin content and color intensity. The inclusion of SP as a foaming agent significantly enhanced the process by improving foam stability and expansion. The foam-mat drying method yielded encapsulated betacyanin with favorable properties, including high solubility (~80%) and encapsulation efficiency (up to 85%), making it suitable as a natural coloring agent. These findings highlight foam-mat drying as a viable, cost-effective alternative to conventional encapsulation methods, offering a sustainable solution for utilizing dragon fruit peel by-products, with potential applications in the food industry, such as natural colorants. Additionally, it can be utilized for beverages, snacks, and other food formulations, leveraging its rich nutrient content.

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NOMENCLATURE

A	absorbance
m	mass, mg
V	volume, cm^3

Greek symbols

λ	wavelenght, nm
ε	mean molar absorptivity, mol L^{-1} cm^{-1}