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RESEARCH PAPER FEEDING THE FUTURE

Optimization of foam mat drying for producing high-quality butterfly pea flower (*Clitoria ternatea* L.) extract powder

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Abstract

The high anthocyanin content of butterfly pea flowers (*Clitoria ternatea* L.) can provide natural antioxidants for use in food and medicine. However, the use of butterfly pea flower (BPF) extract is limited by the instability of its anthocyanins during transformation and storage. Therefore, to convert the liquid BPF extract into a dry powder, we propose the foam mat drying (FMD) process. The dry powder form will improve the stability of the extract and ease handling during storage and distribution. In this method, bioactive compounds in the liquid extract are coated with biopolymers to form foam elements, which are then converted into powder. This study adopts an experimental multi-objective optimization approach, in which drying efficiency, physicochemical quality, and anthocyanin stability are evaluated simultaneously by systematically varying formulation composition and drying temperature, rather than relying on mathematical optimization models. Such an integrated evaluation is still rarely addressed in previous FMD studies, which typically focus on individual quality attributes or drying performance alone. The effect of the foaming and stabilizing agents ratio at various temperatures on the physicochemical properties of the resulting powder will be studied and evaluated. The results showed that the formulation of foaming agent (egg white powder, EWP) and foam stabilizers (maltodextrin, MD, and carboxymethyl cellulose, CMC) affected the physicochemical properties of BPF extract powder prepared by the FMD. Among all the foaming agent formulations, the compositions EWP:MD:CMC of 16:20:1 and 8:10:1, with a drying temperature of 70 °C, showed the fastest drying time and produced extract powder with high anthocyanin content and solubility, as well as increased color intensity. Principal component analysis (PCA) supported the results, showing that the formula (8:10:1) has the highest evaluation score for physicochemical properties.

Keywords

Butterfly pea flower, extract powder, foam mat drying, physicochemical properties

Introduction

The butterfly pea flower (*Clitoria ternatea* L.), known in Indonesian as telang, contains anthocyanins (Gamage et al. 2021; Jeyaraj, Lim and Choo 2021). The characteristic of anthocyanins in butterfly pea flowers (BPF) is the abundant presence of ternatin, which is a polyacylated anthocyanin. Ternatin gives the flower a bright blue color. The high levels of phytochemicals in the flower have potential antidiabetic, antimicrobial, antioxidant,

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anti-inflammatory, and anticancer properties (Li et al. 2022; Wang et al. 2022). The nutritional analysis results of BPF showed that the fat, carbohydrate, fibre, and protein content were 2.50, 2.20, 2.10, and 0.32%, respectively, while the water content was 92.4% (Gamage et al. 2021). In addition to anthocyanins, the flowers' bioactive compounds include steroids, flavonoids, phenolic acids, alkaloids, and tannins. Therefore, BPF is a potential source of natural antioxidants for use in food and pharmaceutical products (Escher et al. 2020; Gamage et al. 2021; Jeyaraj et al. 2021; Netravati et al. 2022).

Bioactive compounds in BPF can be extracted with solvents, yielding a liquid extract. However, the application of BPF extracts is limited by the instability of anthocyanins during transformation and storage, which is influenced by factors such as light, temperature, oxygen, or pH, leading to their degradation into colorless substances (Escher et al. 2020; Thuy et al. 2021; Tuan Putra et al. 2021; Santos and Martins 2023). Therefore, a foam-mat drying (FMD) method was proposed to convert liquid extract into a dry powder. It will improve stability and ease of handling during transportation and storage.

The FMD method is a simpler drying method than others, such as spray drying and freeze drying. In the FMD, bioactive compounds are coated with organic materials or biopolymers, forming foam elements that are then converted into solids. This methodology is cost-effective and requires a shorter processing time. FMD mitigates the limitations of conventional drying techniques, such as insufficient sensory properties, inadequate water retention, and extended processing times. FMD involves spreading a foamed slurry or liquid as a thin layer on a tray, facilitated by a foaming agent and foam stabilizer (Azizpour et al. 2016; Dehghannya et al. 2019).

Researchers widely use the FMD to process liquid extracts that encompass anthocyanins and various other secondary metabolites, such as the production of cherry powder (Abbasi and Azizpour 2016), lime juice (Dehghannya et al. 2018), mango juice powder (Lobo et al. 2017), cheese powder (Izadi et al. 2020), chocolate powder (Benković et al. 2019), bacaba fruit juice powder (de Cól et al. 2021), blueberry extract powder (Gao et al. 2022), and black raspberry powder (Ershadfarkar et al. 2023). The preparation of BPF extract powder by the FMD method has also been carried out using monoglyceride and maltodextrin as foaming agents and stabilizers, respectively (Maneeratanachot et al. 2024). However, this study did not examine the effect of the FMD method on the physicochemical properties of the BPF extract powder obtained.

Maltodextrin (MD) is widely used in the food industry as a foam stabilizer due to its low viscosity, water solubility, cost-effectiveness, and neutral flavour and color (Ruengdech and Siripatrawan 2022; Islam et al. 2024; Maneeratanachot et al. 2024). MD is frequently used in FMD with alternative foam-forming agents, such as gum arabic [23] and either egg or potato protein (Thuy et al. 2021). The effects of egg white powder (EWP) and methylcellulose as foaming agents on the volume and density of foam in FMD of sour cherries have been investigated (Abbasi and Azizpour 2016). Methylcellulose and EWP were utilized as foaming agents, along with maltodextrin as a stabilizer, which was added to the sour cherry concentrate. The sour cherry powder obtained at a drying temperature of 65 °C exhibited the highest solubility (Dehghannya et al. 2018; Gao et al. 2022). However, the application of EWP as a foaming agent and a mixture of maltodextrin (MD) and carboxymethylcellulose (CMC) as a foam stabilizer has not been applied in FMD to produce BPF dry extract. To obtain the right formula for the foaming and stabilizing agents, optimization in the FMD process must be carried out.

Despite extensive use of FMD for anthocyanin-rich extracts, systematic formulation-level optimization that integrates drying efficiency, physicochemical quality, microstructure, and storage stability remains limited. Moreover, most studies rely on single-response optimization, which does not reflect practical trade-offs in quality. Therefore, this paper will comprehensively examine the effects of various ratios of foaming and stabilizing agents (EWP, MD, and MC) on the physicochemical properties of the BPF extract powder. The evaluated physicochemical characteristics are total anthocyanin content, flavonoid content, antioxidant properties, total phenolic content, water solubility, and surface morphology. The comprehensive evaluation will be performed using principal component analysis (PCA), as balancing multiple physicochemical indicators to achieve the desired quality of the final product is challenging. The PCA method can combine several indicators with specific correlations and create a new set of all-encompassing indicators to reach a comprehensive conclusion.

Methods

Dried butterfly pea flowers (*Clitoria ternatea* L.) were obtained from the local market (Surakarta, Indonesia). Food-grade egg white powder, maltodextrin, and carboxymethylcellulose were purchased from a local store (Jakarta, Indonesia). Merck supplied 2,2-diphenyl-1-picrylhydrazyl (DPPH), gallic acid, and quercetin.

This study focuses on the FMD method to produce high-quality BPF extract powder. The research process was carried out in stages: first, the BPF extraction, followed by the FMD. The FMD involves adjusting the composition of foaming and stabilizing agents, as well as the drying temperature. The final product's characterization includes water content and solubility testing, total phenolic content (TPC), total anthocyanin content (TAC), flavonoid content, antioxidant activity, color intensity, and browning index (BI). The TAC was also determined during the storage process for stability evaluation. The surface morphology of the powder was analyzed using a scanning electron microscope (SEM) JSM-IT700HR.

Extraction of BPF (Gamage et al. 2021; Jeyaraj et al. 2021; Netravati et al. 2022)

1 liter of distilled water was mixed with 100 grams of cleaned, dried, and ground BPF crown. The extraction procedure was carried out for 30 minutes at 50 °C in an ultrasonic bath. To further remove the liquid extract from the remaining solid, the extract was vacuum-filtered. TAC, TPC, flavonoid concentration, and antioxidant activity were subsequently measured to characterize the liquid extract.

Foam mat drying (FMD) of the liquid extract (Maneeratanachot et al. 2024)

Fifty milliliters of the liquid extract were encapsulated using EWP as a foaming agent and CMC and MD as foam stabilizers. The formulation is shown in Table 1. The foaming agent and foaming stabilizer were dissolved in 25 mL of distilled water. The BPF liquid extract was added to the foaming agent solution and then shaken for 10 minutes to form the foam. The foam was then poured into a petri dish and dried in a dehydrator. The drying temperature was varied between 60, 70, and 80 °C, which represent commonly used low, medium, and high convective drying regimes in FMD studies, balancing drying efficiency and thermal degradation risk. The water content, solubility, color, BI, TAC, TPC, flavonoid content, and antioxidant activity were determined for each variation.

Table 1. Foaming agent formulation.

Sample	EWP (g/100g)	MD (g/100g)	CMC (g/100g)	EWP: MD:CMC
S1	0	0	0	0 : 0 : 0
S2	4	0	0.5	8 : 0 : 1
S3	8	0	0.5	16 : 0 : 1
S4	0	5	0.5	0 : 10 : 1
S5	0	10	0.5	0 : 20 : 1
S6	0.8	1	0	0.8 : 1 : 0
S7	8	10	0.5	16 : 20 : 1
S8	8	10	1	8 : 10 : 1

S1 was used as a baseline control to demonstrate the necessity of foaming and stabilizing agents in the FMD process.

Water content

Water content was measured according to Moshfegh et al. with a modification (Moshfegh et al. 2025). Two grams of sample were weighed into a pre-dried, pre-weighed petri dish and placed in an oven at 70 °C for 24 hours until a stable mass was reached. Water content was calculated by measuring weight loss before and after drying.

Solubility test

Solubility was determined by mixing 1 g of sample powder with 100 mL of distilled water and stirring at a regulated speed for five minutes. After that, the mixture was centrifuged for ten minutes. To observe the retained solid particles, a 25 mL aliquot of the supernatant was taken, placed in a container, and dried immediately in an oven at 105 °C for 5 hours. Solubility was calculated using Eq. (1).

$$S = \frac{(W_2 - W_1)}{v} \quad (1)$$

W_1 = initial powder mass (g)
W_2 = sample mass after 5 hours of drying (g)
v = supernatant aliquot volume (L)

Determination of TAC using the ph difference method (Santos and Martins 2023)

Two solutions of the sample were prepared. The first solution was prepared using a KCl buffer at pH 1, and the second using a KCl buffer and sodium acetate at pH 4.5. The first solution was left for 15 minutes before being measured, while the second solution was measured after a 5-minute mixing period. The absorbance of each solution was measured using the FLUOstar Omega spectrophotometer at 510 and 700 nm. pH 1 and pH 4.5 buffers were used as blanks. The absorbance of the dissolved sample (A) was calculated using Eq. (2), while the TAC was measured using Eq. (3).

$$A = (A_{510nm} - A_{700nm})\,pH1 - (A_{510nm} - A_{700nm})\,pH4.5 \quad (2)$$

$$TAC\left(\frac{mg}{L}\right) = \frac{AXMWXDF \times 1000}{\varepsilon l} \times 100\% \quad (3)$$

MW is 449.2 g.mol^{-1} for cyanidin-3-glucoside, DF: dilution factor, ε: molar extinction coefficient of cyanidin-3-glucoside (26.900 L.mol^{-1}.cm), l: length of the cuvette (0.294 cm).

Browning index (BI)

The BI test was frequently used to assess color degradation. A smaller BI value indicates increased browning and vice versa (Abbasi and Azizpour 2016). The BI value was determined from the absorbance values of the samples taken individually at 510 nm (Abs 510) for anthocyanins and 420 nm (Abs 420) for browning products using a spectrophotometer (FLUOstar Omega). To prevent alterations in BI due to variations in anthocyanin coloration within the sample, the sample needs to maintain an acidic. The BI was calculated using Eq. (4).

$$BI = \frac{Abs\ \ 510}{Abs\ \ 420} \quad (4)$$

Color test

The color test of BPF extract powder was performed using an Android-based colorimeter to obtain the L*, a*, and b*

values. The total color difference (ΔE) was measured using Eq. (5) according to Gao et al. (Gao et al. 2022).

$$\Delta E = \sqrt{\left(\Delta L^{*2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}\right.} \quad (5)$$

While ΔL*, Δa*, and Δb* were measured using the following equation.

$$\Delta L^{*} = L^{*}\text{sample} - L^{*}\text{standard} \quad (6)$$

$$\Delta a^{*} = a^{*}\text{sample} - a^{*}\text{standard} \quad (7)$$

$$\Delta b^{*} = b^{*}\text{sample} - b^{*}\text{standard} \quad (8)$$

$$C^{*} = \sqrt{(a^{*})^{2} + (b^{*})^{2}} \quad (9)$$

$$H \quad \text{angle} = \arctan\left(b^{*}/a^{*}\right) \quad (10)$$

Standard value of L* = 66.60; a* = -0.48; and b* = 1.45; C* = 1.53; and H angle = 288.32° (Maneeratanachot et al. 2024).

Total phenolic content

The Folin reagent was used to determine total phenolic content (TPC) (Escher et al. 2020; Santos and Martins 2023). After dilution to 10 mL, a solution containing 1 mL of BPF extract, 2.5 mL of 10% (v/v) Folin-Ciocalteu, and 2.0 mL of 7% (v/v) sodium carbonate was incubated for 15 minutes at 50 °C. A spectrophotometer (FLUOstar Omega) was used to measure the absorbance of the mixture at 765 nm. TPC, which is measured in milligrams of gallic acid equivalents (GAE) per 100 grams of material, was calculated using gallic acid.

Flavonoid content (Coelho et al. 2021)

A milliliter of BPF extract was reacted with 1.5 mL of absolute ethanol, 100 µL of 10% (v/v) aluminium chloride, 100 µL of 1 M sodium acetate, and 2.8 mL of distilled water. Following a 40-minute incubation at 35 °C, the mixture was analysed using a spectrophotometer (FLUOstar Omega) at 435 nm. Flavonoid content was expressed as mg of quercetin (QE)/100 g of sample since Quercetin was used as a standard.

Antioxidant activity

The antioxidant activity of the BPF extract was assessed using the DPPH assay and results were expressed as IC_{50}. Before calculating the IC_{50}, the percentage of inhibition was determined using Eq. 11.

$$\%inhibition = \frac{(Abs\ control - Abs\ sample)}{Abs\ control} \times 100\% \quad (11)$$

The IC_{50} was determined from the % inhibition vs concentration graph as the concentration at 50% inhibition.

Evaluation of physicochemical properties using principal component analysis (PCA)

PCA is a statistical analysis method that is widely used to reduce many variables into a few representative dummy variables, called principal components (PCs). The 8 samples (S1–S8) with 8 variables (solubility (S), BI, TPC, TAC, Flavonoid content (Fla), IC_{50}, color, and hypotenuse angle (H)) in this study were analysed through the PCA. The PCA eigenvectors were used to derive the scoring equation for the principal component (PC), and a comprehensive evaluation model for the physicochemical indicators was subsequently established. Data plotting and PCA were carried out using R (http://www.r-project.org).

Results and discussion

Foam mat drying

BPF liquid extract was prepared by ultrasound-assisted maceration with water as a solvent. The obtained extract was then analyzed to determine its physicochemical properties. Firstly, the TAC of the extract was 1630.129 ppm. Meanwhile, the antioxidant activity, expressed as IC50, was 6.278 ppm. The value means that the extract has a very strong antioxidant activity. Phenolic and flavonoid molecules are typically the source of antioxidant action in secondary metabolites. The total phenolic and flavonoid contents of BPF extract are 77.1 mg/100 g and 13.094 mg/100 g, respectively. Anthocyanins' strong antioxidant activity is a result of their glycosylated β-ring structure (Jeyaraj et al. 2021). The presence of orthohydroxylation and methoxylation also significantly increases their antioxidant activity.

The liquid extract was then converted into powder via FMD, using EWP as the foaming agent and a MD/CMC mixture as the stabilizer. All FMD products (S1–S8) were analyzed to determine their physicochemical properties. The water content and solubility of the extract powder are presented in Fig. 1. The water content of the extract powder varied from 99.304 to 3.845%. Sample S1, without the addition of EWP, MD, and CMC, showed incomplete drying, evidenced by a thin and sticky layer on the drying plate and a water content of 99.30–95.35%.

From S2 and S3, where MD is absent, the water content decreases significantly with increasing EWP concentration. A comparison of S5 and S7 indicates that adding EWP can reduce the drying time from 8 to 7 hours. The water content of S7 is significantly lower than S5, with a shorter drying time. Likewise, for S7 and S3, drying time is shortened from 8 to 7 hours by increasing MD concentration from 0 to 20 g/100 g. This is followed by a notable decrease in water content from 17.251–16.350% to 12.607–9.392%. In S7 and S8, the shortest drying time was seven hours. Compared with S2 and S3, which contain only EWP and CMC, S7 and S8, which include EWP, MD, and CMC, showed an enhanced drying rate. The synergistic

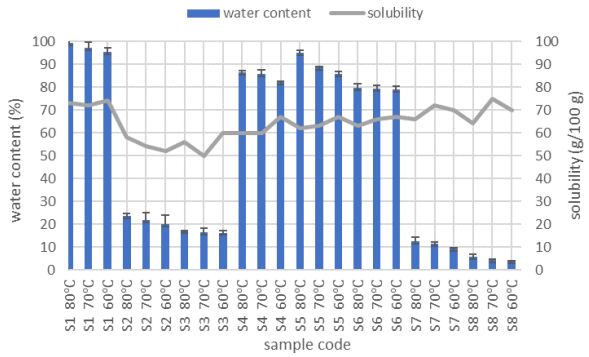

Figure 1. Effect of foaming agent formulation on powder solubility and water content.

effect of EWP and MD can explain how different foaming agent formulations affect the drying process of BPF extract. Consequently, formulas S7 and S8 are probably appropriate for using the FMD process to produce BPF extract powder. Rapid water migration from the inner to the outer surface is enabled by the high surface area and the pores created by foaming. The FMD product for all formulas is shown in Fig. 2.

The findings of this investigation are comparable to those of microwave freeze-drying of foamed raspberry pulp (Ozcelik et al. 2020) and FMD of yellow and white cassava varieties (Ayetigbo et al. 2021). By creating tiny bubbles in the foamy mass, EWP increases the surface area available for water evaporation, hastening the diffusion and evacuation of water. (de Cól et al. 2021). The water content of S8 (3.845–5.895%) is relatively similar to that reported in other FMD studies, such as banana (4.87–7.25%) (Watharkar et al. 2021) and melon (3.29–4.64%) (Suet Li et al. 2021).

The solubility test indicated that the foaming agent increased the solubility of the extract powder. The addition of MD, examined in S4 and S5 with S3 and S7, resulted in significant improvements in powder solubility of 3% and 22%, respectively. MD may inhibit the agglomeration of powder particles when dissolved in liquid (Dehghannya et al. 2019; Gao et al. 2022), thus increasing powder homogeneity. Similarly, from S6 to S8, the solubility of BPF extract powder increased significantly from 66 to 75 per 100 g sample. This may be due to the presence of CMC, which can enhance foam stability and reduce bubble loss (Ruengdech and Siripatrawan 2022). More bubbles mean more pores, and the powder dissolves more easily. In short, the use of a foaming agent resulted in a significant increase in the powder solubility, with S7 and S8 formulas reaching a powder solubility that is higher than the solubility of commercial BPF extract powder (61.6 ± 1.70–72.0 ± 1.70 g/100 g) (Maneeratanachot et al. 2024).

Using a colormeter, the powder's color was measured and converted into L*, a*, and b* values according to the CIELab system (Table 2). Parameters such as lightness (l*), redness (a*), and blueness (b*) are analyzed using the CIE-Lab color space. Luminosity is represented by the L* value (0 = black (dark), 100 = white (bright)), color variation from greenish (-) to reddish (+) is shown by a*, and color variation from bluish (-) to yellowish (+) is indicated by b*. The product's color intensity is indicated by the C* value,

Table 2. Color test results based on the CIELab system.

Sample	L* (lightness)	a* (redness)	b* (blueness)	C*	H angle (°)
Ref (Maneeratanachot et al. 2024)	**66.60**	**-0.48**	**1.45**	**1.53**	**288.32**
S1 80 °C	6.703	-1.227	2.465	3.192	296.517
S1 70 °C	7.879	-1.351	4.508	4.706	286.689
S1 60 °C	4.641	-1.425	2.856	3.192	296.453
S2 80 °C	20.034	0.452	-1.140	2.359	291.655
S2 70 °C	13.122	1.975	-3.946	4.413	296.584
S2 60 °C	6.837	3.162	-4.172	5.235	307.164
S3 80 °C	35.737	0.919	-2.144	2.333	293.206
S3 70 °C	25.526	1.551	-4.665	4.916	288.394
S3 60 °C	21.172	3.239	-4.219	5.319	307.520
S4 80 °C	1.451	0.508	-1.359	1.4515	290.485
S4 70 °C	1.140	0.262	-0.678	4.916	291.097
S4 60 °C	4.641	-3.545	1.418	1.8077	338.198
S5 80 °C	64.840	0.060	6.547	2.570	338.198
S5 70 °C	1.864	3.463	5.542	6.607	275.474
S5 60 °C	1.103	0.262	0.032	0.542	340.719
S6 80 °C	7.598	-1.713	0.028	1.319	352.655
S6 70 °C	19.696	-0.115	0.749	4.534	291.463
S6 60 °C	22.828	-0.846	0.002	0.921	289.050
S7 80 °C	12.454	0.322	-3.451	3.149	275.278
S7 70 °C	32.563	4.942	-6.013	7.783	309.415
S7 60 °C	39.124	3.497	-4.924	6.039	305.381
S8 80 °C	33.836	4.490	-1.439	4.715	275.278
S8 70 °C	31.325	13.337	-3.652	6.498	299.337

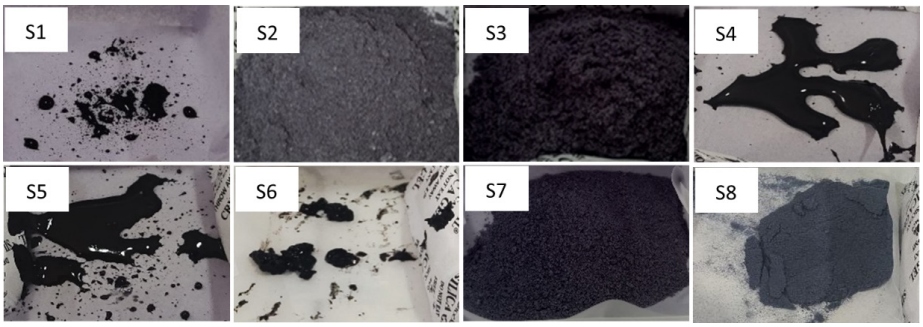

Figure 2. Photograph of BPF extract prepared by FMD with various foaming agent formulations (S1–S8) at 70 °C of drying temperature.

and the angle between the hypotenuse and 0° on the a* and b* axes is described by H°. Red is indicated by the H^2 value of 0° or 360°, whilst yellow, green, and blue are shown by 90°, 180°, and 270°, respectively. Overall, the samples' L*, a*, b*, and C* values increased with increasing amounts of EWP, MD, and CMC, as well as with increasing drying temperature. Increasing the content of the encapsulating agent results in a color of the extract powder in the H° range (275.472847–307.87829), indicating a bright blue color.

The effect of the foaming agent and drying temperature on TAC and BI are presented in Fig. 3. The TAC content in S1, without the foaming agent and stabilizer, ranged from 1116.167 to 1214.302 ppm across all drying temperatures. It shows that S1 has the lowest TAC compared to the other samples because the anthocyanin in S1 is not protected by the encapsulated polymers. The drying period for S1 was achieved within 8 hours. However, the product remained underdried, as evidenced by a thin, sticky layer on the drying plate (Fig. 2). Increasing the EWP and MD ratio, such as on S2–S3 and S7–S8, increases TAC because powder formation decreases water content, thereby increasing TAC. Additionally, the dried extract powder's blue color intensity was also improved as increasing the EWP and MD ratio. Meanwhile, the minor increase in brightness may result from the partial precipitation of EWP or hydrolyzed starch from MD during drying.

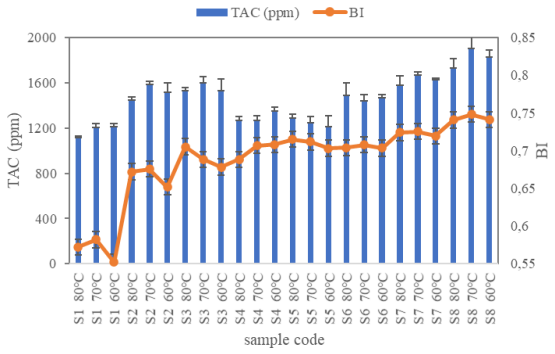

Figure 3. Effect of foaming agent formulation on TAC and BI of powder.

The BI rose as the MD ratio increased in S4 and S5, as well as S3 and S7, suggesting that S5 and S7 had less browning. This could be attributed to the reduced anthocyanin degradation. The increase in BI during drying and storage is closely related to anthocyanin degradation under thermal and oxidative conditions. As anthocyanins break down into phenolic intermediates that participate in non-enzymatic browning reactions, a decrease in total anthocyanin content is often accompanied by an increase in browning index.

In comparison with the reference BPF extract (L* 66.60 and H angle 288.32°), the results generally showed that the combination of EWP and MD as encapsulating agents improved color stability and anthocyanin preservation, producing more vivid colors (Maneeratanachot et al. 2024). Moreover, the red flavylium, an anthocyanin derivative, is responsible for the extract powder's increased color. As the drying temperature increased, a modest increase in the paleness of the BPF powder was observed; this may have been due to anthocyanin thermal degradation (Gao et al. 2022). While the hydroxyl groups in the anthocyanin structure are heat-sensitive, the TAC remains generally constant as the drying temperature rises. Therefore, in addition to increasing the foam's porosity and reducing drying time, the inclusion of EWP, MD, and CMC also serves. Thus, the presence of EWP, MD, and CMC not only increases the foam's porosity and shortens the drying time but also serves as a wall coating material, helping prevent anthocyanins from heat degradation.

Fig. 4 displays the samples' total phenolic content (TPC), flavonoid content, and antioxidant activity. The findings showed that TPC and flavonoids decreased as MD concentration increased. The findings align with a previous study showing that higher MD concentrations led to lower TPC and flavonoid content in blueberry powder dried by microwave-assisted FMD (Gao et al. 2022).

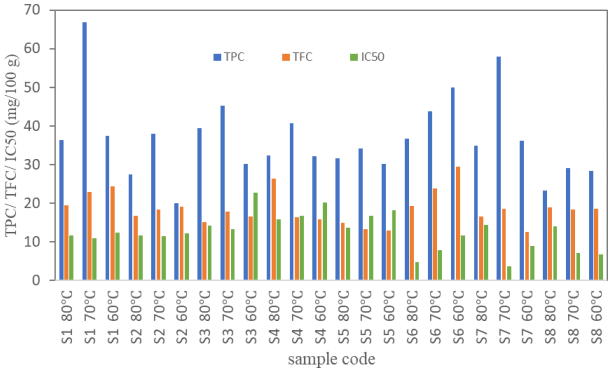

Figure 4. Effect of foaming agent formulation on TPC, flavonoid (Fla) and antioxidant activity (IC_{50}).

The powder surface morphology was evaluated using SEM at 10 kV. Fig. 5 shows that all powder particles added with the foaming agent have slightly rough surfaces. Increasing EWP content in samples S2 and S3 facilitates higher porosity and larger powder size. Adding EWP enhances the foam's air circulation and helps create the voids that remain within the dry particles after drying, as shown in Fig. 5a–d. Fig. 5g–h shows that sample S8 has a denser dry powder structure, as observed when EWP and MD contents are decreased by half compared to sample S7. Sample S8 has a denser dry-powder structure due to the simultaneous decrease in EWP and MD, which also makes the bulk solution more viscous and encourages the formation of thick foam lamellae. Fig. 5a–h also shows that increasing the drying temperature leads to rapid foam collapse and a decrease in dry density.

Anthocyanin stability

The stability test of anthocyanins in BPF extract powder was performed by storing the powder at room temperature in the dark. The percentage reduction in anthocyanin content during storage is shown in Fig. 6. S2 and S3

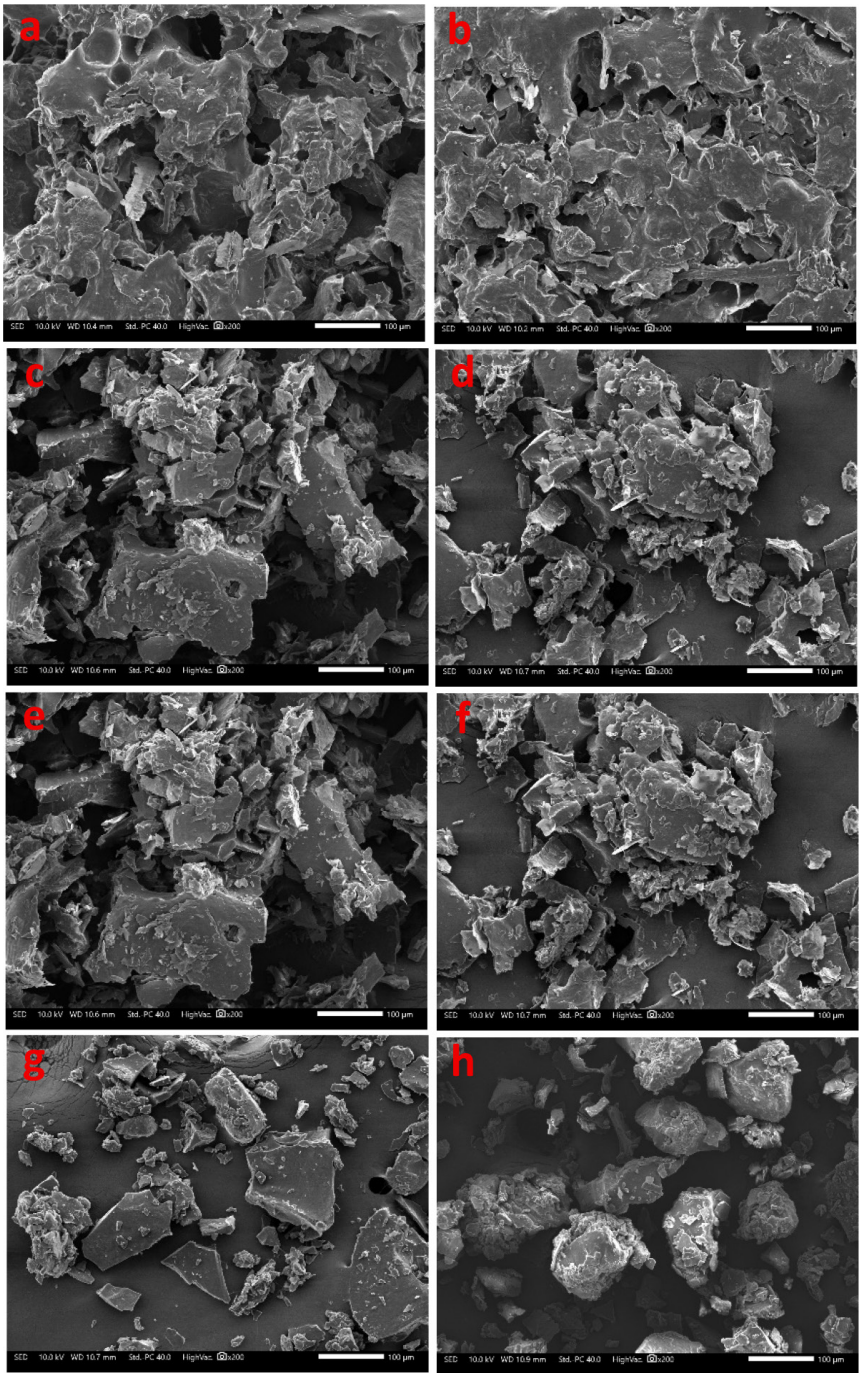

Figure 5. SEM images of S2 powder 60 °C (**a**) and 70 °C (**b**); S3 powder 60 °C (**c**) and 70 °C (**d**); S7 powder 60 °C (**e**) and 70 °C (**f**); S8 powder 60 °C (**g**) and 70 °C (**h**). Scale bar 100 µm.

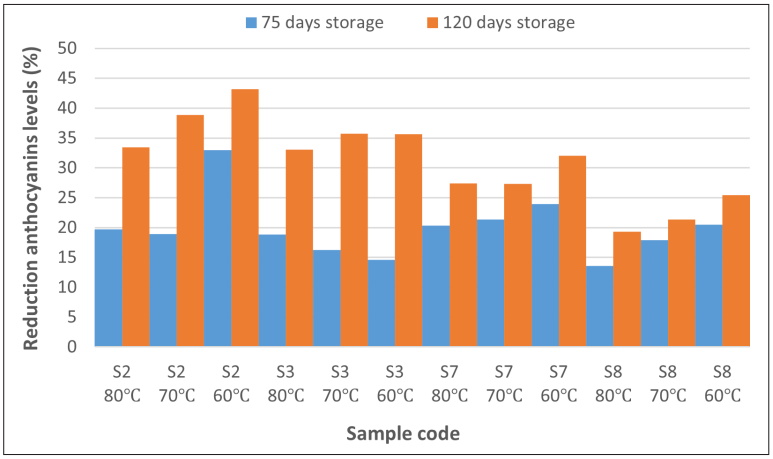

Figure 6. Reduction of anthocyanins under room temperature storage conditions without light.

have a higher percentage of anthocyanin reduction than S7 and S8. This finding indicates that adding MD and CMC as foam stabilizers helps maintain a more stable anthocyanin content in the extract powder. A more stable anthocyanin content was maintained under all storage conditions (room temperature with and without light, and refrigerated without light), thanks to the encapsulation of anthocyanins with MD and the addition of tannic acid for color (Moshfegh et al. 2025).

Recent FMD studies on anthocyanin-rich fruit and plant extracts have reported that formulation composition plays a key role in determining drying behavior, bioactive retention, and powder characteristics. Most previous studies, however, have primarily emphasized individual aspects such as encapsulation efficiency, drying kinetics, or storage stability using specific foaming systems (Table 3). In the present study, a formulation-driven experimental approach was employed to simultaneously evaluate drying efficiency, physicochemical quality, and anthocyanin stability of BPF extract powder under different EWP–MD–CMC ratios and drying temperatures. This integrated evaluation provides a more comprehensive perspective on process–quality relationships relevant to agro-based powder production. The findings, therefore, complement the existing literature on BPF and offer practical insights for improving the quality and stability of plant-based powders.

PCA based on physicochemical properties.

Firstly, the dimensionality of the physicochemical properties of TAC, color (C), H angle, solubility (S), BI, TPC, Flavonoids (Fla), and IC50 was reduced using PCA. The top two main components are usually visible in PCA findings. Usually, more than 70% of the variables are explained by these two main components (Niu et al. 2024). In this study, the top two principal components (PC1 and PC2) accounted for 38.38% and 35.44%, respectively, for a cumulative contribution of 73.82%. As a result, PC1 and PC2 can be successfully identified as the PC factors for thoroughly assessing physicochemical characteristics and computing the PCA model.

The distribution of several formulations (S1–S8) and physicochemical indcators is displayed in Fig. 7a. Based on the score plot of the factors in Fig. 7a, PC1 positively correlates with solubility, BI, TAC, flavonoids, color, and negatively correlates with IC_{50} and TPC. Meanwhile, PC2 is positively correlated with TPC, flavonoids, and solubility and negatively correlated with IC_{50}, color, and BI.

The evaluation of the physicochemical properties was conducted to obtain a suitable formulation that produces a sample with high physicochemical quality. As shown in Fig. 7b, a new set of standardized variables was created from the raw data on the sample's physicochemical characteristics to produce a comprehensive

Table 3. Comparison of foam mat drying (FMD) studies on anthocyanin-rich materials.

Raw Material	Foaming Agents	Method	Result	Reference
Butterfly pea flower extract	EWP, MD, CMC	Hot-air FMD, experimental multi-objective, PCA-based evaluation	Fast drying, high anthocyanin retention, good solubility, strong color	This study
Butterfly pea flower extract	MG, MD	Hot-air FMD, encapsulation-focused	High encapsulation efficiency, stable anthocyanin	(Maneeratanachot Chetpattananondh and Kungsanant 2024)
Black mulberry juice	MD, CMC, GMS	Hot-air FMD, formulation optimization	>90% anthocyanin retention, stable powder	(Khatri et al. 2024)
Jackfruit juice	EWP, MD	Microwave-assisted FMD, kinetic modeling	Reduced drying time, good flowability	(Islam et al. 2024)
Grumixama (*Eugenia brasiliensis* Lamarck)	soy protein isolate, CMC	Drying and stability evaluation	Improved antioxidant and physicochemical stability	(de Andrade et al. 2026)

*MG: monoglycerides, GMS: glycerol monostearates.

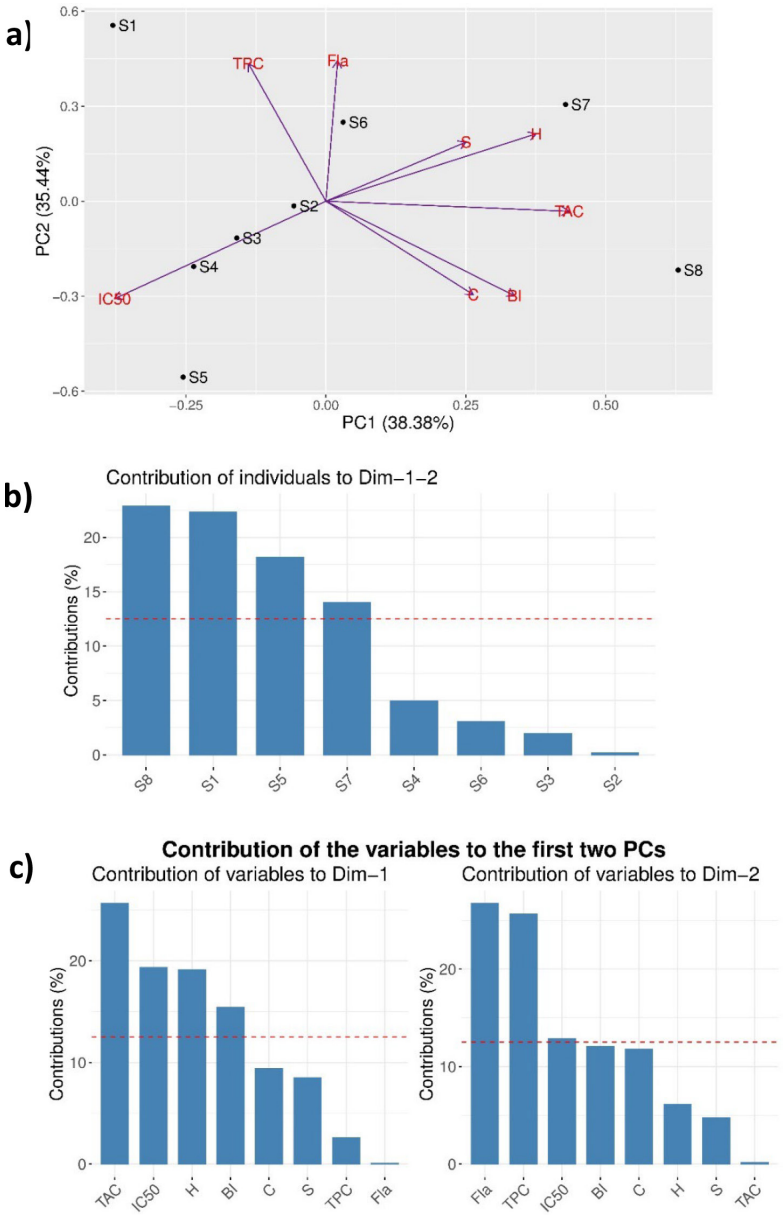

Figure 7. a. PCA loading diagram and factor score plots. The formulations are represented by the black dots on the factor plane, while the physicochemical indications are represented by the violet arrows; **b.** Results of the comprehensive evaluation of physicochemical properties; **c.** Contributions of the variables to the two PCs.

evaluation score and ranking. Out of all the formulations, S8 had the highest assessment score (26), while S2 had the lowest. Individuals, TAC, TPC, and flavonoid make the largest contributions to both dimensions, as indicated by the location of the red dashed line (average contribution) (Fig. 7c). The higher PCA score obtained for S8 compared to S7 and others indicates a more favorable overall balance between drying efficiency, physicochemical quality, and anthocyanin stability, confirming S8 as the more practically suitable formulation for producing high-quality BPF powder.

Overall, the formulation-driven foam mat drying approach presented in this study shows potential for industrial-scale production of BPF extract powder. The method is compatible with conventional drying systems, requires lower capital and energy input, and uses food-grade materials, supporting feasibility in terms of cost, energy efficiency, and food safety. The optimized formulation exhibited a short drying time, good solubility, stable anthocyanin content, and free-flowing powder characteristics, all of which are essential for large-scale handling and application. Although conducted at laboratory scale, the results indicate favorable prospects for scale-up, with future work recommended to include pilot-scale validation.

Conclusion

The formulation of the foaming agent (EWP) and stabilizers (MD and CMC) affects the physicochemical properties of the BPF extract prepared using the FMD method.

Among all the foaming agent formulations (S1–S8), S8 had the fastest drying time (7 hours) and produced a free-flowing BPF extract powder. Moreover, the S8 formula has higher stability, solubility, and TAC and improved color than other formulas. The PCA analysis also supported this result, which showed that S8 has the highest evaluation score for physicochemical properties.

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Additional information

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Regarding the publishing of this work, the authors declare that they have no conflicts of interest. The authors confirmed that the paper is free of plagiarism.

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Data availability
All of the data that support the findings of this study are available in the main text.