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Effect of foam-mat drying conditions on drying rate and anthocyanin content in purple sweet potato powder

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Abstract: The study aimed to optimise foam-mat drying parameters for producing purple-fleshed sweet potato (PFSP) powder. Egg albumin (EA) (5–15%), xanthan gum (XG) (0.1–0.5%), and drying temperature (50–70 °C) were used as independent variables for optimisation via Response Surface Methodology with a Box-Behnken design. The response variables (drying rate and anthocyanin content) were assessed by 18 treatments, which included 6 central points. The analysis of variance showed a high coefficient of determination (> 88%) between predicted and experimental values across all models. Optimal foam-mat drying conditions were 11.02% EA, 0.34% XG, and 65.1 °C to achieve the highest drying rate (2.49 g water.g dry matter^{-1}.min^{-1}) and anthocyanin content (1.01 mg.g^{-1}). After 3.5 h of drying at 65.1 °C, the foam-mat dried PFSP showed a low moisture content (4.35%) and water activity (0.29). Its water solubility index, water absorption index, rehydration ratio, total polyphenols, and antioxidant activity were determined to be 56.49%, 3.55%, 3.82, 3.66 ± 0.06 mg GAE.g^{-1}, and 58.49 ± 0.88%, respectively. Under these conditions, the powder maintained its natural beautiful and characteristic purple colour. The microstructure of the foam-mat dried PFSP powder (via SEM images) was also observed.

Keywords: foam-mat drying; microstructure; nutritional quality; optimisation; purple sweet potato

Sweet potato (*Ipomoea batatas*) (family *Convolvulaceae*) is a significant crop in Asia, the Americas, and Africa. According to FAOSTAT (2023), the world sweet potato production was recorded at 93.5 million tonnes in 2023. Asia and Africa are the largest producers of sweet potatoes, accounting for 62% and 33.3% of the world's total production, respectively. Of which, sweet potato production in Vietnam ranks 15th in the world (914.7 thousand tonnes).

Sweet potatoes are a good source of dietary fibre, low in fat and protein, but rich in carbohydrates, making them a healthy addition to the diet that contributes to improved nutrition. Sweet potatoes contain numerous antioxidant compounds, including phenolic acids, anthocyanins, β-carotene, and tocopherols (Afolabi and Adekunbi 2016). Among them, the purple-fleshed sweet potato (PFSP) variety, characterised by its thick skin and purple flesh, has attracted considerable attention from the food industry and the scientific research community, particularly due to its anthocyanins, secondary metabolites responsible for producing red to blue-purple pigments.

Anthocyanin components in PFSP have been studied for several health benefits, including the

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prevention of obesity, anti-inflammatory properties, diabetes prevention, stress reduction, and cancer prevention. As a result, PFSP has been proposed as a functional food and pharmaceutical ingredient that can preserve physiological functioning and increase human resistance (Ayeleso et al. 2016).

Sweet potatoes are currently consumed fresh or processed in simple manual ways in households in Vietnam, whereas industrial-scale processing operations have yet to develop to meet their potential. Furthermore, the relationship between cultivation and processing is weak, preservation technology is restricted, and there is no coordinated plan for exploiting and creating value-added products from post-harvest agricultural products. These variables have resulted in a significant number of high-quality sweet potatoes remaining in the season without being integrated into the value chain. Furthermore, the short storage time of sweet potatoes (5–20 days) increases the risk of post-harvest losses, necessitating dry processing techniques to extend shelf life and prevent losses.

Drying is a technique used to reduce the damaging effects of microbes and extend the shelf life of products. Foam-mat drying is a simple process that is particularly successful for food items with heat-sensitive components, high viscosity, and high sugar content. This process utilises varying quantities of foaming and foam-stabilising agents, which are then dried at temperatures ranging from 50 °C to 80 °C (Febrianto et al. 2012). The foam-mat drying process quickly and effectively reduces moisture content, conserving energy and increasing production efficiency. At the same time, this procedure produces higher-quality products than traditional drying or spray drying techniques. Thus, using the proper procedure to make PFSP powder not only extends storage time but also allows for variable administration in the diet in combination with other meals. PFSP powder, in particular, can provide nutritional value while also improving health advantages due to its high anthocyanin concentration. To minimise anthocyanin loss in the finished product, production conditions must be optimised.

The effects of foam-mat drying conditions on antioxidant activity, phenolic synthesis, anthocyanin concentration, and colour of PFSP powder were investigated by Jakkranuhwat and Kunchansombat (2021). However, research on optimising foam drying conditions, such as the concentration of foaming agent and foam stabiliser, as well as the ideal drying temperature, to obtain the highest drying rate and maximum protected anthocyanin content in the produced PFSP powder, is still limited. The goal of this study was to optimise the concentration of foaming agent, foam stabiliser, and drying temperature in order to produce PFSP powder with a high bioactive compound content at a high drying rate and a short drying time. The quality of PFSP powder was next assessed in terms of physical and chemical properties, antioxidant activity, and microstructure in order to provide a scientific foundation for the future use of this raw material in the production of nutritional food items.

MATERIAL AND METHODS

Materials. PFSPs were harvested from a growing area in Binh Tan district, Vinh Long province of Vietnam. After harvesting, they were cleaned and peeled. The moisture content and anthocyanin content of fresh PFSPs were analysed immediately, with corresponding values of 73.32% and 0.53 mg.g^{-1} (on a dry basis – DW).

Experimental design for foaming and drying. The Box-Behnken design (BBD) with Response Surface Methodology (RSM) was employed for optimisation in this work. The amounts of input factors included egg albumin (EA) concentration, xanthan gum (XG) concentration, and drying temperature, which ranged from 5% to 15%, 0.1% to 0.5%, and 50 °C to 70 °C. The low and high levels of each factor were coded as –1 and +1, respectively, with 0 °C as the central value (Table 1). Drying rate and anthocyanin content were selected as dependent variables in the study. RSM was utilised in 18 trials to assess the interaction of EA, XG, and drying temperatures, with 6 runs occurring at the centre point.

Sample preparation and foam-mat drying. PFSP (200 g) was mixed with water at a ratio of 1 : 2 (w : v) and ground for 2 min using a blender. The

Table 1. Independent variables with range and factor level

Variables	Coded	Range and levels		
		–1	0	1
Egg albumin (% w : w)	X_1	5	10	15
Xanthan gum (% w : w)	X_2	0.1	0.3	0.5
Drying temperature (°C)	X_3	50	60	70

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suspension was transferred to a 1 000 mL glass beaker, and then EA and XG were added according to the prescribed ratio. The whipping process was performed using an egg beater (Philips HR3705, 300W, P.R. China) at the highest speed for 5.8 min (Thuy et al. 2022). The foam layer was then spread evenly on a stainless steel tray (100 g of sample per tray) with a foam layer thickness of about 4 mm. The sample trays were then placed in a convection hot air drying oven (Memmert UN30, Germany) and dried at 50–70 °C until the final moisture content reached approximately 4–5% (< 10%) (Jakkranuhwat and Kunchansombat 2021). The dried samples were further ground and sieved through a 100-mesh sieve to obtain fine sweet potato powder for further analysis.

Physical properties analysis. The moisture content (%) was analysed according to the method of AOAC (2005). The drying rate was calculated using the formula presented in the study by Thuy et al. (2021). The water activity was measured using an AQUALAB 4 TE (USA). The water rehydration ratio (RR) was recorded according to the method of Kadam et al. (2010). The water solubility index (WSI) and water absorption index (WAI) were calculated according to the method of Grabowski et al. (2006). The microstructure of the dried foam samples was observed using a Scanning Electron Microscope (SEM) (Hitachi S-4800, Japan) with a magnification of × 2 000.

Chemical properties analysis. The Folin determined total polyphenol content (TPC)–Ciocalteau method (Teixeira et al. 2013). Anthocyanin content ($mg.g^{-1}$) was determined by the differential method based on the principle that anthocyanin pigments change with pH (Giusti and Wrolstad 2001). DPPH free radical scavenging activity (%) of the products was analysed based on the ability to scavenge 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radicals (Brand-Williams et al. 1995).

Statistical analysis. The experiments were repeated three times, and the findings are reported as mean value ± standard deviation (STD). The regression equations were obtained by fitting a quadratic polynomial model to the experimental mean values using Stratigraphic XV.I software. Analysis of variance was used to determine the statistical significance of the model terms at a 0.05 probability level. The coefficients of determination (R^2) values were used to assess the model's ability to accurately explain the response variables.

RESULTS AND DISCUSSION

Effect of foaming and drying conditions on drying rate and anthocyanin content

The findings revealed that all of the factors studied had an effect on the drying rate and anthocyanin content (Table 2). The highest drying rate attained was 2.60 g water.g dry $matter^{-1}.min^{-1}$ at a drying temperature of 70 °C with EA and XG at 15% and 0.3%, respectively; the lowest value (1.30 g water.g dry $matter^{-1}.min^{-1}$) was recorded when 10% EA and 0.1% XG were employed at a drying temperature of 50 °C. The drying rate increases as the drying temperature rises, resulting in a shorter drying time. This phenomenon occurs as a result of increased moisture diffusion and evaporation rates at the product surface due to high temperatures. Drying rate is a function of temperature and time, higher temperature corresponds to higher drying rate and faster drying time while the effect of air velocity is almost negligible or has little impact (Caparanga et al. 2017).

In addition, drying temperature had a substantial effect on anthocyanin degradation. The lowest (0.64 $mg.g^{-1}$) and highest (1.05 $mg.g^{-1}$) anthocyanin contents were recorded when EA, XG, drying temperature were 5%, 0.3%, 50 °C and 10% and 0.3%, 60 °C, respectively. Pashazadeh et al. (2024) investigated the effects of drying temperature and air velocity on anthocyanin content in black rosehip fruit and found that drying at 70 °C was the best setting.

Heydari et al. (2014) reported the same effects of high temperatures on anthocyanin degradation in saffron petals. Tan et al. (2022) found similar results regarding the decrease in anthocyanin concentration in blood-flesh peach. Abbasi and Azizpour (2016) produced dehydrated sour cherry juices by foam-mat drying at 50, 65, and 80 °C, and observed the highest concentration of anthocyanins in the dry powder at intermediate temperature (65 °C). The optimum temperature was 70 °C to preserve the anthocyanin content during the drying of Brazilian jambolan fruit (de Carvalho et al. 2017).

Analysis of variance (ANOVA) revealed that six parameters significantly influenced the drying rate and anthocyanin content ($P < 0.05$, 95% confidence level) (Table 3). For the drying rate, the linear (X_1, X_2, X_3) and quadratic (X_1X_1, X_2X_2, X_3X_3) coefficients had significant effects ($P > 0.05$), while the interac-

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Table 2. Effect of EA concentration (%), XG (%), and drying temperature (°C) on drying rate and anthocyanin content

No.	Coded values			Drying rate (water.g dry matter^{-1}.min^{-1})	Anthocyanin (mg.g^{-1})
	X_1 (EA, %)	X_2 (XG, %)	X_3 (drying temp., °C)		
1	(0) 10	(0) 0.3	(0) 60	2.24 ± 0.04	1.03 ± 0.04
2	(+1) 15	(+1) 0.5	(0) 60	2.29 ± 0.07	0.88 ± 0.03
3	(0) 10	(0) 0.3	(0) 60	2.22 ± 0.04	1.03 ± 0.04
4	(–1) 5	(–1) 0.1	(0) 60	1.93 ± 0.23	0.79 ± 0.04
5	(0) 10	(–1) 0.1	(–1) 50	1.30 ± 0.01	0.69 ± 0.08
6	(0) 10	(0) 0.3	(0) 60	2.19 ± 0.05	1.00 ± 0.05
7	(+1) 15	(–1) 0.1	(0) 60	2.14 ± 0.12	0.79 ± 0.06
8	(0) 10	(0) 0.3	(0) 60	2.20 ± 0.02	1.04 ± 0.09
9	(0) 10	(0) 0.3	(0) 60	2.21 ± 0.06	1.05 ± 0.07
10	(0) 10	(+1) 0.5	(–1) 50	1.36 ± 0.09	0.75 ± 0.05
11	(–1) 5	(0) 0.3	(–1) 50	1.31 ± 0.08	0.64 ± 0.05
12	(0) 10	(0) 0.3	(0) 60	2.21 ± 0.03	1.02 ± 0.07
13	(0) 10	(+1) 0.5	(+1) 70	2.59 ± 0.08	0.83 ± 0.06
14	(–1) 5	(0) 0.3	(+1) 70	2.53 ± 0.10	0.74 ± 0.05
15	(+1) 15	(0) 0.3	(–1) 50	1.40 ± 0.09	0.72 ± 0.02
16	(–1) 5	(+1) 0.5	(0) 60	2.01 ± 0.11	0.82 ± 0.06
17	(0) 10	(–1) 0.1	(+1) 70	2.52 ± 0.05	0.79 ± 0.04
18	(+1) 15	(0) 0.3	(+1) 70	2.60 ± 0.09	0.83 ± 0.01

Mean ± STD; EA – egg albumin; XG – xanthan gum; temp. – temperature

Table 3. ANOVA results for drying rate and anthocyanin content

Source	*df*	Drying rate			Anthocyanin		
		sum of squares	*F*-ratio	*P*-value	sum of squares	*F*-ratio	*P*-value
X_1: EA	1	0.1549	23.29	0.0000*	0.0212	7.31	0.0099*
X_2: XG	1	0.0482	7.25	0.0102*	0.0170	5.85	0.0201*
X_3: Drying temperature	1	8.9036	1 338.69	0.0000*	0.0578	19.91	0.0001*
X_1X_1	1	0.0345	5.19	0.0280*	0.1889	65.09	0.0000*
X_1X_2	1	0.0040	0.60	0.4447	0.0031	1.06	0.3100
X_1X_3	1	0.0007	0.11	0.7410	0.0001	0.02	0.8869
X_2X_2	1	0.0612	9.20	0.0042*	0.1046	36.05	0.0000*
X_2X_3	1	0.0002	0.04	0.8494	0.0006	0.22	0.6439
X_3X_3	1	0.5273	79.28	0.0000*	0.4006	138.07	0.0000*
Lack-of-fit	3	0.0410	2.06	0.1210^{ns}	0.0059	0.67	0.5725^{ns}
Pure error	41	0.2727	–	–	0.1190	–	–
Total (corr.)	53		10.1333			1.0578	
R^2			96.90%			88.20%	
R^2 (adjusted for *df*)			96.27%			85.79%	
Standard error of estimate			0.08			0.05	

*Significant at the 5% level, ^{ns}Lack-of-fit is not significant at $P > 0.05$; EA – egg albumin; XG – xanthan gum

tions X_1X_2, X_1X_3, and X_2X_3 showed no significant differences ($P > 0.05$). These results highlight the important role of the main variables and some interactions on the drying rate under the established

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experimental conditions. Likewise, anthocyanin content was significantly affected by the independent variables (X_1, X_2, X_3) and the quadratic coefficients (X_1X_1, X_2X_2, X_3X_3) ($P < 0.05$), whereas the interaction coefficients did not show statistical significance ($P > 0.05$).

The two regression models had *R*-squared values of 96.90% and 88.20%, respectively, which explained a significant portion of the variation in drying rate and anthocyanin content. When comparing models with varying numbers of independent variables, the modified *R*-squared value was deemed more reliable, reaching 96.27% for drying rate and 85.79% for anthocyanin content. The standard errors for the estimates were 0.08 (drying rate model) and 0.05 (anthocyanin content model). The lack-of-fit test in the ANOVA table for drying rate (0.1210) and anthocyanin content (0.5725) yielded *P*-values greater than 0.05, indicating that the models fit the experimental data with 95% confidence.

The model terms that had no significant effect (*P*-value > 0.05) on the drying rate (X_1X_2, X_1X_3, X_2X_3) or anthocyanin content (X_1X_2, X_1X_3, X_2X_3) were eliminated from the model. New models (Y_1 and Y_2) for predicting the drying rate [Equation (1)] and anthocyanin content [Equation (2)] based on the independent variables were developed.

$$Y_1 = -9.256 + 0.057X_1 + 1.250X_2 + 0.302X_3 - 0.002X_1^2 - 1.709X_2^2 - 0.002X_3^2 \quad (1)$$

$$Y_2 = -6.343 + 0.102X_1 + 1.474X_2 + 0.215X_3 - 0.005X_1^2 - 2.235X_2^2 - 0.002X_3^2 \quad (2)$$

where: Y_1 – the drying rate (water.g dry matter^{-1}.min^{-1}); Y_2 – the anthocyanin content (mg.g^{-1}); X_1 – the EA concentration (%); X_2 – the XG concentration (%); X_3 – the drying temperature (°C).

Response surface plots and simultaneous optimisation

Drying rate. Response optimisation was conducted using the experimental data set and Statgraphics software (version XV.I). The results indicated that the drying rate reached the highest value of 2.66 g water.g dry matter^{-1}.min^{-1}. The lowest concentrations were 13.94% EA and 0.39% XG, with an optimal drying temperature of 70 °C.

The response surface and contour plots in Figure 1 show that the concentrations of the foaming agent (EA), the foam stabilising agent (XG), and the drying temperatures all influence the drying rate. When the concentrations of EA and XG were set at 10% (Figure 1A) and 0.3% (Figure 1B), respectively, the drying rate increased (1.23–2.67 g water.g dry matter^{-1}.min^{-1}) as the temperature rose from 50 °C to 70 °C. At a drying temperature of 60 °C (Figure 1C), the drying rate also increased when the concentrations of EA and XG were elevated from 5% to 13.91% and 0% to 0.37%, respectively. However, as their concentrations increased, the drying rate did not show any further change. At this temperature, the highest drying rate was 2.25 g water.g dry matter^{-1}.min^{-1} with EA and XG concentrations of 13.91% and 0.37%, respectively.

The use of a high concentration of foaming agent (EA) facilitates air penetration into the foam struc-

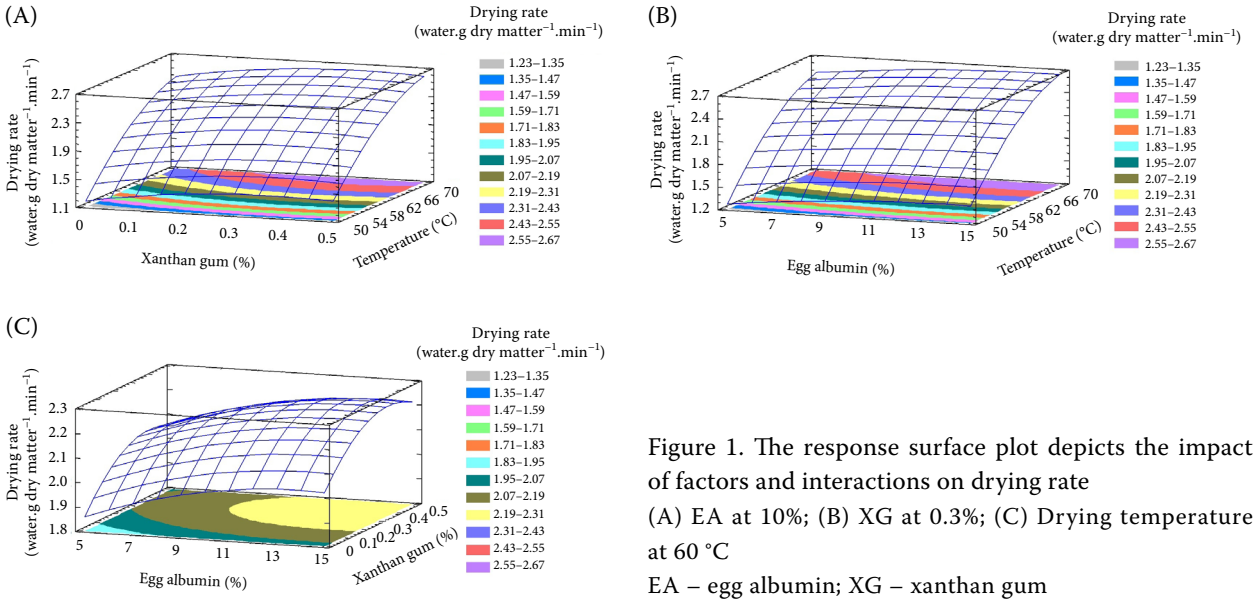

Figure 1. The response surface plot depicts the impact of factors and interactions on drying rate

(A) EA at 10%; (B) XG at 0.3%; (C) Drying temperature at 60 °C

EA – egg albumin; XG – xanthan gum

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ture, thereby increasing porosity, enlarging the contact surface area, and enhancing moisture diffusion, which ultimately accelerates drying. EA increases the product's surface contact area, facilitating the transmission of mass and heat. The vast surface area in contact with the drying air has boosted the ability to remove moisture quickly, resulting in faster drying times. Furthermore, as air temperature has increased, humidity has decreased, and heat transmission is quick due to the temperature difference between the foam layer and the drying air. As foaming increases, the porosity of the layer and the surface area to volume ratio of the layer increase. It increases the mass transfer rate, leading to faster drying rates. When used at higher concentrations, the foaming agent facilitates air penetration into the foam structure, thereby increasing the porosity of the structure, enhancing the contact area and moisture diffusion capacity of the foam, and ultimately increasing the drying rate (Thuy et al. 2024a). Dehghannya et al. (2018) also reported that foaming agents such as EA reduce the interfacial tension and form a thin film on the air-liquid interface to facilitate foaming.

XG also helped support the foam structure, preventing collapse and water separation (Thuy et al. 2024a). The increase in XG addition improved the stability and quality of the foam structure, allowing for faster moisture mass transfer during both constant and decreasing rate periods. As the drying process progressed, the foam structure's stability facilitated the mass movement of free water in the drying air by removing impediments produced by closed pores. During the period of lowering drying rate, the foam structure's integrity enabled the mass transfer of bound water within the foam through the diffusion process (Susanti et al. 2021).

Along with EA and XG, temperature can be considered the most important factor affecting drying rate. Higher temperatures correspond to higher drying rates and faster drying times. The effect of air velocity is almost negligible or has a small effect. Increasing the drying temperature increases molecular motion, which in turn increases the rate of moisture removal in the sample, resulting in a higher drying rate and shorter drying time. Some previous studies have shown that the foam drying rate of "Gấc" peel and tomato increases with increasing drying temperature (Thuy et al. 2024a; Thuy et al. 2024b). In a study on foam-mat drying of kadam fruit, Osama et al. (2022) reported that increasing the drying temperature also increased the drying rate, with an average drying rate of about 130.53% when the drying temperature was increased from 50 °C to 70 °C. Optimisation of foam drying of papaya powder was also performed, with the optimal conditions of 15% egg white, 0.3% xanthan gum, and 15 min of whipping time. Under all drying conditions, foam-dried papaya powder had the shortest drying time and high drying rate (1.38–2 times faster) than non-foaming powder (Abd El-Salam et al. 2021).

Anthocyanin content. The response surface plot and contour plots in Figure 2 revealed that EA,

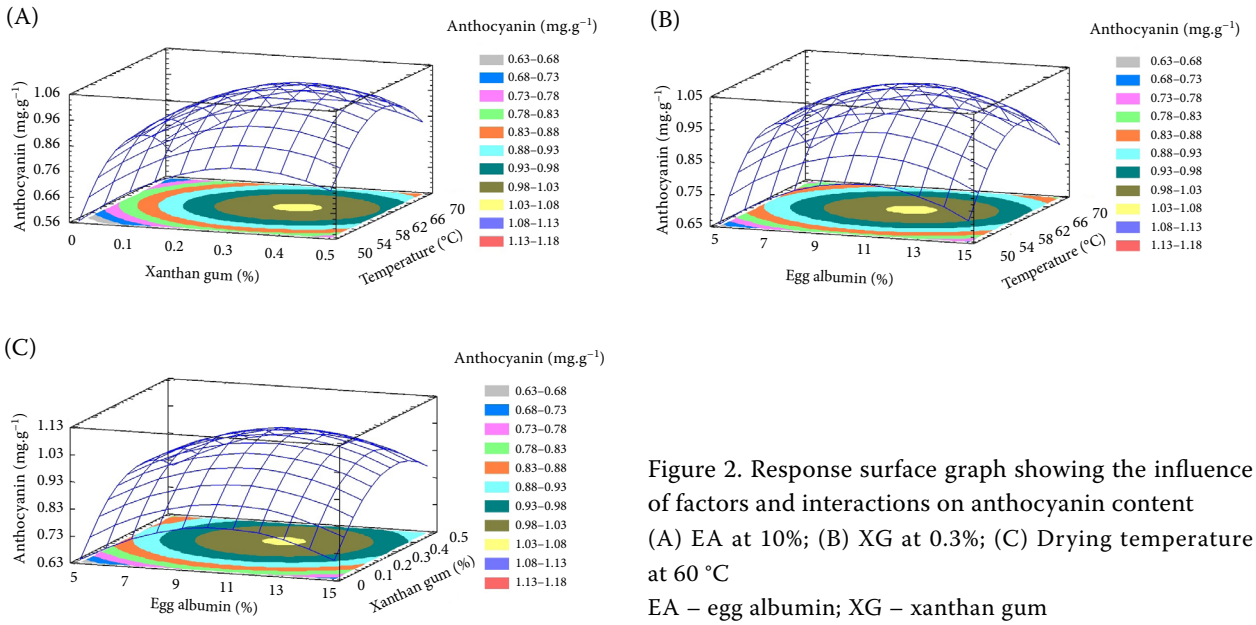

Figure 2. Response surface graph showing the influence of factors and interactions on anthocyanin content

(A) EA at 10%; (B) XG at 0.3%; (C) Drying temperature at 60 °C

EA – egg albumin; XG – xanthan gum

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XG, and drying temperature all have an impact on anthocyanin content. When the EA content used was fixed at 10% (Figure 2A), the highest value (1.03 $mg.g^{-1}$) was obtained with 0.33% XG at 61.43 °C. However, when the XG content was used and the drying temperature increased, the anthocyanin content of PFSP powder tended to decrease. Furthermore, when the XG content was held constant at 0.3% (Figure 2B), the highest value (1.04 $mg.g^{-1}$) was observed with 10.63% EA at 61.43 °C. On the other hand, when the drying temperature was fixed at 60 °C (Figure 2C), the EA and XG content used was 10.63% and 0.33%, respectively, and the anthocyanin content was maintained at the highest (1.03 $mg.g^{-1}$). However, when the EA and XG content used increased, the anthocyanin content in PFSP powder after the end of the drying process tended to decrease. Using Statgraphics software, the optimal foaming conditions were discovered to be 10.62% EA and 0.33% XG at 61.3 °C. Under these optimal conditions, the powder's anthocyanin content peaked at 1.04 $mg.g^{-1}$.

Anthocyanins are bioactive compounds that are easily degraded at high temperatures, so the longer the drying time, the more likely anthocyanin degradation will be. However, when the drying temperature was increased from 50 °C to 65 °C, the anthocyanin content was better preserved, most likely due to the short drying duration, which reduced the exposure time of this sensitive compound to high temperatures. However, at temperatures above 65 °C, anthocyanin was thermally destroyed, resulting in a decrease in its content, this result is quite similar to the announcement of Reis et al. (2021). Abbasi and Azizpour (2016) also reported that increasing the temperature from 65 °C to 80 °C yielded an increase in the anthocyanin degradation rate because of exceeding the temperature more than threshold resistance of anthocyanins.

Maintaining high anthocyanin content is associated with high temperatures and short processing times; this could be attributed to a combination of the foam-mat approach, which increased moisture loss rates during drying. Abbasi and Azizpour (2016) found that the total anthocyanin content of foam-mat dried sour cherry at 65 °C (drying time of 230 min) was significantly greater than that at 50 °C (drying time of 165 minutes). Kanha et al. (2022) also studied the anthocyanin retention efficiency of foam-mat dried powders compared with other drying methods, showing that compared to spray- and freeze-dried anthocyanin powders, the total anthocyanin content and encapsulation efficiency of the foam-mat dried powders were comparable and higher to those of the spray- and freeze-dried powders, respectively. So, although anthocyanin is a heat-sensitive chemical, the foaming process appears the rapid removal of moisture, resulting in reduced drying time and better maintenance of anthocyanin content compared to conventional procedures.

Proteins have a certain binding ability to anthocyanins. However, different proteins have certain differences in affinity for different anthocyanins. Shaari et al. (2018) showed that high albumin concentrations resulted in greater retention of phenolic compounds. EA supplementation also affected the anthocyanin content in the foam-mat dried PFSP powder product. Abbasi and Azizpour (2016) announced that the total anthocyanin content decreased with increasing albumin level, probably due to the dilution effect of anthocyanins in the presence of these compounds.

Susanti et al. (2021) discovered that adding 0.3–0.5% XG to red sorghum extract greatly enhanced foam stability while also retaining larger quantities of phenolics, including anthocyanins.

Simultaneous optimisation. The responses (dependent variables), such as drying rate and anthocyanin content, were examined and optimised separately (as detailed above). The obtained results showed that the optimal conditions (EA, XG, and drying temperature) may differ slightly; therefore, an experimental design in conjunction with the desired function can be used for simultaneous optimisation to achieve the most common optimal operating conditions for the responses. This multi-criteria technique was developed to optimise multiple responses simultaneously. This technology is straightforward, easy to implement, and saves energy costs for future large-scale applications. In this study, Statgraphics Centurion XV.I was used to performing simultaneous optimisation and selecting the optimal parameters of drying rate and anthocyanin content in PFSP powder. The optimum conditions for powder production were established using the desirability function method and the superposition plotting technique, as illustrated in Figure 3. The optimum conditions were selected for the experimental values with the highest drying rate and anthocyanin content. All parameters (EA, XG, and drying temperature) were adjusted to produce PFSP powder via foam-mat dry-

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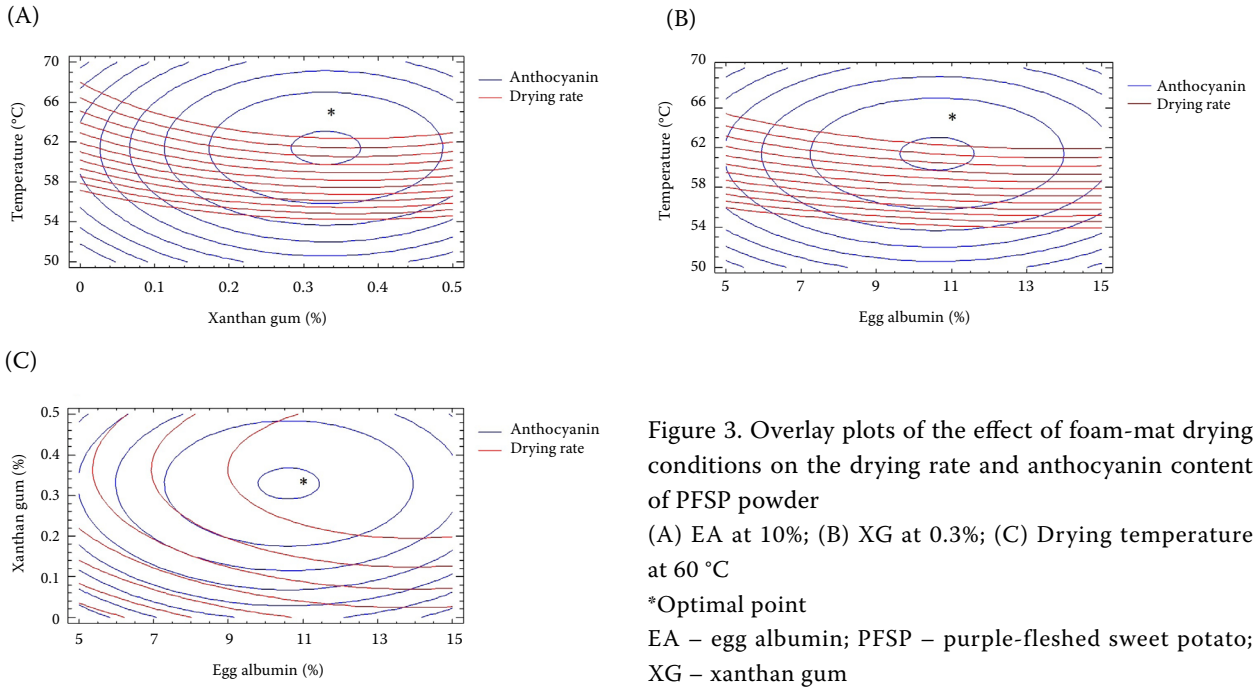

Figure 3. Overlay plots of the effect of foam-mat drying conditions on the drying rate and anthocyanin content of PFSP powder

(A) EA at 10%; (B) XG at 0.3%; (C) Drying temperature at 60 °C

*Optimal point

EA – egg albumin; PFSP – purple-fleshed sweet potato; XG – xanthan gum

ing with the optimum conditions of EA, XG content, and drying temperature of 11.02%, 0.34%, and 65.1 °C, respectively, with a desired level of 0.85. At these maximum levels, the expected responses for drying rate and anthocyanin content in the final product were determined to be 2.49 g water.g dry matter^{-1}.min^{-1} and 1.01 mg.g^{-1}, respectively, shown in asterisk (*).

The verification of the optimal parameters was also performed. The results showed a good correlation between the experimental data and the predicted data, with errors within acceptable limits (< 5%) (Table 4), where the differences in data for the drying rate and anthocyanin were 4.23% and 4.72%, respectively.

The quality of the foam-mat dried PFSP powder

Scanning electron micrograph (SEM). The morphological properties of PFSP powder particles dried by the foaming process (obtained from this work) were compared to a typical convection-dried powder sample from fresh sweet potato tubers, as described by Thuy et al. (2020). SEM image at × 2 000 magnification (Figure 4) shows that the PFSP powder particles dried by the conventional convection method (Figure 4A) have different sizes, mostly oval and polygonal shapes, uneven surface, signs of slight cracking due to rapid water loss, and uneven shrinkage.

Meanwhile, the powder particles from the foam-mat drying process (Figure 4B) have a polygonal shape, are uneven, and have a rough surface; many of the particles are shattered, while others have a flaky structure. Furthermore, the powder particles' structures contain open pores caused by the flow of moisture. This structural unevenness could be attributed to the voids left by air bubbles in the foam, which represent the porosity of the powder

Table 4. The optimal parameters for the drying process of PFSP foam were determined based on the dependent variables (drying rate and anthocyanin content) and the verification

	Optimum process parameters			Dependent variables	
	EA (%)	XG (%)	drying temperature (°C)	drying rate (g water.g dry matter^{-1}.min^{-1})	anthocyanin (mg.g^{-1})
Predicted value	11.02	0.34	65.1	2.49	1.01
Actual value				2.60 ± 0.07	1.06 ± 0.13

Mean ± STD; EA – egg albumin; PFSP – purple-fleshed sweet potato; temp. – temperature; XG – xanthan gum

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(A) (B)

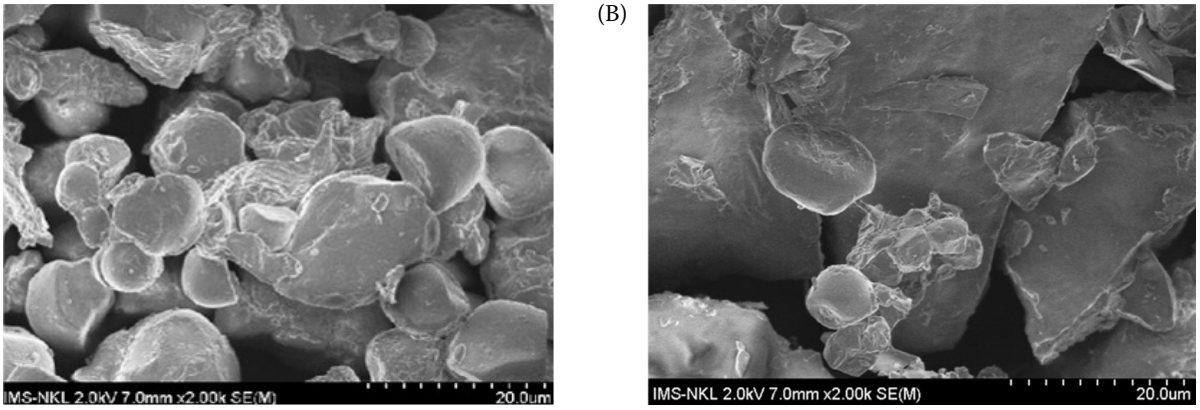

Figure 4. SEM of PFSP powder samples dried using (A) convection drying and (B) foam-mat drying – 20 µm (× 2 000)
PFSP – purple-fleshed sweet potato

after drying and differ from regular dried powder particles. With increasing temperature, the homogeneity reduces as the porosity increases. The explanation is that when the temperature rises, the degree of collapse and mixing of nearby bubbles lowers because the drying period shortens, resulting in higher porosity. Similar morphological properties were observed in the investigation of dried peach powder (Brar et al. 2020) and dried banana powder (Thuwapanichayanan et al. 2008) using the foam-mat drying method.

Some physical and chemical properties of foam-mat dried PFSP powder. Figure 5 shows the foam-mat dried PFSP powder with the optimal parameters (foaming agent EA, stabiliser XG, and drying temperature). Despite a short drying period (3.5 h), the powder preserved its vivid hue, which was similar to the original colour. The analysis of bioactive components, including anthocyanin (1.03 ± 0.08 mg.g^{-1}) and TPC (3.66 ± 0.06 mg GAE.g^{-1}), revealed that antioxidant activity (58.49 ± 0.88%) was maintained. Product analysis revealed that the foam-mat dried PFSP powder had a low moisture content and water activity, at 4.35 ± 0.24% and 0.29, respectively, which are favourable for good storage at room temperature. On the other hand, other physical properties, such as the water solubility index (WSI), water absorption index (WAI), and rehydration ratio, were determined to be 56.49 ± 0.16%, 3.55 ± 0.12%, and 3.82, respectively. The powder had a porous structure, could absorb water quickly, and was easily regenerated.

Figure 5. Foam-mat dried PFSP powder
PFSP – purple-fleshed sweet potato

CONCLUSIONS

The BBD statistical experimental design, utilising RSM, was successfully employed to model and optimise the parameters of the PFSP foam-mat drying process. The study's findings revealed that the addition of EA and XG, as well as the drying temperature, altered the drying rate and anthocyanin concentration in the foam-mat dried PFSP powder. The regression equations generated by the model in this study are highly reliable and have the potential to be used to predict the drying process and product quality at the actual production scale. For the manufacturing of PFSP powder with a high drying rate and high anthocyanin content in the finished product, foaming agent EA and foam stabiliser XG are used with optimal concentrations of 11.02% and 0.34%, respectively, at an optimal drying temperature of 65.1 °C. PFSP powder preserves its natural purple colour due to carefully researched physicochemical properties. The findings of this study can be used as an input material for a variety of nutritional food processing techniques

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and formulations. The inclusion of nutrients and bioactive chemicals ensures that the finished product has strong antioxidant qualities and contributes to human health when consumed.

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