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RESEARCH PAPER

Application of foam-mat drying technique in producing egg white powder and yam bean (*Pachyrhizus erosus* (L.) Urb.) powder: Potential and applications

Narisara Janpleng[1], Pheeraya Chottanom[1], Apichaya Bunyatratchata[1]

1 *Department of Food Technology and Nutrition, Faculty of Technology, Mahasarakham University, Mahasarakham, 44150, Thailand*

Corresponding author: Pheeraya Chottanom (pheeraya.c@msu.ac.th)

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Abstract

This study investigated the effectiveness of foam-mat drying for producing functionalized egg white powder, focusing on the influence of two stabilizers on foam properties, powder quality (color, solubility, functionality), and nutritional value. Pasteurized egg white was foamed with either 0.5% (w/w) xanthan gum or gum arabic. The resulting foams were dried at 70 °C and subsequently ground into fine powders, with potential application in yam bean-based food systems requiring improved foam stability. The incorporation of stabilizers significantly enhanced the water solubility of the egg white powder. Xanthan gum demonstrated superior performance over gum arabic, significantly enhancing foam capacity and stability, which subsequently resulted in improved powder color. Optimal foam density (0.26 g/mL), foam capacity (250%), and 100% foam stability were achieved. The egg white powder produced with xanthan gum was a good foaming agent for a yam bean matrix. The resulting powder demonstrated significant improvement in solubility and presented a satisfactory in valuable nutritional profile, providing 10% inulin and 34% protein. The research validated this approach by successfully formulating a kidney-specific nutritional drink using the foam-mat yam bean powder. Optimal formulas, enhanced with milk powder, achieved the highest sensory acceptability and were concluded to meet an acceptable standard, despite comparison to a superior commercial spray-dried product. This research establishes a robust methodology for producing functionalized egg white powder via foam-mat drying. This approach offers a low-cost, accessible production alternative, making it particularly appealing for startup entrepreneurs and food applications.

Keywords

egg albumin, foam-mat drying, functional food ingredient, kidney-specific

Introduction

Egg whites are a rich source of protein, containing over 40 different types. A major protein in egg white matrix includes ovalbumin (54%), ovotransferrin (12–13%), ovomucoid (11%), lysozyme (3.4–3.5%), ovo-globulins G2 and G3 (2%), and ovomucin (1.5–3%) (Mine 2014). These proteins play crucial roles in foaming, gelling, and emulsification. Egg whites provide a complete profile of essential amino acids, with leucine being particularly abundant. Leucine plays a vital role in tissue repair, growth, and blood sugar regulation (Tallman et al. 2018). Theses make egg whites a cost-effective protein source, often used in various food products, including baked goods and meat products. Egg white, primarily composed of water (over 80%) (Li et al. 2023), is a highly perishable food due to its high moisture content. Dehydrated egg white

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powder offers extended shelf life, reduced costs, and specific functional properties (Lechevalier et al. 2007). Egg white powder is a popular choice for athletes (Hida et al. 2012), the elderly (Ullevig et al. 2022), and individuals with specific dietary needs, like those with kidney disease (Taylor et al. 2011). Industrially, egg white powder is produced by separating yolks, pasteurizing, and spray-drying. (Ma et al. 2013). It is widely recognized that the production of high-quality powdered food typically involves advanced and costly techniques, such as freeze-drying and spray-drying. Therefore, to empower smaller-scale producers who cannot afford advanced technologies, cost-effective alternatives to expensive techniques are crucial for supporting food powder production.

Freeze drying, spray drying, and oven drying are commonly used protein drying techniques. Freeze drying is primarily used to characterize protein functionality, and spray drying is predominantly used for commercial large-scale protein production. Although oven drying is comparatively less expensive and allows the temperature to be set below the protein denaturation point (Feyzi et al. 2018; Brishti et al. 2020), the process involves a much longer drying time. To solve this problem, drying under vacuum pressure is often used, but this method comes with a higher cost.

Foam-mat drying involves incorporating air into a liquid to form a stable foam, followed by drying. It is an economical alternative to drum, spray, and freeze-drying for the production of food powders. This process is also ideal for large-scale production of food powders, especially those derived from viscous and sticky materials. Foaming the product before drying can preserve its nutritional quality, and facilitate reconstitution. The porous structure of the foam significantly increases the surface area, leading to faster drying rates at lower temperatures (Chandrasekar et al. 2015; Hardy and Jideani 2017; Mounir and Allaf 2018; Chottanom et al. 2020; Afifah et al. 2023). Stable foam formation and rapid drying are influenced by factors like liquid concentration, foaming agent, stabilizer, and whipping technique. Egg albumin, whey protein concentrate, and soy protein isolate are common foaming agents due to their globular structure and surface activity. The capacity of a protein molecule to create a stable foam is influenced by factors such as intermolecular bonds, cohesiveness, elasticity, hydrophobicity, and its ability to undergo conformational changes to form elastic films (Rahayu et al. 2015). Stabilizers like gums, maltodextrins, and cellulosic derivatives can enhance foam stability, especially for low-concentration or low-viscosity liquids.

Foam-mat drying has emerged as a promising technique for producing powdered food proteins. Factors like the choice of foaming agents, stabilizers, and processing conditions play a crucial role in determining the quality of the final product. For example, maltodextrin concentration of 15% was found to be suitable for producing milk powder, resulting in a yield value of 19.40%, solubility of 71.08%, water content of 3.73% and protein content of 10.26%. These properties were comparable to those achieved with 6% gum Arabic (Mulyadi et al. 2012). Foam-mat drying has been successfully applied to various dairy products including milk (Ho et al. 2024; Patange et al. 2026), yogurt (Krasaekoopt and Bhatia 2012) and cream (Ikizler et al. 2020). However, there is a lack of published information on the production of egg white powder using the foam-mat method. Moreover, the application of foam-mat-derived protein powders remains understudied.

Yam bean (*Jicama*, *Pachyrhizus erosus* (L.) Urb) originated from Mexico and Central America, and has been introduced and widely cultivated in various countries, including Thailand, the Philippines, China, Malaysia, India, Indonesia, and Africa, where it contributes significantly to local economies. It is primarily composed of water, carbohydrates, fiber, sugar, and protein, accounting for approximately 90.07%, 8.82%, 4.90%, 1.80%, and 0.72% of its total weight, respectively. It is also a good source of vitamin C (20 mg/100 g) and various minerals (USDA 2019). Yam bean contains prebiotic compounds, including inulin and fructooligosaccharides (FOS), which have gained significant attention for their health-promoting properties (Sarkar et al. 2021; González-Vázquez et al. 2022; Bhanja et al. 2023). These compounds are frequently incorporated into functional food products due to their contribution to digestive health and their unique combination of properties: prebiotic activity, high dietary fiber content, naturally sweet taste, and low caloric value. Additionally, it aids in digestion and stimulates the immune system. Owing to these characteristics, yam bean is a suitable food for those who want to manage their weight and people with diabetes. One strategic approach to maximizing the utility of yam bean is to process it into value-added products, such as powdered ingredients suitable for the health food market.

This study aimed to develop and characterize an optimized foam-mat drying method for producing egg white powder. The primary objective was to investigate the impact of various stabilizers on the expansion and stability of egg white foam during the drying process, and subsequently on the functional properties (solubility, foaming, and gelation) of the resulting egg white foam-mat powder (FEP). Furthermore, the foaming ability of the obtained FEP was compared against commercial egg white powder (CEP), when integrated into a yam bean pulp matrix for foam production. Based on the benefits derived from egg white and yam bean components, the resulting foam-mat yam bean powder (FYBP) was used to formulate a novel kidney-specific nutrition drink.

Materials and methods

Materials and chemicals

Fresh eggs (0–7days old) and 0.5-0.7 kg/seed fresh yam bean (*Jicama*, *Pachyrhizus erosus* (L.) Urb) were purchased from Mahasarakham province in Thailand. Xanthan gum and gum arbic, food grade obtained from Chemipan Corporation Co., Ltd. (Bangkok, Thailand) were used in this study.

Preparation of egg white powder

Egg whites were separated from whole eggs followed by pasteurization using a modified method (Froning 2002) at 60 °C for 4 min. Foaming agents including xanthan gum (XG) or gum arabic (GA) at 0.5% (w/w) were added in egg white. The ingredients were mixed using a kitchen mixer (HR3741/Philips hand mixer 450 watt/Thailand) at speed 3 for 5 min to create a foam. The egg white foam was transferred to stainless tray and dried at 70 °C (BWS5, B.W.S. Trading Limited, Thailand) for 4.25–4.5 h until the water activity (α_w) of the dried foam reached 0.3–0.4. Subsequently dried foam was blended and filtered through an 80-mesh sieve to obtain the egg white powder (FEP). The sample without stabilizer agents was used as the control.

Preparation of yam bean powder

Fresh yam beans were thoroughly washed, peeled, and cut into uniform pieces. To prevent enzymatic browning and maintain color stability, the cut yam bean pieces were immediately immersed in a 0.1% (w/v) ascorbic acid solution for 2–3 minutes. The treated yam bean pieces were then blended with deionized water using a high-speed blender (Imarflex IF-329) at a yam bean to water ratio of 4:1 (w/w). The resulting slurry was then filtered through a cheesecloth to remove some coarse particles. The obtained pulp was then thoroughly mixed with selected foaming agents, FEP (5, 10 % W/W) or CEP (5% W/W). The mixture was foamed using a kitchen mixer at speed 3 for 10 min to create a stable foam. The resulting foam was poured onto a pre-weighed stainless-steel tray (20×30 cm) and uniformly spread to an approximate thickness of 2 mm. The foam-filled trays were then immediately placed in a hot-air oven and dried at 80 °C (BWS5, B.W.S. Trading Limited, Thailand) until the water activity (α_w) of the dried foam reached 0.3–0.4. The dried foam was then ground into a fine powder using a laboratory-scale dry grinder (Panasonic MX-AC400) to achieve a desired particle size (60-mesh sieve). The resulting foam-mat yam bean powder (FYBP) was immediately transferred into polyethylene plastic bags until further analysis. The sample without foaming agents was used as the control.

Preparation of the kidney-specific nutrition drink

The study developed four formulations (Table 1) from 3 major ingredients, foam-mat yam bean powder (FYBP), milk powder, and sucrose to optimize palatability within the strict dietary constraints for CKD dialysis patients. The goal was to test the sensory impact of milk powder and sucrose concentration to achieve high protein product. Given the product's high protein content, it aligns with the dietary recommendation of 1.0–1.2g/kg body weight/day for protein intake for stable adult patients with chronic kidney disease stage 5D on dialysis (Ikizler et al. 2020). All recipes had the same vanilla flavor. Dry ingredients were homogenized with a hand mixer, prepared by adding 70 °C water at 1:10 weight ratio, and served at 50–60 °C. All drink properties were assessed via sensory evaluation.

Table 1. The kidney-specific nutrition drink formulation (g/ 100 g).

Formulars	FYBP	Milk powder	sucrose
1	98	0	2
2	96	0	4
3	88	10	2
4	86	10	4

Foam density, foam capacity, foam stability

The density of egg white foam was determined by measuring the volume and weight of foam as described by Zhu et al (2017). The initial volume of egg white before whipping was used to assess the foam capacity. Foam density and foam capacity were calculated using equations (1) and (2), respectively:

$$Foam\ density = \frac{foam\ weight(g)}{foam\ volume(ml)} \quad (1)$$

$$Foam\ capacity = \frac{foam\ volume(ml) - sample\ volume(ml)}{sample\ volume(ml)} \times 100 \quad (2)$$

To assess foam stability, the volume of foam was measured in a 200 mL beaker every hour over a 3-hour period at a room temperature. Foam stability was calculated using equation (3):

$$Foam\ stability = \frac{foam\ volume(final)(ml)}{foam\ volume(initial)(ml)} \times 100 \quad (3)$$

Moisture content and Water activity

The moisture content was determined according to the standard AOAC method (A.O.A.C, 2000, method 925.09). Briefly, 5 g of egg white powder was dried in a hot air oven at 105 °C until a constant weight was achieved. The moisture content (g water/g solids) of egg white powder was calculated using equation (4). Water activity (a_w) was measured using a water activity meter AQUA LAB model Series 3 TE (Decagon Devices Inc., Pullman WA, USA).

$$Moisture\ content = \frac{W_0 - W_1}{W_0} \times 100 \quad (4)$$

Where w_0= weight of initial sample (g)
w_1= weight of final sample (g).

Color

The egg white samples were analyzed for color using a Chroma meter CR-400 (Konica Minolta Inc., Osaka, Japan) following the manufacturing procedure. A 2 g sample of egg white powder was placed into the powder holder of the Chroma Meter, and color measurements were taken in triplicate. The final color results were expressed as mean values in the CIE L*a*b* color space. The total color change (ΔE*) was calculated using equation 5:

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

Where L*, a* and b* are lightness to darkness, redness to greenness, and yellowness to blueness, respectively. The ΔE* values are calculated as the difference between the color parameters of the sample after drying and the sample before drying.

The browning index was calculated (Ding and Ling 2014) using equation (6):

$$Browning\ index = \frac{\mathrm{x} - 0.31}{0.172} \times 100 \quad (6)$$

where $x = \dfrac{(\mathrm{a} * + 1.75L*)}{(5.645L* + a* - 0.3012b*)}$

Water solubility index and Water absorption index

The water solubility index and water absorption index were determined using a modified method described by Zeng et al. (2023). Briefly, 0.2 g egg white powder was dissolved in 20 mL of DI water and stirred at 25 °C for 30 min. The mixture was then centrifuged at 1000 × g for 10 min to separate the supernatant from the sediments. Subsequently, the supernatant and the precipitate were dried at 105 °C until a stable weight was achieved. The weight of the supernatant and the precipitates were used to determine the water solubility index and water absorption index following equations (7) and (8), respectively (Wani et al. 2016; Zeng et al. 2023).

$$Water\ solubility\ index(\%) = \frac{weight\ of\ solid\ in\ suppernatant(\mathrm{g})}{weight\ of\ sample \times (1 - \mathrm{MC})(\mathrm{g})} \cdot 100 \quad (7)$$

$$Water\ absorption\ index(\%) = \frac{weight\ of\ solid\ in\ precipitant(\mathrm{g})}{weight\ of\ sample \times (1 - \mathrm{MC})(\mathrm{g})} \cdot 100 \quad (8)$$

Where MC= Moisture content (dimensionless).

Yield

The product yield (%) was calculated based on the weight of dried foam and wet foam. The yield calculation was determined using the following formula:

$$Yield = \frac{weight\ of\ dried\ sample(g)}{weight\ of\ wet\ sample(g)} \times 100 \quad (9)$$

Protein, Fat, Ash and Carbohydrate Content

The AOAC (2000) method was used to determine the protein (method 984.13), fat (method 920.39), carbohydrate (determined by subtraction), and ash (method 942.05) content. The protein content was determined using the Kjeldahl method. Briefly, a tube was loaded with 0.3 g of samples, Kjeldahl catalyst and concentrated sulfuric acid (H_2SO_4). The samples were digestion, followed by distillation and titration with 0.1 N hydrochloric acid according to the standard procedure. Total fat was determined using Soxhlet extraction method with petroleum ether as the extraction solvent. Ash content was obtained combustion of sample in muffle furnace at 550 °C for 24 hr. Carbohydrate was calculated with difference method.

Inulin

The inulin content was estimated based on the total fructose release following hydrolysis. The total fructose content was determined using a modified method of Saengkanuk et al. (2011). To extract inulin, mix 2 g samples and 25 mL DI water in a tube, heat at 80 °C for 20 min using water bath. The solution was filtrated and then mixed 3 mL of supernatant with 3% HCl 5 mL. This mixture was diluted with DI water to a total of 25 mL. After that heat the mixture at 97 °C for 45 min. Analysis of inulin content by measuring the mixed solution of 5 mL citrate buffer pH 6 (70 mM), 0.15 mL inulin extraction sample, 4.4 mL DI water and 0.2 mL sodium metaperiodate (10 mM) then add 0.25 mL potassium iodide (100 mM) in the mixture. The solution absorbance was measured at 390 nm by using a UV-Vis spectrophotometer. Inulin content was calculated from the calibration curve of standard fructose.

Total sugar

The total sugar content of the sample was determined using the phenol-sulfuric acid method, with slight modifications based on Lam et al. (2021). In brief, the sample was extracted with 3% HCl. The extracted sample was mixed with 0.5 mL phenol in a tube, followed by the addition of

2.5 mL of concentrated H_2SO_4. The solution was mixed at room temperature for 30 min. Subsequently, the mixture was measured absorbance at 490 nm by using a UV-Vis spectrophotometer. Total sugar content of sample was calculated from the calibration curve of standard glucose.

Reducing sugar

The reducing sugar content of the samples was determined using the 3,5-dinitrosalicylic acid (DNS) method, based on the procedure published by Gusakov et al. (2011) with minor modifications. The DNS solution was mixed with the sample solution, boiling 10 min. The solution was then cooled down, and 5 mL DI water was added. The absorbance of mixture was determined at 540 nm by using a UV-Vis spectrophotometer. Reducing sugar was calculated from the calibration curve of standard glucose.

Sensory evaluation

Sensory evaluation was conducted by 30 semi-trained panelists (students and staff from the Faculty of Technology, Mahasarakham University) using the Hedonic scale and the Just About Right (JAR) scale to assess overall acceptance and product suitability. Panelists used a 9-point hedonic scale (1 = extremely dislike, 5 = neutral, 9 = extremely like) to rate the product's liking for its appearance, color, odor, flavor, and overall acceptability. Product suitability testing also used a 5-point Just-About-Right (JAR) scale to optimize the product formula for target sensory attributes (flavor). The scale ranged from 1=Much too weak to 5=Much too intense, with 3=Just Right. The 70% JAR target was set for formulation success. If the JAR score was below 70%, a net effect threshold of 20% was used to determine the necessity and direction of reformulation (Rothman and Parker 2009). Net effect or the net score represent the size and polarity of the difference between samples, which is obtained by taking the percentage of "too intense" responses minus the percentage of "too weak" responses.

Statistical analysis

The experiment was performed in triplicate and the reported data are presented as mean ± standard deviation. Analysis of variance (ANOVA) and Duncan's new multiple range test were used to assess the statistical significance at a significant level $p < .05$ using IBM SPSS statistic software (Demo version).

Results and discussion

Preliminary experiments showed maximum egg white foam capacity within 5 minutes of whipping, followed by gradual foam collapse. This phenomenon can be attributed to the increasing temperature and coalescence, a key mechanism of foam aging where individual air bubbles merge, increasing bubble size. The important factors affecting the foaming properties of egg white includes protein composition, structure, amino acid sequence, net charge, charge distribution, solubility, concentration, and surface hydrophobicity.

Statistically significant differences ($p < .05$) were observed in foam capacity and stability (Fig. 1). The sample containing 0.5% xanthan gum exhibited the highest values for these parameters. While xanthan gum and gum arabic did not improve foam capacity compared to the control, xanthan gum markedly improved foam stability. After 3 hours, xanthan gum-treated samples exhibited no volume reduction or foam drainage. Furthermore, xanthan gum treatment expedited the drying process by an average of 25%. The control sample, lacking a stabilizer, exhibited a thin, airy structure and was highly susceptible to collapse. The gum arabic treatment did not improve foam stability, likely due to the insufficient viscosity. This is supported by previous findings demonstrating that even 30% gum arabic solutions exhibit lower viscosity than 1% xanthan gum at low shear rates (Williams and Phillips 2009). Rheological analysis revealed that gum arabic exhibited Newtonian behavior with shear-rate independent viscosity (Williams and Phillips 2009; Mine 2014), whereas xanthan gum demonstrated shear-thinning behavior, a characteristic of non-Newtonian fluids. This difference is attributed to the distinct molecular structures of xanthan gum and gum arabic. Xanthan gum, composed of linear molecules with a larger hydrodynamic volume, exhibits a greater propensity for intermolecular entanglement at relatively low concentrations compared to the more compact and branched structure of gum arabic (Rodd et al. 2000; Kersten et al.2025).

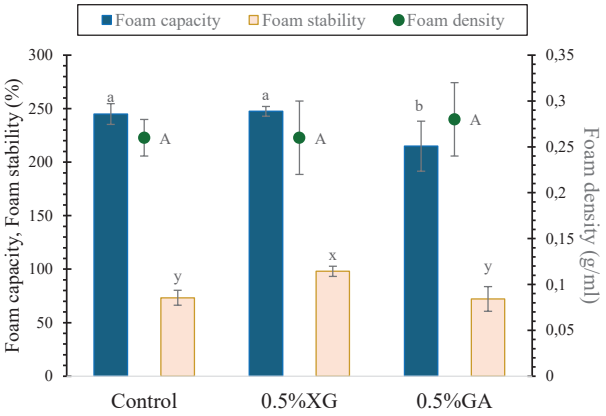


Figure 1. The effect of foaming stabilizer types on the characteristics of egg white foams.

Xanthan gum, an anionic polysaccharide produced by *Xanthomonas campestris*, possesses a unique structure with a cellulose backbone and trisaccharide side chains. Beyond its thickening properties, xanthan gum acts as

a surfactant, forming a viscoelastic film at the air-water interface to protect the foam from mechanical or thermal damage. This stabilizing effect has been observed in various systems, including soy protein isolate foams. Furthermore, xanthan gum is recognized as a versatile food additive, functioning as a thickener, stabilizer, and foam enhancer. Despite whey protein isolate is high solubility and foaming capacity, xanthan gum addition is necessary to improve its foam stability, especially to reduce the natural temperature sensitivity of protein isolate (Mott et al. 1999). Similarly, addition of xanthan gum from 0.125% and above in egg white sample exhibited minimal foam drainage, with only 1 mL of liquid observed after 120 minutes. The lowest liquid drainage inferred that there is a good interaction between egg white and xanthan gum in terms of stability (Muthukumarana, et.al. 2008).

Although viscosity influences the properties of foam, the strength of the resulting foam films remains a crucial consideration. The film's strength may be influenced by distinct bonding mechanisms: the anionic polysaccharide xanthan gum forms cationic bridges with particles, whereas guar gum primarily binds to particles through hydrogen bonding. There are many reports on the effectiveness of encapsulation with xanthan gum, which is related to the strength of the film or shell layer. The encapsulation efficiency and volatile release controlling of xanthan gum were relatively higher than that of guar gum, making it suitable for formulations that focus on encapsulating volatile compounds using the spray drying process (Carneiro et al. 2013; Ribeiro et al. 2024). The xanthan gum's structural benefits in creating a robust encapsulation matrix. Conversely, the quicker release observed in guar gum-dominant samples points to a less restrictive matrix, facilitating the faster release of volatiles (Thombare et al. 2021). The retention capacity is therefore less than that of xanthan gum.

Fig. 2 presents the yield, moisture content, and water activity of egg white powder produced using foam-mat drying. Yield remained largely unaffected by the low stabilizer levels employed in this study (This research does not focus on the yield of products containing bulking agents, as future work will explore their use in health products). This observation supports the known principle that powder volume increases proportionally with filler content, with typical variations in filling levels ranging from 2% to 6% (Asokapandian et al. 2015). The resulting egg white powders exhibited average water activity and moisture content values, ranging from 0.29 to 0.37 and 9–10%, respectively. The water activity range of the powders is suitable for ensuring their shelf life. The water activity is the important parameter to determine shelf life of the powder products. High water activity leads to shorter shelf life due to high free-water for biochemical degradations. To prevent microbial growth, dried foods should ideally have an aw below 0.6 (Lewicki 2004). Due to their hygroscopic properties, protein-based powders, compared to dried fruit and vegetable pieces, typically require lower water activity to ensure product stability during storage (Ng and Sulaiman

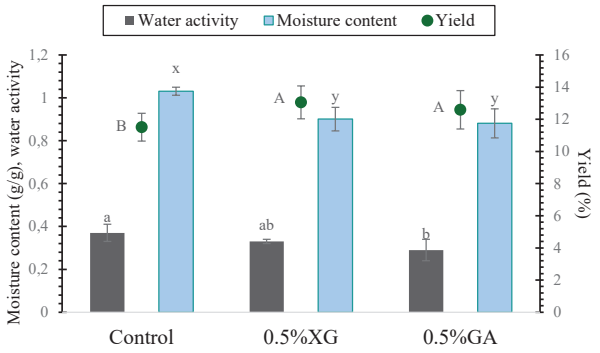


Figure 2. The effect of foaming stabilizer types on moisture content, water activity, and yield of egg white powder.

2017). An anti-plasticization phenomenon was observed in the starch-protein model (6% protein) at moisture contents below 9%, as evidenced by increased glass transition temperature (Tg). Conversely, a significant decrease in Tg was observed at higher moisture levels (Pérez et al. 2022), and these observations could be attributed to the presence of hydrophilic groups within the food model (Luk et al. 2013; Madrigal et al. 2011). Despite exhibiting a low water activity (0.29–0.37), the resulting egg white powder still maintained a relatively high moisture content (9–10%). This can be attributed to the strong hydrogen bonding within the egg white protein matrix, which could retain bound water molecules at low water activity levels. The major proteins in egg white including ovalbumin, ovotransferrin, ovomucoid, lysozyme, and ovomucin, through their diverse amino acid compositions and interactions, contribute significantly to the extensive network of hydrogen bonds that provide structural stability to the egg white matrix and water-hydrogen bonding. Furthermore, the presence of hydrophilic components such as carbohydrates and proteins within the matrix further enhances this strong hydrogen bonding network, as evidenced by the greater enhancement observed by incorporating xanthan gum and gum arabic in the egg white matrix.

Among the three experimental samples, the color parameters of egg white powder were significantly affected by the characteristics of the stabilizers, (Table 2). The sample containing 0.5% XG exhibited the highest L* and significantly lower a* and b* and ΔE* values, confirming a lighter color. Furthermore, this 0.5% XG sample demonstrated the lowest BI, resulting in a color profile similar to that of the commercial sample (Egg albumin). Browning in dried foods is influenced by a combination of factors, including food composition and the conditions of hot air exposure, such as time and temperature. According to Elbert et al. (2001), a synergistic effect between temperature and time was observed on browning development during the parboiling process. Air temperatures not exceeding 70 °C were deemed suitable for producing parboiled rice with acceptable light-yellow coloration. In our study, browning was observed when egg white was dried at 60 °C, likely due to Maillard reactions between its high protein content and residual reducing sugars. Enhanced foam stability,

Table 2. The effect of foaming stabilizer types on color parameters of egg white powder.

Sample	L*	a*	b*	ΔE*	BI
Control**	70.44±0.24^{a}	-2.58±0.05^{b}	16.73±0.13^{b}	21.57+0.16b	23.62+0.09^{b}
0.5% XG	71.95±0.43^{b}	-2.51±0.01^{b}	13.10±0.15^{a}	18.66+0.34a	17.08+0.12^{a}
0.5% GA	70.90±0.0.33^{a}	-2.92±0.06^{a}	15.98±0.16b	21.63+0.22b	22.48+0.18^{b}
Egg albumin	74.62+0.06	-2.78+0.02	14.18+0.13	-	17.70+0.05

Difference superscript letters in the same column indicate significant differences ($p < .05$).
**Without stabilizers.

achieved through the addition of xanthan gum, contributed to improved powder color during drying. Xanthan gum-stabilized foams exhibited less collapse during drying and showed a more porous structure compared to other samples, particularly the control. This superior stability can be attributed to the advantageous properties of xanthan gum solutions, including their remarkably high viscosity at low concentrations and their temperature stability within the range of 0–100 °C (Kuppuswami 2014).

The effect of stabilizer type on the water absorption and solubility properties of egg white powders was observed (Fig. 3). The incorporation of stabilizers significantly enhanced the water solubility of the egg white powder compared to the control sample and consistent with the decreased water absorption index. This study demonstrates that foaming with added stabilizers prior to drying offers several advantages of the powder reconstitution. The mechanisms underlying these benefits include a reduction in heat exposure due to shorter drying times and the encapsulation of solids within a protective film layer. The reconstitution yield of the protein powder may have been influenced by heat and pH. According to Punidadas and McKellar (2007), above 57.5 °C, the egg white underwent gelation due to the thermal denaturation of proteins and the concurrent evaporation of water molecules at a pH of approximately 6.0. It has been reported that heat crystallization during the drying process can negatively impact the reconstitution of food powders (Marabi et al. 2007). This phenomenon is attributed to protein denaturation and the Maillard reaction, the reaction between proteins (amino group) and reducing sugar to yield the Heyns rearrangement products, further compromising powder solubility.

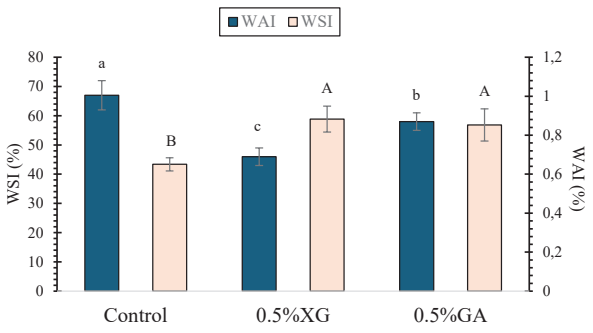


Figure 3. The effect of foaming stabilizer types on water adsorption index (WAI) and water solubility index (WSI) of egg white powder.

Therefore, mitigating degradation during drying will help maintain the recovery capacity of egg white powder, as excessive heat can denature proteins and/or create brown compounds, which can aggregate and become insoluble.

The application of egg white powder, derived from foam-mat drying, to yam bean pulp revealed its potential as a sufficient foaming agent (Fig. 4). The addition of both FEP and CEP significantly increased the foam capacity of the yam bean foam compared to the control sample. Increasing the FEP concentration from 5% to 10% led to a significant increase in foam capacity (from around 35 to over 160), demonstrating a concentration-dependent effect on the foaming ability. Despite achieving the maximum foam capacity with the 5%CEP treatment, the foam stability did not show a significant difference compared to the 5%FEP and 10%FEP samples. The volume reduction and drainage were observed only the control sample. This indicated the similar efficiency between FEP and CEP. The foaming ability of protein-based foamers is influenced by a multitude of factors, which can generally be categorized into intrinsic properties of the protein (e.g., protein structure and availability of surface-active molecules), compositional characteristics of the solution (e.g., solids concentration and viscosity), and processing parameters (e.g., temperature, dispersion method, and aeration rate). In our result, increasing the FEP concentration led to enhanced foam capacity while foam stability was concurrently maintained, attributed to the sufficient presence of surfactant molecules and an increase in viscosity of the matrix. The yam bean foam stability can be enhanced by controlling the rheology of the aqueous medium and increasing the hydrodynamic thickness of the adsorbed macromolecular layer, both of which can resist bubble coalescence and film thinning (see Fig. 5A). On the contrary, the insufficient presence of surfactant molecules and low solution viscosity results in a thin and unstable interfacial film, which is inadequate to entrap air, thereby leading to rapid bubble coalescence and subsequent extensive liquid drainage (see Fig. 5B).

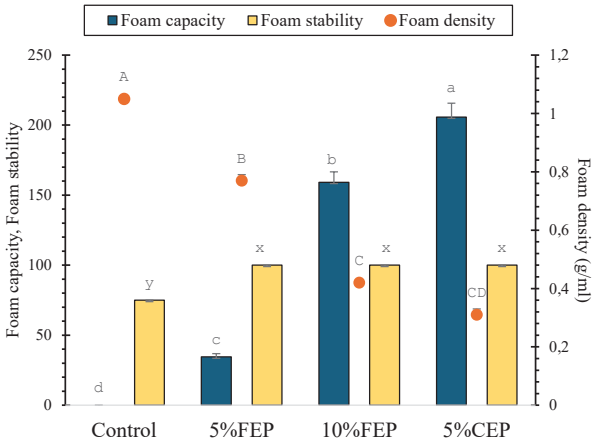


Figure 4. Evaluation of egg white powders as foaming agents in yam bean pulp foams.

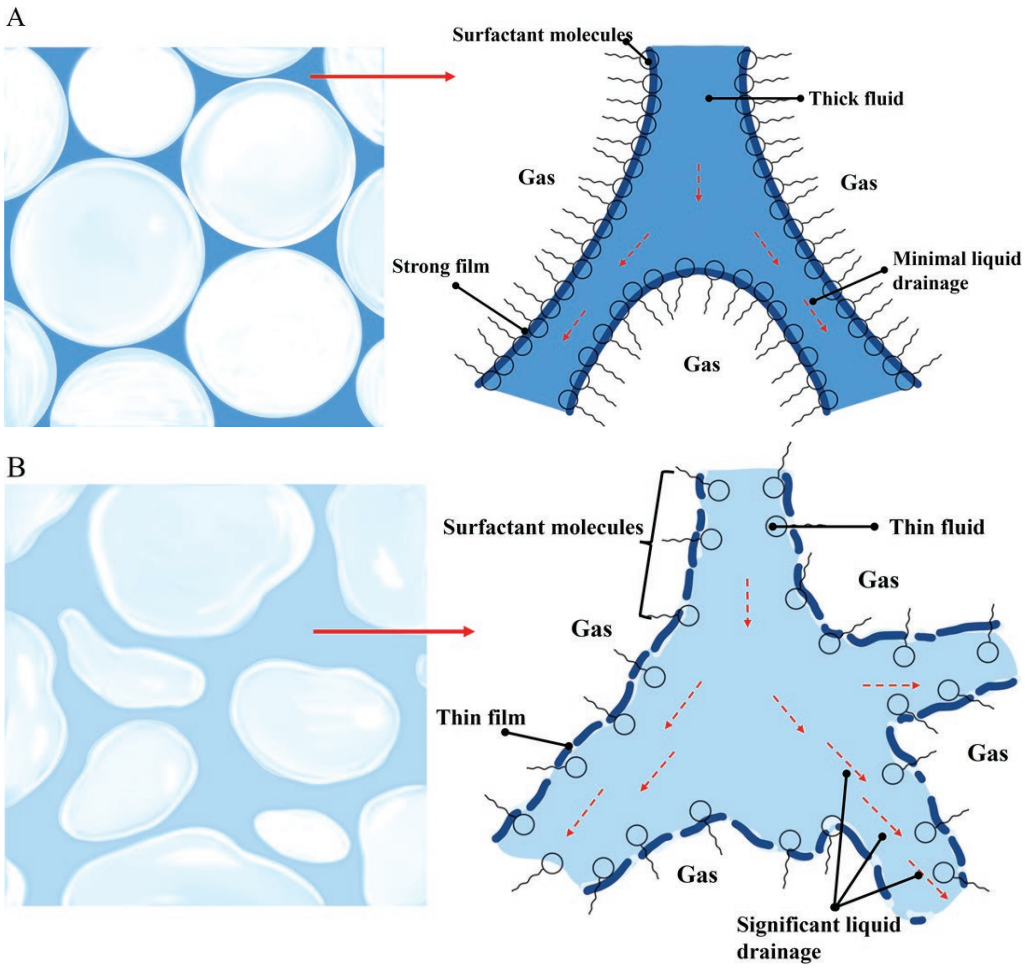


Figure 5. Explanatory illustrations: Structure of foam films and plateau borders of the strong foam (**A**), and weak foam (**B**) systems.

The optimum viscosity enhances foam stability by minimizing liquid drainage and air bubble coalescence (Gamboa and Barraquio 2012). Martinez-Padilla et al. (2014) found that increasing the solids concentration from 10% to 25% improved both foam formation and stability, even though the viscosity of the system increased almost fourfold. However, excessively high viscosity can hinder molecular diffusion and protein adsorption at the air-liquid interface, potentially reducing foam formation.

Factors effecting foam ability of protein as foaming agent include protein structure and concentration, surface tension, charge density, ionic strength, liquid concentration, temperature, whipping force, and dispersibility (Wijaya et. al 2017; Deotale 2023). In the foaming process, when subjected to mechanical force, proteins undergo conformational changes, exposing their hydrophobic nature and confirmative rearrangements. This allows the proteins to interact with water and form a cohesive elastic adsorption layer or lamella that can trap air. The strong viscoelastic layer at the air-liquid contact plays a crucial role in maintaining foam stability.

In our study, the foaming capacity of FEP treatments showed a lower foam expansion than that achieved with CEF. As mentioned earlier, FEP exhibits lower solubility compared to CEP, which is produced by spray drying. Consequently, higher protein concentrations of FEP may be necessary to achieve complete gel formation. Boye et al. (2010) reported a wide range of least gelation capacity values (8–16%) for freeze-dried and spray-dried lentil protein isolates, suggesting that protein solubility significantly influences gelation properties. Similarly, the least gelation capacity for freeze drying and spray drying was 12% while hot air drying required 18% protein to form a gel (Brishti et al. 2020). The observed differences in foaming ability between FEP and CEP may be attributed to their distinct morphologies, particle size, dispersibility and solubility. FEP, produced by hot air drying, exhibited significantly larger particle size and higher crystallinity compared to CEP, resulting in lower water solubility. As noted by Vojdani (2006), although drying improves storage stability, it can result in the formation of irreversible and insoluble protein aggregates, consequently altering the protein's structural integrity and functional properties. Previous studies have demonstrated that drying significantly impacts the structural and functional properties of protein powder (Zhao et al. 2013 ; Rasli and Sarbon 2015; Timilsena et al. 2016; Feyzi et al. 2018). According to Brishti et al. (2020), the fine protein powder from spray drying had wrinkled structures while the powder from hot air drying, significantly larger particles had compact crystalline structures.

Color parameters of yam bean powder as affected by foaming stabilizer types are presented in Table 3. The 5% CEP sample showed the lightest color (L*=72.00±3.46), which was significantly higher than all other samples. The FEP samples exhibited browning, evidenced by a significant decrease in lightness (L^*) compared to both the control and the 5%CEP sample. This change was consistently accompanied by a significant increase in both a* (redness) and b* (yellowness) values, with the 10%FEP sample demonstrating the most pronounced overall color change across these parameters. However, the color of 10%FEP sample remained statistically similar to the color observed in the 5% FEP sample. The significant increase in the a*value (from 0.22 to 1.39) was not reflective of a significant increase in browning across the FEP samples, as quantified by the overall BI and ΔE*, likely due to the accompanying non-significant difference in the L* and b*values between the two concentrations. Browning of dried yam bean involved the oxidation of vitamin C, enzymatic and non-enzymatic reactions. In our result, the Maillard reaction proceeded rapidly during drying, driven by the high concentration of reducing sugars and amino acids inherent in yam bean. Furthermore, adding egg white to the yam bean matrix increases the concentration of amino acids. The Maillard reaction in dehydrated fruits is most active within low moisture content, with water activity levels approaching 0.6, optimizing reactant interaction (Eskin and Shahidi 2013). Principally, the production of powdered yam bean requires a significantly lower moisture content and water activity compared to dried pieces, as previously discussed. Consequently, the sample was likely exposed to conditions conducive to the Maillard reaction for a long time. The use of anti-browning additives is often necessary to prevent browning occurred during drying. The superior color quality of yam bean powder produced with commercial egg white powder may be attributed to the specialized production processes employed for the egg white powder, which may include spray drying, partial removal of reducing sugars, and the incorporation of various food additives.

Table 3. Effect of egg white foam powders on color parameters of yam bean powder.

Sample	L*	a*	b*	ΔE*	BI
Control**	65.25±3.50^{b}	0.18±0.02^{b}	14.17±1.45^{b}	25.35±2.96^{b}	24.06±1.40^{b}
5%FEP	63.43±2.95^{bc}	0.22±0.04^{b}	19.25±1.19^{a}	28.94±2.19^{ab}	35.50±0.79^{a}
10%FEP	60.63±2.42^{c}	1.39±0.19^{a}	18.15±1.43^{a}	32.03±1.76^{b}	37.13±1.86^{a}
5%CEP	72.00+3.46^{a}	-1.27±1.22^{c}	14.42+1.11^{b}	19.12±2.39^{c}	20.60±2.51^{c}

Difference superscript letters in the same column indicate significant differences ($p < .05$).
**Without foaming agents.

The effect of different foaming stabilizers on yam bean powders' water absorption and solubility properties was summarized (Fig. 6). Compared to the control sample, FEP treatments resulted in a significant increase in solubility, which was inversely correlated with a decrease in water absorption. Samples using 5% FEP and 10% FEP exhibited similar solubility, potentially due to their comparable foam stability. The use of FEP significantly impacts foam stability during foam-mat drying. This directly influences the number of air bubbles retained during drying, contributes to enhanced porosity and solubility of the final powder. Variations in foam structural stability are caused by the proteins and polysaccharides availability. More stable foams hold on to more bubbles retained during dry-up. According to Abbasi and Azizpour (2016), these bubbles thereby boost the powder's porosity and solubility. Varhan et al. (2019) reported that the stability of a combination consisting of dissolved particles in a liquid is shown by the solubility of the powder, which signifies its capacity to stay uniformly mixed with water. An increase in foam thickness resulted in a corresponding rise in fig powder sample solubility which may be due to a more stable foam bubble during drying, causing increased porosity and solubility.

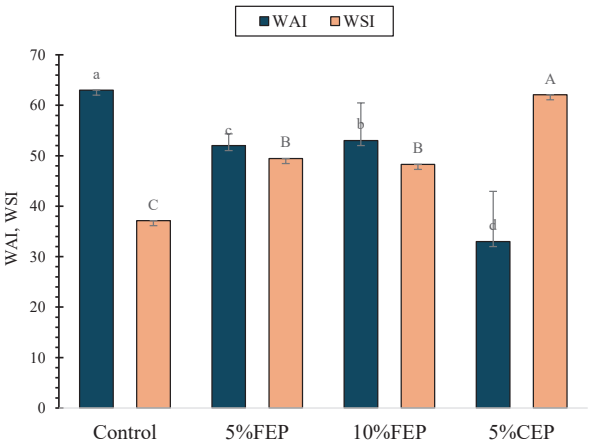


Figure 6. Effect of egg white foam powders on water absorption and solubility of yam bean powder.

The chemical compositions of yam bean powders were analyzed (Table 4). Overall, most proximate compositions (e.g., moisture, ash, and fat) remained relatively comparable between the control and 5% FEP-treated samples. However, significant compositional changes were observed with the addition of FEP. The protein content in the FEP-treated powder increased dramatically, by approximately 6 to 7-fold, compared to the control sample (34.16% vs. 4.91%). Simultaneously, both total sugars and reducing sugars were significantly higher in the FEP-treated powder. Conversely, the carbohydrate content (determined by subtraction) showed a notable decrease, which can be attributed to the significantly increased proportions of protein and sugars. Moreover, FEP-treated powder was a good source of prebiotics with an inulin content of 9–10 mg /g. These findings indicate that FEP effectively enriches the protein and sugar profiles of the yam bean powder. Therefore, FEP will be positioned as a valuable ingredient for the functional food market, particularly in high-protein products catering to specialized nutritional needs, such as those of athletes and clinical populations like the elderly or patients with kidney disease.

Table 4. A comparative analysis of the chemical composition of a control sample versus a sample treated with 5% FEP.

Composition	Control	5%FEP
MC (%)	9.25+0.53	8.51+0.31
Protein (%)	4.91±0.24	34.16±0.54
Ash (%)	4.19±0.80	3.02±0.42
Fat (%)	1.68±0.02	1.92±0.02
Carbohydrate (%)	80.22±0.57	51.89±0.63
Inulin (mg/g)	8.63±1.08	9.63±0.94
Total sugar (mg/g)	62.03±2.02	69.94±3.03
Reducing sugar (mg/g)	23.23±2.09	25.85±2.07

Four formulations (F1 to F4) were developed from three main ingredients – foam-mat yam bean powder (5%FEP), milk powder, and sucrose, while the commercial one was from spray drying.

The spider plot (Fig. 7) illustrates the mean scores for five sensory attributes – Appearance, Color, Odor, Flavor, and Overall Preference – rated on a 9-point scale. The commercial product received the highest preference score in all dimensions, with an overall preference mean of 7.07±1.14 (ranging from 'moderately like' to 'very like'), which was significantly higher than all the tested formula (1, 2, 3, 4) products ($p < .05$). The commercial product's advantage in appearance and color scores is likely attributed to the synergistic effect of spray drying technology and its specific composition of major ingredients, notably isomaltulose, maltodextrin, and milk protein. This sophisticated process is known to produce powder with excellent physical characteristics that visually outperform those made through foam-mat drying. Among the developed formulations, the acceptance evaluation indicated that Formulations F3 and F4 performed very similarly and were the best-performing developed samples. Formulas 1 and 2 received the lowest liking scores for overall preference, at 5.53 and 5.00, respectively. Formulas 3 and 4, which were supplemented with powdered milk, achieved significantly higher overall acceptability scores. This improvement was associated with a corresponding increase in scores for appearance, color, odor, and flavor. While

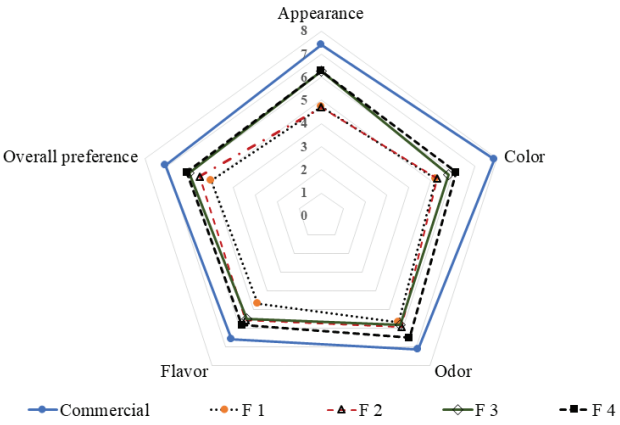


Figure 7. Spider plot of the mean sensory scores of the commercial product and developed formulations (F1 to F4).

Formulation F4's odor score was numerically higher than F3 and not significantly different from the commercial product, the overall preference between F3 and F4 was not statistically different ($p>0.05$). Although Formulations F1 and F2 had odor scores that were not significantly different from F3, their overall acceptance was significantly lower. This suggests that panelists' final judgment was primarily driven by differences in appearance, color, and flavor, rather than the odor attribute. This research also utilized the Just About Right (JAR) scale to specifically assess the product's suitability in terms of flavor intensity, thereby determining if the formulation was acceptable or if adjustments to the flavor profile were necessary.

JAR scaling (Table 5) is criticized for measuring attribute intensity and acceptability simultaneously, most commonly used for flavor or taste. Research aimed at developing food products often sets an acceptability criterion at 70% satisfaction. However, achieving this is difficult for medical and nutritional food products due to constraints on ingredient concentration, which is necessary to reduce the burden on the renal system. Consequently, there are limitations regarding the use of various additives. As seen from the evaluation results of the commercial product in this research, the just about right value was lower than 70% (56.67). However, if the value is found to be lower than 70, the Net effect value can also be considered. A value lower than 20 indicates the appropriateness of the evaluated characteristics. It may not be necessary to adjust the formula. This research found that the just about right values for all tested formulas were below the 70% criterion. Upon evaluating the net effect values, Formula 4 demonstrated the lowest score, falling below 20. Initially, there is no need to further improve the product based on current information, while Formulations F1, F2, and F3 require adjustment to achieve a stronger flavor intensity. Despite these somewhat low scores (Hedonic scores) in some attributes when compared to the commercial product, the assessors ultimately concluded that the developed product met an acceptable standard.

Table 5. Just about right scale of the flavor of a kidney-specific nutrition drink.

Products	Much too little	Too little	Just about right	Too much	Much too much	Net effect
Commercial	0.00	16.67	56.67	23.33	3.33	10.00
F 1	30.00	50.00	20.00	0.00	0.00	80.00
F 2	6.67	26.67	53.33	13.33	0.00	20.00
F 3	13.33	26.67	53.33	6.67	0.00	33.33
F 4	6.67	20.00	63.33	10.00	0.00	16.67

Consequently, the resulting FEP is a promising, cost-effective alternative to commercial egg white powder and yam bean powder, specifically appealing to the health-conscious consumer market. However, despite the significant economic advantages of the foam-mat drying (FMD) technique for entrepreneurs, a key limitation remains the slightly lower solubility and increased brown color development of the resulting powders compared

to commercial alternatives. For applications where food additives and cost are not restricted, color quality can be substantially improved through specific treatments, such as glucose oxidase (for desugaring), the addition of an acid (to minimize the rate of the Maillard reaction), and sulfite treatments (for effective browning management).

Conclusions

This research provides a methodology for producing functionalized egg white powder with potential applications in food systems requiring improved foam stability. The appropriate selection of stabilizers, which facilitates adequate foam capacity and stability during drying, is essential for achieving desirable color and solubility attributes of egg white powder. This study demonstrates that xanthan gum is more effective than gum arabic, improving both foam properties and powder quality. Samples using 5% FEP and 10% FEP exhibited similar solubility, potentially due to their comparable foam stability. These experimental results clearly demonstrate a direct correlation: the low foam stability observed in the control samples is associated with a subsequently low solubility value in the final powders. The resulting FEP exhibited foaming properties that were comparable to those of CEP in terms of functional performance. Furthermore, the yam bean powder using FEP provides a valuable source of dietary carbohydrates and protein, with an inulin content of approximately 10% and a protein content of 34%. This study demonstrates the promising potential of foam-mat drying for egg white/ yam bean powder production. Our finding represents a low-cost egg white powder production, accessible alternative for startup entrepreneurs. In future research, some disadvantages of the current powders could be mitigated by removing restrictions on the use of food additives or by allowing for higher production costs, such as enzyme treatment. Increasing the solubility of fibrous powdered foods may be achieved by increasing the proportion of stabilizers with good solubility properties and/or high hygroscopicity. Generally, maltodextrin and dextrose have been effective in improving the solubility of many fruit powders. However, they should be limited in its use in health products, especially those requiring a low glycemic index.

The research successfully applied foam-mat yam bean powder to formulate a kidney-specific nutritional drink. Optimal formulas achieved the highest overall acceptability, largely due to the positive effect of milk powder. In addition, Formulation with milk and sucrose was determined to be the most optimized formula, achieving the necessary JAR threshold for suitability despite the lower hedonic scores as compared to a spray- dried product. The final kidney-specific nutrition drink developed using foam-mat drying was thus considered to meet an acceptable sensory standard.

Author contributions

Narisara Janpleng: Methodology, Investigation, Apichaya Bunyatratchata: Writing – review & editing, Pheeraya Chottamom: Methodology, Writing – review & editing, Visualization, Supervision, Project administration, Conceptualization.

Data collection and analysis

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

This experiment was conducted in accordance with ethics approval number 511-502/2024 obtained from Mahasarakham University (Mahasarakham University Ethic Committee for Research Involving human subjects).

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