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Optimization of Process Parameters for Foam Mat Drying of Coconut Inflorescence Sap

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ABSTRACT

Coconut inflorescence sap (palm nectar) is a rich source of sugars, vitamins, minerals, and micronutrients. As coconut inflorescence sap ferments quickly due to microorganisms, converting it into a powder form would enhance its accessibility and availability for longer durations. This study investigated the effects of foaming process parameters, such as egg albumin concentration and whipping time, on foam expansion and foam density. In addition, the physicochemical properties, including water activity, bulk density, water absorption index (WAI), water solubility index (WSI), pH, ascorbic acid, acidity, reducing sugar, phenolic content, and protein content of foam mat dried coconut inflorescence sap, were also measured. A face-centered central composite design (FCCCD) was employed to create regression models for each response and to optimize the process parameters. It was observed that a stable foam was produced using the foam mat drying process that facilitated quick drying and retained the nutritional quality in the dried powder. The optimum conditions for foaming process, while retaining physiochemical and nutrient properties, were found to be 5% concentration of egg albumin and a whipping time of 10 min. Under these optimal conditions, the ascorbic acid content, acidity, reducing sugar, total phenolic content, and protein content of coconut inflorescence sap powder were 2.38±0.05 mg/100mL, 0.20±0.01 %, 13.2±0.38 %, 2.3±0.05 CE/g, and 21.9±0.39 mg/100mL, respectively. The results indicate that foam mat drying is a viable option to increase the shelf life and retain the nutritional value of coconut inflorescence sap.

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INTRODUCTION

Coconut is primarily grown in coastal regions and islands of more than 93 countries in the tropics and subtropics. Annual global production of coconut is estimated to be approximately 96.15 billion nuts, cultivated across 11.58 million ha, yielding an average of 8,307 nuts per hectare (Rani, 2019). India is the third-largest producer of coconut globally, following Indonesia and the Philippines, producing 12.67 to 22.96 billion nuts, averaging between 6,951 to 10,668 nuts per ha from 2000-01 to 2020-21 (FAO, 2021). Many products are developed from coconut including coconut inflorescence sap, honey, jaggery, palm syrup, and coconut sugar. Among these, coconut inflorescence sap, also known as palm nectar, is the coconut sap extracted from the coconut inflorescence by tapping. It is a sweet, translucent liquid that contains highly nutritious components such as vitamins and minerals. As inflorescence sap is a rich source of sugars, vitamins, micronutrients, and minerals, it ferments quickly after the extraction due to the influence of natural yeast present in the air (Jose et al., 2018).

Coconut inflorescence sap could help keep body hydrated as the supplement sustains the body and can make it a vigorous and revived. It has good digestive properties, facilitates clear urination and can prevent jaundice (Vishnu Priya et al., 2023). The health benefits of coconut inflorescence sap include improving the immune system, reducing blood pressure, improving skin health, being ideal for diabetic patients (low glycemic index), and helping to cure liver diseases (Divya et al., 2019). Consuming 250 mg to 10 g of coconut inflorescence sap powder per day results in numerous health benefits for sportspersons, children, the elderly, people with malnutrition, pregnant women, asthma patients, patients undergoing chemo/radio therapy, alcoholics, people with poor cognition, depression, patients with poor electrolyte balance, anxiety and fatigue, liver disorders, sodium-potassium imbalance, anaemia, skin problems, inflammation, gastrointestinal disorders, and postmenopausal women (Meghwal, 2021). Many scientific methods have been developed to preserve coconut inflorescence sap for longer duration, such as pasteurization, refrigeration, filtration, and addition of preservatives to retain its vitamins, sugar and other nutrients beneficial for health (Hebbar et al., 2018; Pandiselvam et al., 2020; Priya et al., 2024; Yoghapriya & Sivakami, 2011). Coconut inflorescence sap, if marketed effectively, has the potential to serve as a nutritious beverage, presenting a wholesome substitute for carbonated drinks (Jose et al., 2018). However, low shelf life limits the marketability of inflorescence sap. Enhancing the accessibility of coconut inflorescence sap by converting it into powder form could significantly expand its availability.

Coconut inflorescence sap can be made into powder form using spray-drying (Yoghapriya & Sivakami, 2011). However, the high temperatures involved in this process pose a risk of compromising heat-sensitive nutrients and volatile components. Additionally, the cost associated with machine maintenance stands as a notable drawback in the application of spray-drying technology for coconut inflorescence sap powder production. Foam mat drying is a technique of transforming liquid food product into stable foam and subsequently drying at 60-90°C by incorporating edible foaming agent. This technique is particularly suitable for heat sensitive, sticky and viscous products that can't be dried by other drying methods.

Foam mat drying is a simple and cost-effective process (Sangamithra et al., 2015). However, challenges such as unstable foam during heating leads to cellular breakdown, impairing drying. Variables like type of product, foaming agent and its concentration, and soluble solids present in the product affect foam formation, density, and stability, impacting the success of drying process. Foam mat drying technology has been successfully adopted to produce pineapple powder (Shaari et al., 2018), mango pulp powder (Rajkumar et al., 2007), starfruit powder (Abd Karim & Wai, 1999), papaya powder (Kandasamy et al., 2012), plum powder (S. A. Sifat et al., 2021), and sour cherry powder (Abbasi & Azizpour, 2016).

With the abundant availability of coconut inflorescence sap and considering the disadvantages from high temperature drying, foam mat drying could be a cost-effective method to produce unfermented inflorescence sap powder that would allow for prolonged storage. Since there are no published literature on foam mat drying of coconut inflorescence sap, this study was conducted to develop an optimized methodology to produce coconut inflorescence sap powder. The objectives of this study are to: i) assess the effect of egg albumin concentration and whipping time on the quality of foam mat dried coconut inflorescence sap powder, ii) to optimize the foam mat drying of coconut inflorescence sap using response surface methodology.

MATERIALS AND METHODS

Raw materials

Fresh inflorescence sap was collected from a local farm in Thondamuthur, Coimbatore, India, and transported to the food processing laboratory, Agricultural Engineering College & Research Institute (AEC&RI), Tamil Nadu Agricultural University (TNAU), Coimbatore, India under refrigerated conditions (4±2°C). Egg albumin powder (HIMEDIA) and maltodextrin (HIMEDIA) used in this study were purchased from Precision Scientific Pvt. Ltd. (Coimbatore, Tamil Nadu, India).

Preparation of foam

A 100 mL coconut inflorescence sap sample was added with different concentrations of egg albumin powder (5%, 10%, 15% w/v) as a foaming agent and maltodextrin (5% w/v concentration) as a stabilizing agent. The mixture was continuously whipped in a blender to produce foam. Whipping duration of 10, 20, and 30 min was evaluated in this study for stable foam formation properties. Foaming characteristics, such as foam expansion and foam density were analysed to understand the effects of foaming, which influence drying characteristics and powder properties.

Analysis of foam properties

The prepared foam from the 100 mL of inflorescence sap sample was gently transferred into a pre-weighed measuring cylinder ensuring that no air voids were trapped into the foam and that the foam structure was not destroyed. The weight and volume were then measured. Foam expansion which represents the percentage increase in the volume of juice, was calculated using the following equation:

$$\text{Foam expansion (\%)} = \frac{V_1 - V_0}{V_0} \qquad (1)$$

where, V_1 is volume after foaming and V_0 is volume before foaming

Foam density was calculated using the equation:

$$\text{Foam density} = \frac{\text{Mass of foam (g)}}{\text{Volume of foam (mL)}} \qquad (2)$$

Drying of coconut inflorescence sap foam

The prepared inflorescence foam was subjected to drying at a temperature of 60 °C with a constant air velocity of 1 ms^{-1}. The foam, with a thickness of 2.5 cm, was evenly spread on the trays. The weight of the dried product was recorded every 30 min using a weighing balance with an accuracy of ±0.001 g. Drying was stopped when the weight of the samples reached constant values. The dried product was then scraped off and packed in polypropylene packs. The entire process steps involved in producing the foam mat dried powder from coconut infloresence sap is presented in Fig.1.

Physicochemical properties of dried coconut inflorescence sap powder

Physical properties: The moisture content of the samples was determined gravimetrically by drying 5 g of sample in hot air oven at 70°C for 4 h and measuring the loss in weight (Horwitz & Latimer, 2000). Bulk density of the dried powders was determined using the procedure described by Yalçın (2007). The bulk density was calculated from the volume of a known weight of the sample (10 g).

Chemical properties: Ascorbic acid content was analysed volumetrically based on the principle that ascorbic acid reduces the blue coloured dye solution (2, 6, Dichlorophenol indophenol) into a colourless compound, and the dye solution becomes pink in acidic medium (Saavedra et al., 2024). Ten mL of sample solution were added to 10 mL of 4% oxalic acid solution and titrated against the dye. The consumption of dye is proportional to the amount of ascorbic acid in the sample. To determine the ascorbic acid content, the reduction in dye solution by a known standard ascorbic acid solution was compared and validated against the sample.

The titratable acidity of the reconstituted powder sample was determined by titrating 10mL of the sample solution with 0.1N NaOH and two drops of phenolphthalein as an indicator until the pink colour persisted for a few seconds. The percentage acidity was calculated following (Horwitz & Latimer, 2000) as anhydrous acetic acid using the equation below:

$$Acidity\ (\%) = \frac{Titre\ value * Normality\ of\ NaOH * milliequivalent\ factor * 100}{Weight\ of\ sample\ (g)} \quad (3)$$

The pH and water activity of the reconstituted powder sample were measured using a digital pH meter (Eutech Instruments, Singapore) and water activity meter (Lab Start – novasina, Lachen, Switzerland).

Reducing sugars were estimated by the Nelson-Somogyi method as described by (Ranganna, 1986). Sugars with free aldehyde and ketone groups reduce Fehling's solution (cupric oxide to cuprous oxide) and are hence called reducing sugars. The sugar present in the sample was extracted using 80% hot methanol. One mL of the extract was placed in the test tube, and diluted to a volume of 2 mL with distilled water. The test tube was then added with 1 mL of alkaline copper tartrate, mixed well and boiled in a water bath. Arsenomolybdate reagent was added to the test tube, and the volume made up to 10 mL. The absorbance was measured at 620 nm using a UV-VIS spectrophotometer. The standard reducing sugar curve was plotted, and the reducing sugar present in 100 g of the sample was measured by linear interpolation.

For determining total phenols, about 1 mL of the sample extract was added to the test tube, and the volume was made up to 3.5 mL with distilled water. The test tube was then added with 0.5 mL of Folin-Ciocalteau reagent (Gonçalves et al., 2010). After mixing well, the test tube was allowed to stand for 5 min. Then, 1 mL of 20% Na_2CO_3 was added to the test tube. After 30 min, absorbance was measured at 660 nm using a UV-VIS spectrophotometer. Catechol was used as the standard. The standard curve was plotted using different concentrations (0.2, 0.4, 0.6, 0.8, 1.0 mg/mL) of catechol, and the phenolic content present in the sample was measured from the graph by linear interpolation.

The protein content was determined using Lowry's method (Lowry et al., 1951). Bovine serum albumin (BSA) was used as the standard reagent. One mL of each sample extract was added to test tubes and 0.4, 0.8, 1.2, 1.6 and 2.0 mL of the working (BSA) standard was added into the series of test tubes, and the volume was adjusted to 2 mL. Subsequently, 5 mL of alkaline copper solution was added to each test tube, thoroughly mixed, and left to stand for 10 min. Then, 0.5 mL of Folin Ciocalteau reagent was added to the solution, mixed thoroughly, and incubated in darkness for 30 min. A blue colour developed and the absorbance was measured at 660 nm using a UV-VIS spectrophotometer. The standard curve was obtained from the working standards, and the protein content present in the sample was determined from the standard curve.

Water solubility index: About 2.5 g of the dried sample was dissolved in 30 mL of distilled water, mixed well for 30 min, and then centrifuged at 10000 rpm for 10 min. The supernatant was then transferred to a petri dish and dried overnight in an oven at 102°C (Alam et al., 2019). The water solubility index was determined by comparing the weight of remaining dry solids to the initial weight of the powder sample taken.

$$Water\ solubility\ index = \frac{Weight\ of\ dried\ solids\ (g)}{Weight\ of\ sample\ (g)} \times 100 \quad (4)$$

Water absorption index: Water absorption index was determined along with the water solubility index, wherein the wet solids remaining in the centrifuge tube were also measured. The water absorption index was calculated by dividing the weight of wet solids by the weight of the initial sample, providing a measure of the powder's capability to absorb water.

$$Water\ absorption\ index = \frac{Weight\ of\ remaining\ wet\ solids\ after\ centrifuge\ (g)}{Weight\ of\ initial\ dry\ powder\ sample\ (g)} \quad (5)$$

Experimental design and optimization

Response surface methodology was employed to establish the optimum conditions of foaming parameters to produce stable foam and retaining nutritional properties. The Design Expert software (Version 13.0.5.0) was used to analyse various response factors and generate response surface plots for optimizing process variables (Asokapandian et al., 2016). Face-centered central composite design (FCCCD) was employed to design experiments for foam mat drying using two factors and three levels. The rotatable CCD design requires experiments at axial points that falls beyond the feasible operating ranges, that could affect foam formation and compromise the reproducibility of the analytical results. Hence, the FCCCD was selected to ensure that all experimental runs remained within the practical limits. The number of experiments (N) required for developing the FCCCD was determined by the following formula:

$$N = k^2 + 2k + n \qquad (6)$$

where, n is the number of center points and k is the number of factors. In this study, a total of 13 experimental runs were conducted, each utilizing different combinations of parameters. Details of the experimental design employed in this study are provided in Table 1.

Table 1 Independent variables and levels of the face-centered central composite design

Factors	Independent variables	Units	Levels		
			-1	0	+1
A	Egg albumin concentration	%	5	10	15
B	Whipping time	min	10	20	30

Note: In the FCCCD, the axial points were positioned at $\alpha = 1$, corresponding to a face-centered configuration.

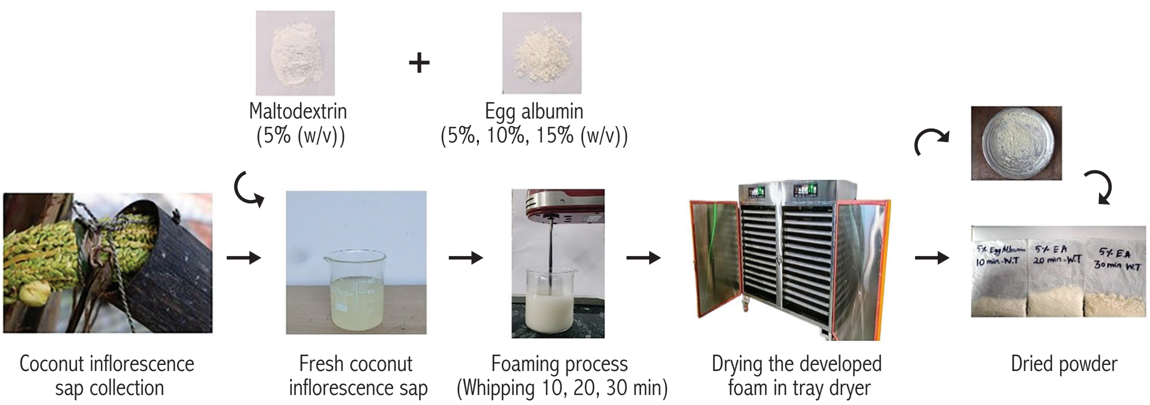


Figure 1 Process flow chart of foam mat drying, from fresh coconut inflorescence sap to the final foam mat dried powder.

RESULTS AND DISCUSSION

The experimental results of foaming trails including the responses of physical properties such as TSS, weight, pH, moisture content, water activity, water solubility index (WSI), water absorption index (WAI), bulk density, and foaming properties of foam density and foam expansion are presented in Table 2.

Foaming properties

Effect of concentration of foaming agent and whipping time on foam properties: The foaming ability of the foaming agent can be accessed through foam density (Shaari et al., 2018). During the foaming process, more air molecules are incorporated into the foam, producing a lighter foam and resulting in a reduction of foam density. In this study, we observed a faster drying rate for the conversion of foamed coconut inflorescence sap into powder. This phenomenon is attributed to the low density of the foam, which provides a large surface area for drying (Asokapandian et al., 2016). Increasing egg albumin concentration induces the transfer of more aqueous phase into the air-liquid interface and produces larger foam volumes, thus reducing foam density (Fig. 2) (Abd Karim & Wai, 1999).

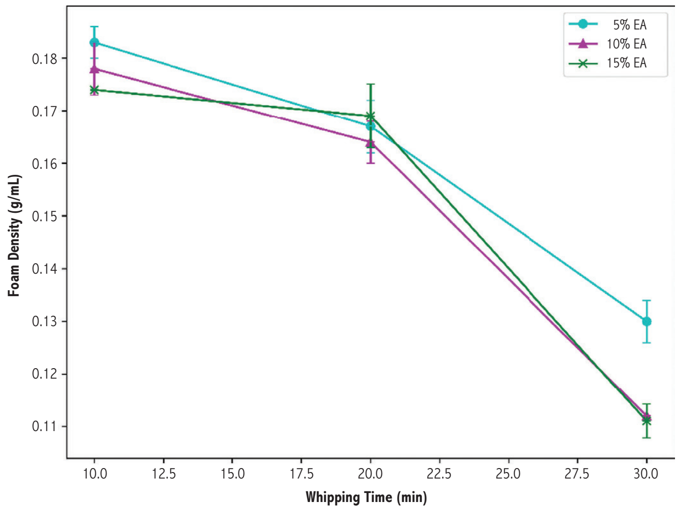


Figure 2 Effect of egg albumin concentration and whipping time on coconut inflorescence sap foam density

From Table 2, it can be observed that the higher the egg albumin concentrations, the lower the foam density at a constant whipping time, as the foaming agent reduces the surface tension and increases the necessary critical thickness required for the interfacial film, thus promoting stable foam formation during phase transfer. This critical thickness is needed to retain air molecules. Abbasi and Azizpour (2016) observed similar trends in foam mat dried sour cherry powder and S. A. Sifat et al. (2021) observed similar trends in foam mat dried plum powder. Additionally, increasing viscosity beyond the critical limit prevents air molecules from getting trapped, resulting in an increase in foam density (Khamjae & Rojanakorn, 2018). A 15% of egg albumin concentration and a whipping time of 30 min resulted in low density (0.11g/cm^3) and high foam expansion (890 ± 20%).

In the case of whipping time, increasing whipping time causes more air molecules to get trapped into the foam, increasing foam volume (Fig. 3). However, excessive whipping destroys the foam structure, so the optimum whipping time is necessary for stable foam. Kandasamy et al. (2012) reported that an increase in foam volume was observed when increasing whipping time upto 15min, and beyond that, increasing whipping time (over-beating) caused significant loss in foam volume due to the breakdown of the foam structure.

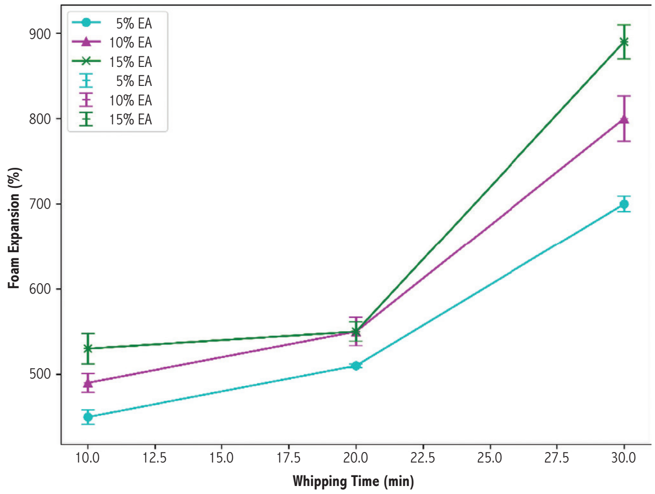


Figure 3 Effect of egg albumin concentration and whipping time on foam expansion

Table 2 Experimental results of face-centered central composite design with observed physical properties of foam mat dried coconut inflorescence sap powder

S. No	Egg albumin (%)	Whipping time (min)	TSS of Foam (Brix)	Weight (g)	pH	Moisture content (%wb)	Water activity, a_w	WSI (%)	WAI	Foam density (g/cm³)	Foam Expansion (%)	Bulk Density (g/cm³)
1	5	10	24	11.0	4.62 ± 0.16	15.80 ±0.22	0.60 ± 0.01	46.8 ± 0.73	1.49 ± 0.04	0.18 ± 0.00	450 ± 9	0.34 ± 0.01
2	5	20	23	13.0	4.47 ± 0.02	14.28 ±0.40	0.58 ± 0.00	56.4 ± 1.08	1.68 ± 0.02	0.16 ± 0.01	510 ± 2	0.28 ± 0.01
3	5	30	24	14.0	4.40 ± 0.02	22.69 ±0.45	0.57 ± 0.02	57.6 ± 0.13	1.45 ± 0.03	0.13 ± 0.01	700 ± 9	0.43 ± 0.01
4	10	10	24	14.5	4.80 ± 0.12	23.45 ±0.38	0.55 ± 0.00	59.5 ± 0.26	1.56 ± 0.01	0.18 ± 0.01	490 ± 11	0.52 ± 0.02
5	10	20	26	22.5	4.95 ± 0.15	22.69 ±0.02	0.50 ± 0.01	60.4 ± 0.98	1.51 ± 0.01	0.16 ± 0.00	550 ± 9	0.39 ± 0.00
6	10	20	26	22.5	4.95 ± 0.03	22.69 ±0.68	0.50 ± 0.00	60.4 ± 1.02	1.51 ± 0.03	0.16 ± 0.00	550 ± 17	0.39 ± 0.00
7	10	20	26	22.5	4.95 ± 0.13	22.69 ±0.07	0.50 ± 0.02	60.4 ± 0.58	1.51 ± 0.05	0.16 ± 0.00	550 ± 17	0.39 ± 0.01
8	10	20	26	22.5	4.95 ± 0.04	22.69 ±0.37	0.50 ± 0.00	60.4 ± 1.69	1.51 ± 0.03	0.16 ± 0.00	550 ± 17	0.39 ± 0.00
9	10	20	26	22.5	4.95 ± 0.13	22.69 ±0.08	0.53 ± 0.01	60.4 ± 2.13	1.51 ± 0.01	0.16 ± 0.00	550 ± 3	0.39 ± 0.01
10	10	30	26	17.0	5.17 ± 0.08	18.24 ±0.58	0.55 ± 0.00	61.2 ± 1.17	1.14 ± 0.01	0.11 ± 0.00	800 ± 27	0.37 ± 0.01
11	15	10	26.2	19.0	4.60 ± 0.10	24.22 ±0.84	0.51 ± 0.02	66.4 ± 1.76	1.23 ± 0.04	0.17 ± 0.00	530 ± 18	0.59 ± 0.02
12	15	20	26.2	23.5	4.50 ± 0.10	21.95 ±0.11	0.51 ± 0.00	68.4 ± 1.16	1.60 ± 0.01	0.17 ± 0.01	550 ± 11	0.51 ± 0.00
13	15	30	26.2	16.0	4.40 ± 0.16	16.27± 0.16	0.56 ± 0.01	67.7 ± 1.61	1.62 ± 0.03	0.11 ± 0.00	890 ± 20	0.42 ± 0.01

*TSS - Total Soluble Solids; WSI - Water Solubility Index; WAI - Water Absorption Index.

Physical properties

Moisture content of powdered inflorescence sap ranged from 14.28±0.40% to 24.22±0.84% (wet basis). Removal of moisture or low moisture present in the product prevents the growth and reproduction of microorganisms responsible for decay and mitigates moisture mediated deterioration (Afolabi, 2014). The lowest moisture content was observed in the powder produced with a 5% concentration of egg albumin (EA) and a whipping time of 20 min, while the highest moisture content was observed in powders prepared with 15% EA and 10 min whipping time. It was observed that as the concentration of egg albumin and whipping time increased, there was a corresponding rise in moisture content, and this increase was found to be statistically significant ($p<0.05$). Dehghannya et al. (2019) reported a similar observation in foam mat drying of lime, where increasing egg albumin concentration from 2% to 4% resulted in a significant increase in moisture content.

The water activity of dried coconut inflorescence sap powder ranged from 0.51±0.02 to 0.60±0.01. These values are favourable for microbial stability, as no microbial proliferation occurs below a water activity value of 0.61 (Tapia et al., 2020). As the concentration of egg albumin and whipping time increase, resulting in higher foam expansion that accelerates the drying rate, the increase in drying rate significantly reduces the water activity of the product ($p<0.05$). Similar observations were reported by Azizpour et al. (2016), where an increase in temperature significantly reduced the water activity of dried shrimp powder. Conversely, protein denaturation leads to the unfolding of proteins, decreasing their ability to retain water and consequently lowering the water activity of the powder (Watharkar et al., 2021). The reported water activity values are comparable to those of foam mat dried banana powder (Watharkar et al., 2021) and blue berry powder (Darniadi et al., 2018), which fall within the range of 0.30 to 0.40.

Bulk density serves as a characterization measure for the obtained product by the processes such as drying and grinding. It is influenced by various parameters including moisture content, particle size, particle shape, and drying conditions (Walton & Mumford, 1999). In this study, bulk density of inflorescence sap powder ranged from 0.29±0.01 to 0.59±0.02 g/cm3. These values are similar to those found in foam mat dried muskmelon (Asokapandian et al., 2016), blue berry (Darniadi et al., 2018), and lime (Dehghannya et al., 2019). Bulk density is significantly influenced ($p<0.05$) by EA concentration and whipping time. As EA concentration and whipping time increase, bulk density rises, which can be attributed to the high molecular weight of the protein in egg albumin. However, over-whipping can lead to the formation of fragile structures that collapse during drying, resulting in more porous particles with lower bulk density. A similar increase in bulk density with egg albumin concentration was noted in foam mat drying of pineapple juice by Shaari et al. (2018). However, at an EA concentration of 15% and whipping times of 20 min and 30 min, bulk density values reduced. This reduction may be due to the denaturation of proteins during the whipping process, producing hydrophobic groups that lower the particle binding capacity.

Chemical properties

The experimental design, including the observed responses of the chemical properties such as ascorbic acid, titratable acidity, reducing sugar, phenolic content, and protein is presented in Table 3. The statistical parameters, including F-Values, P-Values, and the significance of each variable on foam mat drying of coconut inflorescence sap on dependent parameters, are given in Table 4.Ascorbic acid stability can be influenced by various factors, including temperature, pH, exposure to sunlight, and the presence of metals such as copper and iron (Singh & Sharma, 2017). Ascorbic acid gets oxidized quickly and is also affected by storage time (Pavlovska et al., 2015). Monica et al. (2021) reported that each process at elevated temperature causes a reduction in ascorbic acid content compared to the fresh product, as ascorbic acid is heat liable in nature. The ascorbic acid value ranged from 0.75±0.02 to 2.85±0.01 mg/100mL. Egg albumin concentration significantly ($p<0.05$) affected ascorbic acid retention. The protein contributes to foam formation, which increases oxygen exposure during drying and also facilitates a faster heating rate. The faster heating rate reduces the drying time, while the increased surface area during foam formation promotes oxidative degradation of ascorbic acid. Whipping did not significantly affect the ascorbic acid retention ($p=0.0643$), as it mainly relates to the duration of the foaming process and does not involve chemical interactions.

The interaction between egg albumin concentration and whipping time was not significant, indicating that their combined effect does not cause greater changes in ascorbic acid content than their individual effects. This may be because ascorbic acid degradation is primarily driven by oxygen exposure and heat sensitivity rather than the duration of whipping, so the interaction of these factors has little additional impact.

The quadratic terms (A^2 and B^2) also did not significantly influence the ascorbic acid content. The lack of fit is non-significant ($p>0.05$) implying that the model is adequate. Similar reductions in ascorbic acid content were observed during foam mat drying of tomato pulp (Qadri & Srivastava, 2014), mandarin powder (Kadam et al., 2011), guava pulp powder (Qadri & Srivastava, 2017), and papaya powder (Kandasamy et al., 2012). Ascorbic acid content should be retained at higher levels in the powder to preserve its nutritional quality and antioxidant properties (Yin et al., 2022). A quadratic polynomial model was selected for ascorbic acid as a function of egg albumin concentration (A) and whipping time (B). The corresponding regression equation is:

$$\text{Ascorbic acid (mg/100mL)} = 1.044 - 0.528 \times A - 0.423 \times B - 0.040 \times AB + 0.609 \times A^2 + 0.294 \times B^2 \quad (7)$$

where A is EA concentration and B is whipping time.

Titratable acidity of fresh coconut inflorescence sap sample was 0.02%, and upon storage, it increased to 0.28%. This increase in acidity is due to the action of bacteria and yeast upon sugars present in inflorescence sap during the fermentation process, with acetic acid being the predominant acid (Pandiselvam et al., 2021). In the foam mat dried inflorescence sap from this study, the titratable acidity value ranged from 0.205±0.01 to 0.380±0.01%. The statistical data indicated that EA concentration significantly influenced ($p<0.05$) the titratable acidity of the foam mat dried powder. An increase in EA concentration increased acidity, likely due to the acidity of egg albumin itself. Whereas, whipping time exhibited a marginal but non-significant effect ($p=0.06$) on acidity, the interaction term (AB) and the quadratic terms (A^2 and B^2) were not statistically significant ($p>0.05$). This indicates that acidity did not exhibit curvature in the studied range. Whipping time does not cause major physical or chemical changes that influence acidity, hence the variation remains small. The lack of fit was not significant ($p>0.05$), so the model is considered adequate for acidity. Kandasamy et al. (2012) observed a slight increase in acidity in foam mat dried papaya powder, which was not considered significant ($p>0.05$). In contrast, an increase in egg albumin concentration significantly reduced the acidity of foam mat dried plum powder, and whipping time also had a diminishing effect on acidity (S. A. Sifat et al., 2021). Abbasi and Azizpour (2016) observed that increasing the drying temperature resulted in an increase in acidity, suggesting that this phenomenon might be attributed to the conversion of sugars in sour cherry juice into organic acids. A linear model was selected for the titratable acidity as a function of egg albumin concentration (A) and whipping time (B), and the corresponding regression equation is:

$$\text{Titratable acidity (\%)} = 0.304 + 0.055 \times A + 0.024 \times B \quad (8)$$

where, A is EA concentration and B is whipping time.

The pH value for reconstituted powder ranged from 4.62±0.16 to 5.17±0.08, as shown in Fig. 4. Increasing EA concentration increases the pH value, attributed to the higher pH of egg white. The highest pH was recorded at a concentration of 10% egg albumin with a whipping time of 30 min. Similar results were obtained by Abbasi and Azizpour (2016) in foam mat drying process of sour cherry, where increasing the egg albumin concentration from 1%, 2% to 3% caused an increase in the pH value up to 11%. Another study conducted on foam mat drying of banana by Falade and Okocha (2012) reported that increasing the concentration of glyceryl monostearate (GMS) led to rise in the pH of the dried banana powder. Increasing whipping time also increases the pH of the dried powder. However, when 15% concentration of egg albumin and a whipping time of 30 min were utilized, a slight decline in pH value was observed. This may be due to the denaturation that occurs during excessive whipping, which diminishes the egg white's ability to elevate the pH of the dried powder. Most microorganisms prefer to grow at neutral pH, hence these low pH characteristics are significant for product safety.

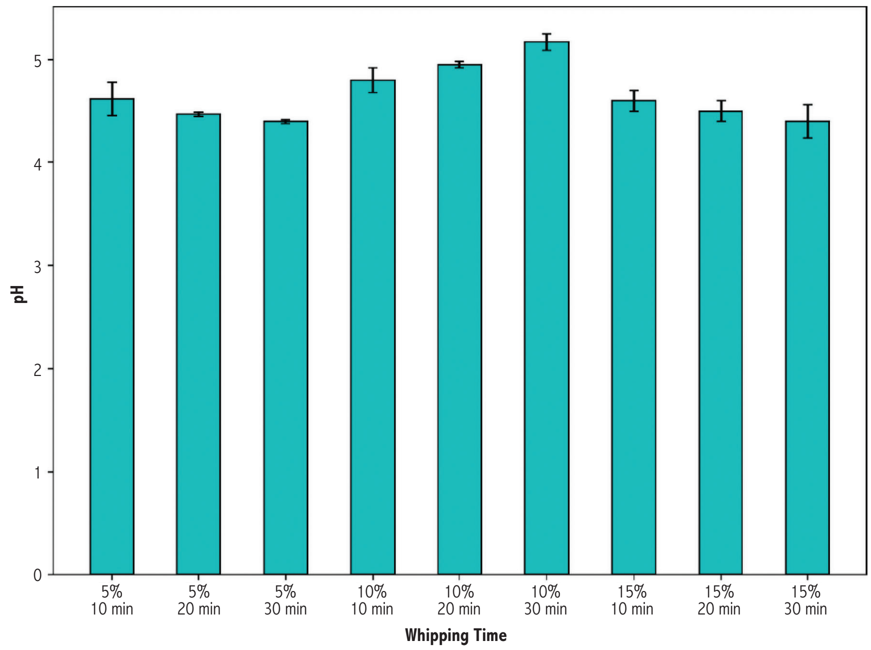


Figure 4 pH of the foam mat dried coconut inflorescence sap powder samples

The reducing sugar content of foam mat dried powder ranged from 5.5±0.06 to 22.6±0.52%. As the EA concentration increases, the reducing sugar content decreases significantly ($p<0.05$). This may be due to higher foam expansion produced by high foaming agent concentration, causing more surface area available for drying and significant loss in reducing sugar contents, as the reducing sugar gets converted during high temperature exposure. Whipping time did not significantly affect reducing sugar content ($p>0.05$), as whipping primarily contributes to foam formation and does not induce chemical changes that alter sugar content. However, the interaction between whipping time and egg albumin concentration (AB) significantly influenced reducing sugar content, indicating that their combined effect plays a role in modifying the response. The quadratic term of egg albumin concentration (A^2) was also significant, whereas the quadratic term of whipping time (B^2) was not, showing that only egg albumin concentration had a nonlinear effect on reducing sugar content. de Brito et al. (2001) observed a decrease in reducing sugar during the drying and roasting of cocoa, which occurred due to the Maillard reaction. A quadratic polynomial model was selected for reducing sugars, as a function of egg albumin concentration (A) and whipping time (B), and the corresponding regression equation is:

$$\text{Reducing sugars (\%)} = 7.56 - 4.92 \times A - 0.4 \times B - 2.6 \times AB + 6.73 \times A^2 - 1.21 \times B^2 \quad (9)$$

where, A is EA concentration and B is whipping time.

Polyphenolics are compounds of plant secondary metabolism with diverse biological functions, making them a large group of bioactive compounds. During drying, an increase in temperature results in the degradation of phenolic content as phenolics are heat-sensitive (Che Sulaiman et al., 2017). In this study, a slight increase in phenolic content was observed with increasing EA concentration and whipping time (Table 2). However, the changes observed during the increase in EA concentration and whipping time were not particularly noticeable; therefore, the alterations in polyphenolic content were not statistically significant ($p>0.05$). Similar observations in the foam mat drying of plum were reported by S. A. Sifat et al. (2021). In contrast, Shaari et al. (2018) found that an increase in EA concentration significantly influenced the phenolic content of foam mat dried pineapple powder, as the increase in foaming agent concentration produced a larger surface area resulting in shorter drying time and thus retaining the heat sensitive properties.

However, in our study, the interaction term (AB) showed a marginally significant effect (p=0.0558), suggesting that phenolic content was influenced by the combined action rather than by each factor independently. Both quadratic terms (A^2 and B^2) were non-significant, indicating the absence of curvature in the response. The model explained a relatively lower portion of response variability (R^2 = 0.3670). The non-significant lack of fit indicates that the model is adequate. Hence, the lower R^2 values may be due to biological variability. The lowest protein content was observed for samples dried with 5% EA concentration and 30 min of whipping time (Table 2). The changes in protein content with an increase or decrease in EA concentration were statistically significant (p<0.05). The protein present in the egg albumin contributes to the protein content of the foam mat dried powder. Franco et al. (2016) suggested that the increase in protein content in foam mat dried yakon juice powder may be due to the protein content present in the foaming agent egg albumin, which is not native to the fresh yakon juice. Whereas, the whipping time does not significantly (p>0.05) affect the protein content. Whipping causes aggregation and crosslinking of protein which may cause the reduced extractability of protein. Also, reduced protein content with higher whipping time indicates that protein denaturation occurred during the increased whipping time. The interaction effect of both egg albumin concentration and whipping time is not significant, as the whipping does not contribute to the protein content and the egg albumin increases the protein, their combined interaction does not give significant effect. The quadratic terms (A^2 and B^2) were also not significant for protein. The lack of fit is non-significant (p>0.05) indicating that the model adequately fits the data. A quadratic model was selected for the protein as a function of egg albumin concentration (A) and whipping time (B), and the corresponding regression equation is:

$$\text{Protein (mg/100 ml)} = 12.95 + 15.3 \times A - 3.03 \times B - 0.8 \times AB + 13.25 \times A^2 + 9.15 \times B^2 \quad (10)$$

where A is EA concentration and B is whipping time.

Table 3 Experimental results of face-centered central composite design with observed biochemical properties of foam mat dried coconut inflorescence sap powder

S. No	Egg albumin (%)	Whipping time (min)	Acidity (%)	Phenolic content (CE/g)	Ascorbic acid (mg/100mL)	Reducing sugars (%)	Protein (mg/100mL)
1	5	10	0.205 ± 0.006	2.3 ± 0.05	2.38 ± 0.07	13.2 ± 0.38	21.9 ± 0.39
2	5	20	0.273 ± 0.004	2.5 ± 0.01	2.85 ± 0.01	22.6 ± 0.52	21.0 ± 0.15
3	5	30	0.285 ± 0.004	2.8 ± 0.09	1.90 ± 0.04	19.4 ± 0.2	8.0 ± 0.30
4	10	10	0.285 ± 0.007	2.7 ± 0.09	2.38 ± 0.05	7.0 ± 0.19	15.1 ± 0.13
5	10	20	0.301 ± 0.009	2.3 ± 0.02	0.83 ± 0.03	6.8 ± 0.09	17.0 ± 0.26
6	10	20	0.301 ± 0.009	2.3 ± 0.02	0.79 ± 0.00	7.2 ± 0.22	8.0 ± 0.31
7	10	20	0.302 ± 0.010	2.3 ± 0.01	0.75 ± 0.02	8.5 ± 0.08	11.0 ± 0.36
8	10	20	0.302 ± 0.003	2.3 ± 0.01	0.76 ± 0.01	5.5 ± 0.06	9.0 ± 0.11
9	10	20	0.331 ± 0.008	2.6 ± 0.03	1.43 ± 0.00	7.9 ± 0.25	21.0 ± 0.02
10	10	30	0.307 ± 0.004	2.3 ± 0.01	0.95 ± 0.02	7.6 ± 0.23	27.9 ± 0.37
11	15	10	0.341 ± 0.009	2.5 ± 0.09	1.74 ± 0.01	11.1 ± 0.08	64.9 ± 1.62
12	15	20	0.371 ± 0.006	2.7 ± 0.04	1.11 ± 0.03	7.9 ± 0.24	30.2 ± 1.02
13	15	30	0.380 ± 0.012	2.2 ± 0.07	1.11 ± 0.01	6.7 ± 0.09	47.8 ± 1.30

Quality characteristics

Water Solubility Index (WSI): Solubility is affected by many parameters such as raw material compositions, feed rate, drying air flow rate, and carrier agents (Jafari et al., 2017). During rehydration, good quality powder should quickly absorb water, sink instead of float, and spread evenly without swelling (Asokapandian et al., 2016). The WSI of foam mat dried coconut inflorescence sap powder ranged from 46.8% to 66.4%. The lower solubility values were obtained for the thicker foams with high density, while higher WSI values were observed for the lighter foams due to greater porosity and smaller particle fragments that enhance dissolution. A higher WSI value indicates that the powder has good solubility characteristics, making it suitable for incorporation into a variety of food products such as bakery and confectionery items, as well as liquid and semi-liquid products. The WSI values of coconut inflorescence sap powder samples were close to the values obtained for foam mat dried lime juice, which ranged from 66.8 to 69.2% (Fig. 5) (Dehghannya et al., 2019) and foam mat dried ripe banana pulp, where the value ranged from 57.1% to 62.1% (Watharkar et al., 2021). The highest foam expansion allows for faster drying and produces more porous, less sticky and less moisture content as well as smaller powder particles with a higher surface area. This enables more water molecules to penetrate into the powder, resulting in increased solubility (Shaari et al., 2018).

Water Absorption Index (WAI): The WAI reflects a food substance's capacity to absorb water, and is closely tied to its rehydration capability (S. A. Sifat et al., 2021).WAI plays a crucial role in food applications like desserts and bakery items. For instance, increased WAI levels can aid in maintaining moisture within the products, thus enhancing their handling qualities and preventing dehydration during storage (Shaari et al., 2018). For inflorescence sap powder, WAI ranged from 1.15±0.01 to 1.68±0.02, as shown in Fig. 6. These were close to the WAI value obtained by foam mat dried plum powder, where the value ranged from 1.424 to 2.763 (S. A. Sifat et al., 2021) and foam mat dried lime juice, where the value ranged from 1.410 to 1.616 (Dehghannya et al., 2019). Higher concentrations of egg albumin and longer whipping times result in an increase in WAI. Nevertheless, there was no statistically significant difference observed in the WAI values (p>0.1). The slight reduction in the absorption index was due to an increase in whipping time, which is caused by the denaturation of EA protein. During this process, hydrophobic groups move towards the protein's surface, leading to a decrease in hydrogen bonding. Extensive denaturation triggers the aggregation and coagulation of the protein molecules, ultimately reducing water absorption due to diminished protein surface area available for contact with water (Dehghannya et al., 2019)

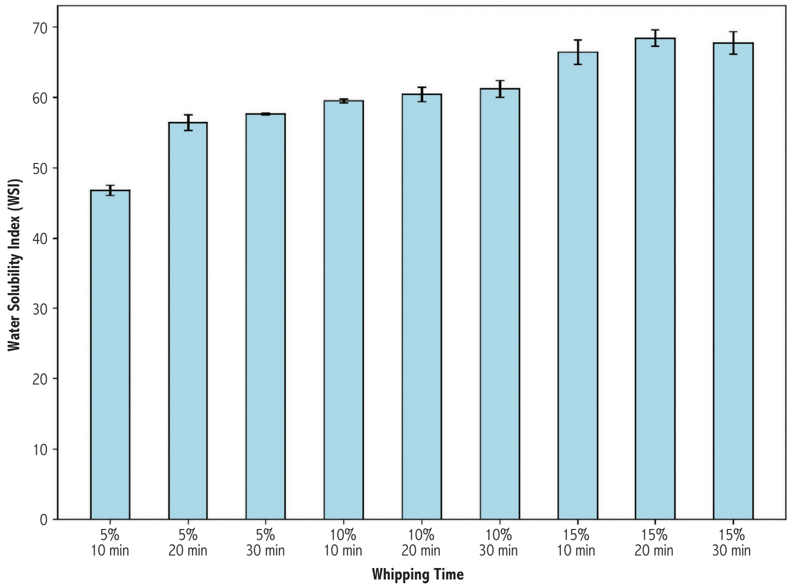


Figure 5 Water solubility index of the foam mat dried coconut inflorescence sap powders

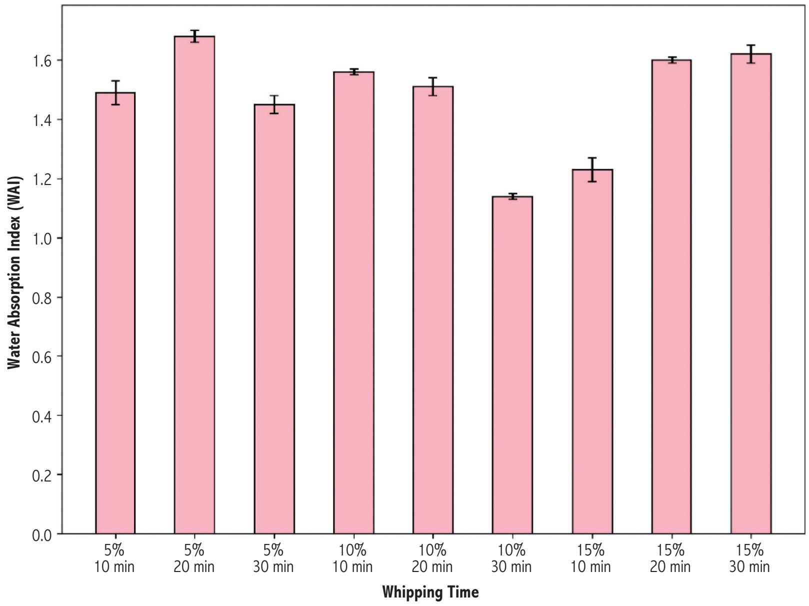


Figure 6 Water absorption index of the foam mat dried coconut inflorescence sap powders

Table 4 F-values, P-values, and significance of each variable on foam mat drying of coconut inflorescence sap on dependent parameters

Parameters	Ascorbic acid		Acidity		Reducing sugars		Phenolic content		Protein	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
A-Egg albumin Conc. (%)	7.49	0.0290	74.27	0.0001	35.86	0.0005	0.20	0.6648	13.35	0.0081
B-Whipping time (min)	4.81	0.0643	13.59	0.0042	0.23	0.6410	0.20	0.6648	0.52	0.4932
AB	0.02	0.8718	-	-	6.94	0.0337	4.82	0.0558	0.02	0.8807
A^2	4.60	0.0692	-	-	30.95	0.0008	-	-	4.59	0.0695
B^2	1.08	0.3339	-	-	1.01	0.3480	-	-	2.19	0.1828
Lack of fit	4.84	0.0810	1.64	0.3299	5.89	0.0598	2.52	0.1955	6.57	0.0503
R^2	0.7496		0.8978		0.9151		0.3670		0.7788	
Adj. R^2	0.5707		0.8774		0.8544		0.1560		0.6208	

Optimization

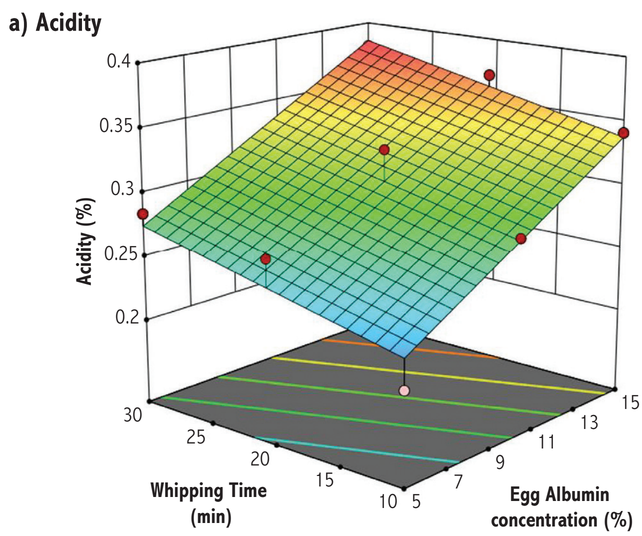
Model evaluation: The effect of various combinations of EA concentration and whipping time was statistically optimized through face-centered central composite design using response surface methodology to determine the optimal combination that maximizes the retention of nutrient contents such as ascorbic acid, reducing sugars, proteins, and phenolic content (Fig. 7). The model performance for all responses has been evaluated using adjusted R^2, predicted R^2, and lack of fit analysis, but these steps did not substantially increase the R^2 values. Acidity (R^2 = 0.898), reducing sugars (R^2 = 0.915), and protein (R^2 = 0.779) showed strong to acceptable fits, whereas ascorbic acid (R^2 = 0.750) and phenolic content (R^2 = 0.367) had lower R^2 values. Lack of fit was ($p>0.05$) non-significant indicating the models are statistically adequate. The lower R^2 values reflect the natural biological variability and the other factors not captured in the model such as raw material composition and subtle processing variations. The results are interpreted with caution, focusing on process optimization rather than precise prediction of the variables.

Optimization of Process Parameters: The numerical optimization provided a desirability function of 0.78. The goals selected for the optimization of dried powder parameters were maximum reducing sugars and ascorbic acid, maintaining total phenols and proteins within a certain range, and minimizing acidity. The optimization goals have been selected based on the desirable nutritional and quality characteristics of the foam mat dried coconut inflorescence sap. Reducing sugars were maximized to enhance the natural sweetness and palatability, as well as to retain the carbohydrate profile. Ascorbic acid was also maximized due to its nutritional importance and antioxidant role, since its retention means less degradation during drying. And protein and phenolic content were maintained within a target range, to preserve antioxidant activity, and foaming functionality and to prevent excessive levels that could negatively impact sensory quality or drying behavior. Acidity was minimized to prevent sourness, improve taste, and enhance product stability. Similar optimization goals have been reported in drying studies of fruit juices, where nutritional retention and sensory acceptability are the key quality determinants (Hossain et al., 2024; Samyor et al., 2020; S. A. D. Sifat et al., 2021). The optimum foaming conditions were determined with these goals in mind.

The optimized data and results are shown in Table 5. The combined optimized foaming parameters were selected as 5% EA concentration and 10 min whipping time. The response values at optimized conditions were ascorbic acid 2.38±0.05 mg/100mL, acidity 0.20±0.006%, reducing sugar 13.2±0.38%, phenolic content 2.3±0.05 CE/g, and protein 21.9±0.39 mg/100mL. The model better fits the experimental data, as the predicted results closely align with the experimentally obtained results.

Table 5 Optimized combination and desirability analysis

Parameters	Egg albumin conc. (%)	Whipping time (min)	Ascorbic acid (mg/100mL)	Acidity (%)	Reducing sugars (%)	Phenolic content (CE/g)	Protein (mg/100mL)
Predicted results	5	10	2.86	0.228	14.9	2.31	22.24
Experimental results	5	10	2.38	0.204	13.2	2.30	21.90



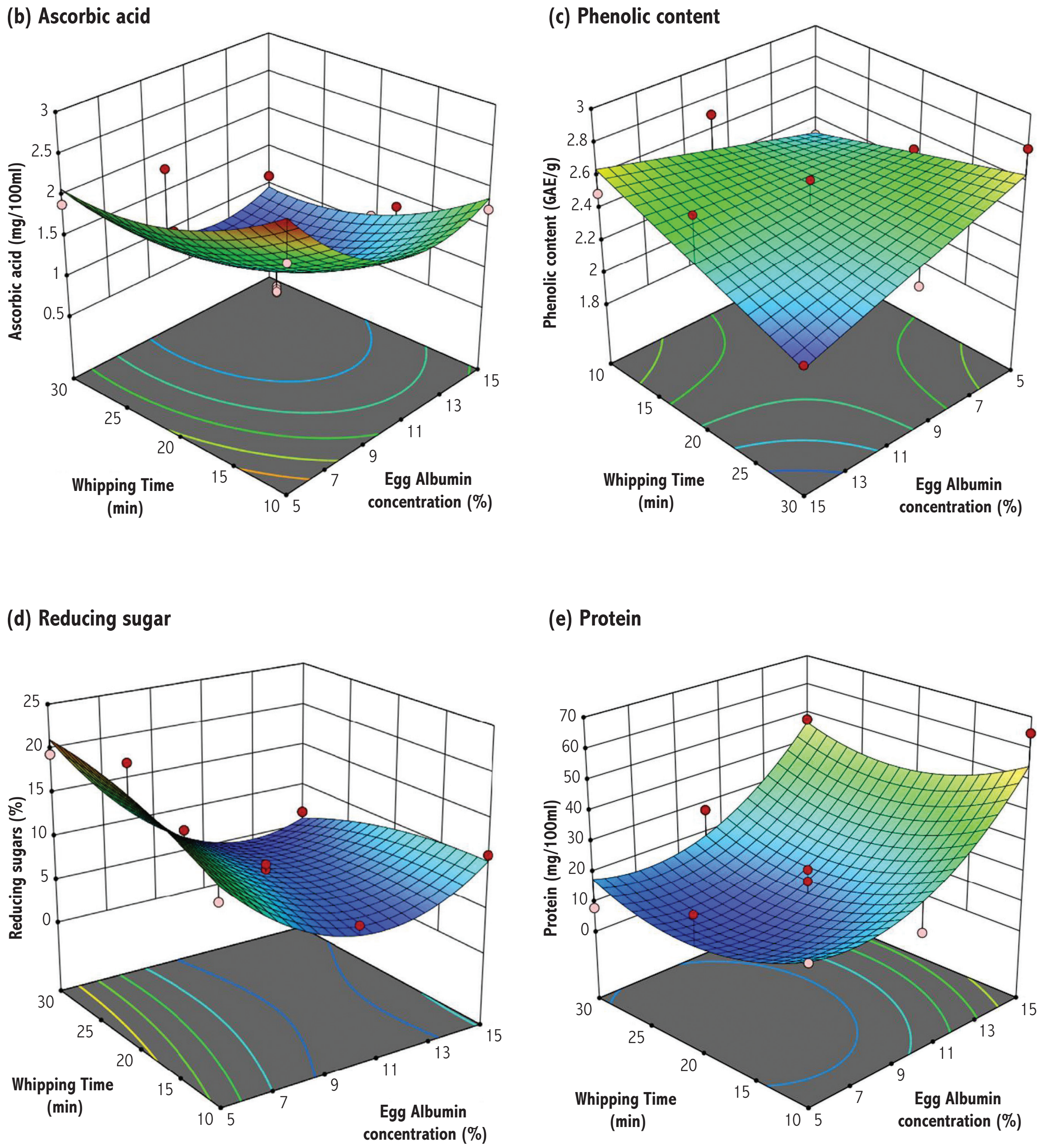


Figure 7 Response surface plot showing the combined effect of egg albumin concentration and whipping time on (a) acidity, (b) ascorbic acid, (c) phenolic content, (d) reducing sugar, (e) protein of foam mat dried coconut inflorescence sap powders

CONCLUSIONS

In this study, coconut inflorescence sap powder was produced using foam mat drying method. The influence of foaming agent concentration and whipping time was investigated, and they have shown a significant effect on foaming properties and biochemical contents of produced inflorescence sap powder. The response surface methodology

(RSM) was effectively employed to optimize the foaming conditions of coconut inflorescence sap. The face-centered central composite design of RSM proved to be efficient in determining the optimum process conditions within experimental region. It was observed that 5% EA concentration and 10 min of whipping time were the most effective treatment combination, which produces stable foam that facilitates quick drying process and retains the nutritional quality parameters. It was concluded that coconut inflorescence sap can be made into powder form with all its nutrient contents retained by foam mat drying method using egg albumin as an effective foaming agent. Further the large-scale production of coconut inflorescence sap powder using foam mat drying technology and assessment of its storage life can be explored.

Credit authorship contribution statement

- **Gopalakrishnan Kishore Kumar:** Methodology, Software, Validation, Writing - original draft, Visualization, Data curation.
- **Sanuujabertini J:** Methodology, Formal analysis.
- **Balasnehitha Shridar:** Methodology, Validation
- **Madhushree M.N:** Formal analysis, Resources.
- **Aswathy T:** Investigation, Methodology.
- **Kingsly Ambrose R.P:** Conceptualization, Resources, Supervision, Writing-review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

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