

Original Research Paper

Development of foam mat dried banana powder using different foaming agents

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ABSTRACT

Overripe banana (*Musa x paradisiaca* L.) is a rich source of sugar which can be used as a natural sweetening agent in foods. The market value for overripe bananas is significantly lower due to flavour defects, brown spots and extremely soft texture. Keeping its high perishability, sugar and mucilaginous texture in view, foam mat drying was standardized by comparing the performance of four different foaming agents *i.e.* egg albumin, casein, soy, and whey protein isolates. Based on their foam stability, expansion, and density; egg albumin was found the best. The impact of the addition of various levels (5 to 12.5%) of four foaming agents was further evaluated on multiple parameters. The water solubility index consistently declined with increased addition levels for all agents and the highest was observed with egg albumin however, the water absorption index showed an increasing trend with experimental conditions. Colour analysis demonstrated an increase in the brightness of foam mat dried powder with increasing levels of addition of foaming agents. Foam characteristics and foam mat dried powder (with various foaming agents) quality characteristics including viscosity demonstrated similar effectiveness at 7.5 and 12.5% (w/w) addition level of egg albumin, therefore, 7.5% level of foaming agent was optimized for powder preparation that enhanced moisture removal by 1.6 folds compared to control while drying. The developed foam mat over ripe banana powder can be used as a naturally sweet ingredient in different food matrices and enhancing taste and nutritional value while addressing waste concerns associated with overripe bananas.

Keywords: Banana, Carr index, foaming agents, foam mat, solubility index

INTRODUCTION

Banana (*Musa x paradisiaca* L.) is a leading fruit crop in India, both in terms of production and cultivation area. Banana has a short lifespan from harvest till the onset of deterioration (~12-14 days) due to its climacteric nature, high respiration, and ethylene production rate. Postharvest losses of banana in India have reached as high as 50% in recent years mainly due to the sensory and handling challenges at the over-ripe stage (Al-Dairi et al., 2023). Overripe banana is an excellent source of vitamins, minerals, dietary fiber, and natural sweeteners (Kumar et al., 2022). Its sugar content is mainly composed of sucrose, fructose and glucose that increases tenfold from 1.26% unripe stage to 12.28% overripe stage (Ng et al., 2020). But their market value is significantly low due to flavor defects, brown spots as well as extremely soft texture. Therefore, utilization of overripe bananas are still challenging, and very little efforts have been put into utilizing its functionality in food applications (Fatemeh et al., 2012). Despite the nutritional potential of overripe bananas, their utilization in food

applications is limited due to high moisture content, dense structure, and rapid microbial deterioration. Various factors such as dense physical structure and high sugar content of banana, restrict moisture mobilization during drying of banana, making its efficient drying a challenging task. Sankat et al. (1996) reported that long drying times are therefore required for banana slices and considerable browning and darkening occur during the process rendering the dried product unpalatable. Some studies have explored foam-mat drying as a viable technique to overcome these limitations, particularly for developing shelf-stable, functional ingredients (Thuy et al., 2022; Farid et al., 2023). One approach for enhancing the drying rate of banana can be to modify its physical structure and make it more porous to facilitate effective internal moisture movement within the pulp. Foaming of the ripe fruit prior to drying may be one such strategy. Foam-mat drying is a process in which liquid or semi solid foods are whipped into stable foams and then air-dried (Thippeswamy et al., 2021). The foam mat drying method is compatible with heat sensitive, viscous and high-sugar foods that cannot be dried



using other drying methods. In this process, liquid or semi solid mass is transformed into a stable foam by whipping after the addition of an edible foaming agent. The stable foam is then dried by circulating hot air exposure (Raharitsifa et al., 2006; Hardy & Jideani, 2020).

In this study, different foaming agents (egg albumin, casein, soy and whey protein isolates) were evaluated for optimizing foam mat drying of overripe banana. The developed overripe banana powder may be used as an ingredient in processed products such as extrudates, nutri bars, infant formulations, and energy drinks as a natural sweetener due to its high sugar content. Undoubtedly, the utilization of overripe bananas will help in diversifying food uses and also deal with the reduction of food waste. Foam-mat drying of overripe bananas offers a sustainable approach to reduce postharvest losses, which could reach maximum up to 50% in India (Al-Dairi et al., 2023). By converting waste into value-added products, this technique minimizes the environmental burden associated with food waste disposal and provides economic opportunities through the development of functional food ingredients, such as natural sweeteners for processed foods. To the best of our knowledge, its a first attempt for the conversion of overripe banana into powder through foam mat drying.

MATERIALS AND METHODS

Materials

The Grand Nain variety of banana was procured from the local market in New Delhi, India and allowed to naturally ripen until they were overripe, with a firmness score of 6.5 N and a total soluble solids level of 25 °Brix achieved. The pulp was then manually separated from the fruit. Subsequently, the entire pulp was blended into a slurry (Sujata Dynamix DX 900-watt mixer grinder) for drying studies.

Foam mat drying of over ripe banana

Four foaming agents namely soy protein, egg albumin, whey protein and casein were used at constant level (10%, w/w) in the banana slurry to compare their foaming ability in terms of foam stability, foam expansion and foam density to know the best foaming agent. At second level of study different concentrations (5, 7.5, 10 and 12.5% w/w each) of above-mentioned foaming agents were used to develop the foam mat banana slurry. The concentration range of 5–12.5% (w/w) for foaming agents was chosen based on preliminary trials and available literature

(Khodifad & Kumar, 2020; Farid et al., 2023). Lower concentrations (<5%) resulted in insufficient foam formation, while higher levels (>12.5%) increased viscosity, impeding whipping efficiency and drying uniformity. The foamed material was evenly spread to a thickness of 3 mm on trays in the cabinet dryer and then dried at a temperature of 60°C until reaching a moisture content of approximately 3.5%. The foam mat dried samples (powdered through a grinder) were stored in zip lock pouches until further analysis for the physico-functional characteristics. Composition analysis (moisture, fat, protein, ash, dietary fibers and carbohydrates) was done as per the standard methodologies reported by Ranganna (2007).

Protein foam characteristics

Foam density, stability and expansion were calculated by the methods given by (Thuwapanichayanan et al., 2008). The foam density was calculated by dividing the mass of the foam by the volume of banana slurry using the following expression:

$$FD \left(\frac{g}{cm^3} \right) = \frac{\text{Mass of foam}}{\text{Initial volume of pulp}}$$

Foam expansion was determined by the foam sample's volume measured before and after expansion using following expression:

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

where,

V_f = Final volume of foamed pulp (cm³)

V_i = Initial volume of pulp (cm³)

The foam volume reduction after 30 min interval of foam development was measured as an index for the foam stability (Thuwapanichayanan et al., 2008).

$$FSt(\%) = \frac{V_t}{V_i} \times 100$$

Where,

V_t = Foam volume at 30 min time interval (cm³)

V_i = Initial volume of pulp (cm³)

Water solubility index (WSI) and water absorption index (WAI)

A 2.5 g milled sample (180–250 µm size) was dispersed in 25 g of distilled water, using a glass rod to manually dissolve the lumps. The dispersion was

stirred for 30 min using a magnetic stirrer, the dispersions were rinsed into tarred 50 mL centrifuge tubes, made up to constant volume and centrifuged at $3000\times g$ for 10 min. The supernatant was decanted for determination of its dissolved solids content, and the sediment was weighed for determination of WSI and WAI according to the below equations (Igual et al., 2021).

$$\text{WAI} = \frac{\text{weight of sediment}}{\text{weight of dry solids}}$$

$$\text{WSI (\%)} = \frac{\text{weight of dissolved solids in supernatant}}{\text{weight of dry solids}} \times 100$$

Colour

Colour of samples was measured after image acquisition and segmentation, under a controlled light source, RGB values of various pixels were quantified. Each colour coordinate may vary from 0 to 255. The RGB values were converted into Hunter's L (lightness), a (redness/greenness) and b (yellowness/blueness) coordinates using online software available at <http://www.rapidtables.com/web/color/colortester.htm>.

Carr index (CI)

Carr index (CI) was determined as the ratio of the difference of the tapped and the bulk densities to the tapped density (Nishad et al., 2017).

$$\text{CI} = \left(\frac{\rho_{\text{tap}} - \rho_{\text{b}}}{\rho_{\text{tap}}} \right) \times 100$$

Where, ρ_{tap} is tapped density, ρ_{b} is bulk density

Hausner ratio (HR)

Hausner Ratio (HR) was also used to characterize the flowability of the powder, which can be determined by the ratio of the tapped density to that of bulk density (Nishad et al., 2017).

$$\text{HR} = \frac{\rho_{\text{tap}}}{\rho_{\text{b}}}$$

Where ρ_{tap} is tapped density, ρ_{b} is bulk density

Viscosity

The apparent viscosity of samples was quantified using a steady-state, stress-controlled rheometer equipped with a Peltier temperature controlling system and set with a parallel plate geometry

(1.5-in. plate diameter, 500 μm gap). The samples were reconstituted (20%, w/w) in deionized water and homogenized at 10,000 rpm for 2 min with a high-speed mixer (MCR 52, Anton paar, Austria) and stored overnight at 4°C to ensure uniform hydration. The sample was loaded onto the rheometer at 25°C. All measurements were performed within the identified linear viscoelastic region (1% strain). Analysis was done in triplicate for all the samples (Arora et al., 2021).

Drying kinetics

The sample was weighed at 30-minute intervals during the drying process, and the weight loss over time was recorded (Ketelaars et al., 1995). The amount of moisture loss versus time was plotted and the slope was calculated as rate of drying. For drying kinetics, the control sample was prepared by converting overripe Grand Nain banana pulp into a slurry without any foaming agents, ensuring identical initial moisture content (~80%) and total soluble solids (25 °Brix) as the foamed samples. The slurry was spread to a 3 mm thickness on trays and dried at 60°C in a cabinet dryer, with weight loss recorded at 30-minute interval to calculate moisture loss and drying rate.

Statistical methods

For screening of foaming agent and its level, experiment was planned and carried out using a completely randomized design. Two-way ANOVA was performed, followed by Tukey's Honest Significant Differences test, to determine the statistical significance of the data obtained in the present investigation. Effect of foam mat drying on different physico-chemical parameters was measured by paired t-test as described by Raghuramulu et al. (2003).

RESULTS AND DISCUSSION

Protein foam characteristics

Four foaming agents *i.e.* egg albumin, casein protein, soy protein and whey protein were compared at 10% (w/w) level for their foam stability, foam expansion and foam density to screen the best foaming agent.

The results indicated that egg albumin exhibited the highest foam stability of 77.1% and foam expansion of 48.69% with a foam density was 0.459g/cm³ (Fig. 2). Egg albumin's superior performance is attributed to its ability to unfold at the air-water

interface, exposing hydrophobic amino acids and forming disulfide bonds that stabilize foam (Zayas, 1997). This aligns with findings in other food matrices, such as pineapple (Shaari et al., 2018) and tamarillo (Rohilla et al., 2022), where egg albumin consistently exhibited higher foam stability compared to soy or whey proteins due to its rapid adsorption and strong film formation. Our interest was for high foam expansion and stability with low foam density. Soy protein isolate performed well in terms of foam stability (67.99%) and expansion (38.63%) and demonstrated a relatively lower foam density (0.55 g/cm³). Casein protein demonstrated moderate foam stability 65.99% and expansion 29.09% but it had a higher foam density 0.56 g/cm³. On the other hand, whey protein isolate showed the lowest foam stability (61.99%) and expansion (27.34%) and thus exhibited the highest foam density (0.64 g/cm³) among all foaming agents studied. Increasing the level of foaming agent increased the foam expansion and consequently reduced the foam density (Sankat & Castaigne, 2004). Overall, the performance of egg albumin was found the best followed by casein, soy protein isolate, and whey protein isolate as a foaming agent. This may be due to egg albumin's structure that unfolds easily at the air-water interface, exposing hydrophobic amino acids that trap air bubbles and disulfide bonds that stabilize the unfolded structure (Zayas, 1997). Overall, the highest foam expansion (FE) was obtained for egg albumin and the lowest for whey protein isolate. Thus, different proteins at different concentrations greatly influenced the foaming expansion, reflecting differences in protein structures in terms of its amino acid sequence and disposition; molecular size and shape. The foam stability (FS) of egg albumin was highest due to its capability of reducing the serum flow within the lamella structure. FS was dependent on the ability of the protein to form a strong, flexible, cohesive film to reduce gas permeability and inhibit bubble coalescence (Vani & Zayas, 1995). The lower foam density of egg albumin due to higher proportion of air bubbles ensured its better performance as a foam mat drying agent. Alternatively, whey protein isolate foam demonstrated a high foam density because the movement of the foaming agent from the aqueous phase towards the air-aqueous interface was limited due to unfolded polypeptides in whey protein could potentially contribute to a denser network within the foam, leading to higher density.

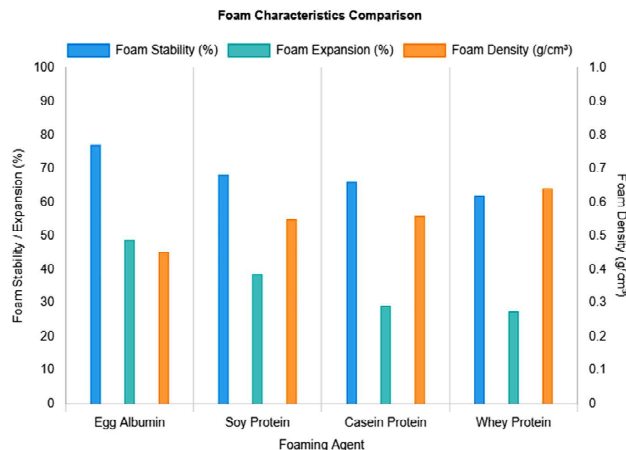


Fig. 2 : Comparison of foam characteristics (stability, expansion and density) for different foaming agents in overripe banana slurry

Properties of foam mat dried banana powder:

Physico-functional properties of foam mat dried over ripe banana powders were compared using different foaming agent as per the description given in Table 1.

Water solubility index

Table 1 indicated increasing concentration of proteins from 5% to 12.5% in the banana powder may have contributed to decreased WSI. Protein denaturation during the hot air drying may render the protein and its associated entities insoluble resulting in a descending trend of WSI with increasing foaming agent concentration. Among all the foaming agents, casein protein exhibited the highest WSI values. At the 5% level of addition, its WSI value was 48.53%, which was the highest among all foaming agents at this level, reaching 26.15% at the 12.5% level of addition. This can be attributed to heat stability of casein protein that does not denature significantly. Soy protein isolate showed intermediate WSI values among the foaming agents with values ranging from 43.64% at the 5% level of addition to 25.79% at the highest level of addition. Whey protein isolate had the lowest WSI values among all four foaming agents. The WSI decreased as the levels of foaming agent addition increased from 5% to 12.5% for all foam mat dry powders, including egg albumin, casein protein, soy protein isolate, and whey protein isolate. This decrease in WSI was attributed to the higher foam density resulting from increased levels of foaming agents. The higher foam density led to prolong the drying period thereby increasing protein denaturation and reduction

Table 1 : Quality characteristics of foam mat dried overripe banana powder using different levels of foaming agent

Foaming agent	Level of addition (% W/W)	WSI (%)	WAI	CI (%)	HR	Porosity	Colour		
							L	a	b
Egg albumin	5.0	41.837 ^b ±1.669	2.262 ^a ±0.147	10.454 ^a ±0.050	1.117 ^a ±0.196	0.104 ^a ±0.001	42.270 ^a ±0.231	27.063 ^a ±0.034	35.477 ^a ±0.485
	7.5	34.567 ^{abc} ±1.194	2.440 ^a ±0.104	13.341 ^a ±0.063	1.154 ^a ±0.015	0.133 ^a ±0.001	57.443 ^a ±0.450	12.710 ^a ±0.700	37.437 ^a ±0.444
	10.0	31.327 ^b ±1.141	2.624 ^a ±0.152	23.034 ^a ±0.267	1.299 ^a ±0.324	0.230 ^a ±0.003	55.553 ^{ab} ±0.550	14.700 ^a ±0.700	37.053 ^a ±0.031
	12.5	29.477 ^{ab} ±0.757	2.752 ^a ±0.089	31.664 ^a ±0.599	1.463 ^a ±0.346	0.317 ^a ±0.006	63.207 ^a ±0.201	13.100 ^a ±0.100	36.777 ^a ±0.795
Casein protein	5.0	48.533 ^a ±2.170	2.151 ^a ±0.060	5.120 ^b ±1.166	1.054 ^b ±0.050	0.051 ^b ±0.012	50.803 ^{abc} ±0.800	22.887 ^a ±0.900	40.077 ^a ±0.101
	7.5	37.127 ^a ±1.457	2.167 ^a ±0.021	10.289 ^a ±1.069	1.115 ^a ±0.196	0.103 ^b ±0.011	51.103 ^{abc} ±0.100	22.463 ^a ±0.450	37.370 ^a ±0.400
	10.0	32.757 ^c ±2.395	2.317 ^a ±0.122	14.905 ^b ±2.682	1.176 ^b ±0.070	0.149 ^b ±0.027	46.443 ^{cd} ±0.425	24.200 ^a ±0.200	38.113 ^a ±0.125
	12.5	26.153 ^{ab} ±1.834	2.477 ^a ±0.063	17.266 ^a ±0.636	1.219 ^a ±0.038	0.180 ^a ±0.006	47.160 ^{cd} ±0.106	22.290 ^a ±0.295	41.483 ^a ±0.500
Soy protein isolate	5.0	43.640 ^b ±3.569	2.151 ^a ±0.028	20.182 ^a ±0.231	1.253 ^a ±0.147	0.202 ^a ±0.002	50.803 ^{abc} ±0.800	22.887 ^a ±0.900	40.077 ^a ±0.052
	7.5	34.127 ^{cd} ±3.507	2.167 ^a ±0.260	24.164 ^{de} ±0.038	1.319 ^d ±0.040	0.242 ^{de} ±0.000	51.103 ^{abc} ±0.100	22.463 ^a ±0.450	37.370 ^a ±0.400
	10.0	32.537 ^c ±2.291	2.317 ^a ±0.307	27.246 ^c ±0.363	1.375 ^c ±0.023	0.272 ^c ±0.004	46.443 ^{cd} ±0.401	24.200 ^a ±0.200	38.113 ^a ±0.125
	12.5	25.790 ^b ±1.540	2.477 ^a ±0.145	29.861 ^c ±0.119	1.414 ^b ±0.146	0.292 ^b ±0.001	47.160 ^{cd} ±0.106	22.290 ^a ±0.300	41.483 ^a ±0.500
Whey protein isolate	5.0	36.933 ^{cd} ±2.339	2.116 ^a ±0.112	19.817 ^a ±0.271	1.247 ^a ±0.156	0.198 ^a ±0.003	48.297 ^{bcd} ±0.295	24.360 ^a ±0.350	40.513 ^a ±0.500
	7.5	33.600 ^{de} ±3.020	2.191 ^a ±0.068	17.266 ^a ±0.216	1.209 ^a ±0.044	0.173 ^a ±0.002	47.840 ^{bcd} ±0.850	25.207 ^a ±0.200	38.140 ^a ±0.125
	10.0	25.153 ^b ±0.939	2.371 ^a ±0.027	24.829 ^d ±0.235	1.330 ^a ±0.070	0.248 ^d ±0.002	54.173 ^{abc} ±0.750	22.230 ^a ±0.225	38.973 ^a ±1.000
	12.5	21.640 ^a ±1.141	2.529 ^a ±0.036	27.861 ^c ±0.032	1.386 ^a ±0.035	0.279 ^b ±0.000	47.160 ^{cd} ±0.250	18.143 ^a ±0.150	38.370 ^a ±0.375

WSI: water solubility index (%), WAI: water absorption index, CI: Carr index (%), HR: Hausner ratio, L: lightness, a: red/green, b: yellow/blue, LS: means with the same letter are not significantly ($p < 0.05$) different

in WSI (Kamali et al., 2022). The high WAI (2.26–2.75 for egg albumin) and moderate WSI (29.47–34.56% at 7.5–12.5%) suggest that the foam-mat dried banana powder is suitable for applications requiring water retention and solubility, such as infant formulations, where it can act as a natural sweetener and thickener, and energy drinks, where it can provide quick-dissolving carbohydrates and soluble fibers.

Water absorption index

Water absorption index (WAI) increased with increasing level of foaming agents (Table 1). Among the foaming agents, at the 5% level of addition, egg albumin had a WAI of 2.26 and it increased to 2.75 at the 12.5% level of addition. Egg albumin provided the highest WAI value among all foaming agents when compared at a constant level. At the same time, whey protein isolate had the lowest WAI values, ranging from 2.11 to 2.52. The WAI for casein protein at the 5% level of addition was 2.15 and it reached 2.47 at the 12.5% level of addition. Thus, WAI, which indicates the water absorption capacity of a dry specimen, showed a positive correlation with foam density as reported by Kamali et al. (2022). The amorphous compounds in the powder provided increased openness and porosity, facilitating external interactions and water adsorption. Additionally, the higher molecular mobility of these compounds could impart a sticky nature to the powder. Despite the

addition of the foaming agent, the inherent hygroscopic nature of overripe banana powder remained unchanged, as noted by (Kumar et al., 2022).

Carr index and Hausner ratio

The research findings revealed that the Carr index (CI) values for all foaming agents exhibited an increasing trend as the level of addition was increased from 5% to 12.5% (Table 1). This trend indicated a reduction in the flowability of the materials with higher levels of foaming agent addition. This observation confirms that flowability varies from excellent to poor with increasing foaming agent levels due to the powder's higher hygroscopicity, as observed by Watharkar et al. (2021). The results of Hausner ratio showed a consistent trend of increasing HR values with increasing levels of addition for all foaming agents, indicating a decrease in powder flowability.

Color

It was observed from Table 1 that with egg albumin, the 'L' values increased from 42.27 at the 5.0% level to 63.20 at the 12.5% level of addition, indicating a clear trend towards brighter color with the level of addition increased. The 'a' values decreased slightly from 27.06 at the 5.0% level to 13.10 at the 12.5% level of addition, showing a shift towards the green hue. The 'b' values remained relatively stable, ranging around 35–37, with a slight shift towards the yellow



Fig. 1 : Overripe banana (a), foamed protein (egg albumin) (b), foam dried banana flakes (c) and (d) foam mat dried overripe banana powder samples

hue at higher addition levels. The increase in L^* values (42.27–63.20 for egg albumin) indicates a brighter powder, which is likely to enhance consumer appeal due to its association with freshness and quality. The slight decrease in a^* (27.06–13.10) suggests a shift toward a less reddish hue, potentially improving acceptability by reducing browning perceptions. Stable b^* values (35–37) maintain the characteristic yellowish tint of banana, aligning with consumer expectations for banana-based products. In the case of casein protein, the ' L ' values ranged from 46.44 to 51.10, demonstrating a slight increase in brightness with higher levels of addition. The ' a ' value remained relatively constant around 22–24, indicating a constant reddish tinge. However, the ' b ' values varied from 37.37 to 41.48, suggesting a trend towards more yellowness at higher addition levels. Similarly, color-indices trends were observed for banana powders made with soy protein isolate and casein. For whey protein isolate, the ' L ' values ranged from 47.16 to 54.17, indicating some variation in brightness with different levels of addition. The ' a ' value remained relatively constant around 18–25, suggesting a constant reddish tinge. The ' b ' values showed a slight shift towards the yellowness at higher levels of addition.

Viscosity

The viscosity of foam mat dried overripe banana powder was observed to be lower than control powder at all shear rates. This may be due to the smooth structure of the foam mat dried banana powder that allows for uniform swelling in the solution and ensures ease of flow as compared to control powder. The findings from this study revealed that the viscosity increased with increasing concentration of foaming agents at low shear rate but variation in viscosity was insignificant at higher shear rates. The measurements of apparent viscosity at various constant shear rates ranging from 1 to 5 per second demonstrated similar results for all the foam mat dried samples. This may be attributed to the concentration-dependent thickening

tendency of protein based foaming agents which contribute to enhanced viscosity of the banana powder solutions. The presence of more protein denaturation and adsorption at the interface contributes to the enhanced viscosity of the foam mat dried powders (Karim & Wai, 1999). The experimental investigation on foam mat dried overripe banana powder examined its viscosity at three constant shear rates: 25, 50, and 75 per second. The study revealed that as the shear rates increased, the viscosity tended to decrease. This behavior can be attributed to the pseudoplastic nature of foam mat dried overripe banana powder (Arora et al., 2021).

Level optimization: On the basis of highest foam stability, foam expansion and lowest foam density egg albumin was finalized as a foaming agent to be used in the development of the overripe banana powder. During further comparison (Table 1) keeping second ranking for WSI WAI in view, egg albumin at 7.5 w/w was optimized for foam mat drying of banana powder (Fig. 1). Drying behaviour of control and foam mat banana slurry (foamed with 7.5%, w/w egg albumin) was further studied.

Drying kinetics

The drying kinetics analysis revealed that the inclusion of 7.5% egg albumin as a foaming agent significantly

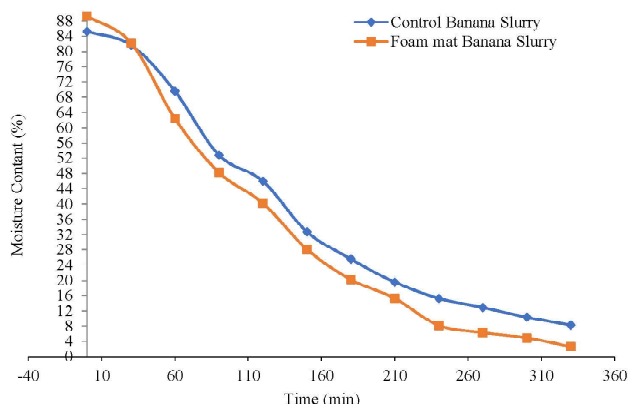


Fig 3 : Effect of foam mat drying with egg albumin as foaming agent on rate of drying of overripe banana slurry

Table 2 : Comparison of control and optimized overripe banana powder

Parameters (%, fwb, %, dwb)	Control sample	Optimized powder	p value	Significance
Moisture	7.81 (-)	3.26 (-)	0.012	s
Fat	0.69 (0.74)	0.73 (0.75)	0.270	ns
Protein	0.95 (1.03)	1.57 (1.62)	0.001	s
Ash	1.32 (1.43)	1.43 (1.48)	0.055	ns
Dietary fiber	12.12 (13.15)	15.16 (15.67)	0.003	s
Carbohydrate	77.11 (83.64)	77.85 (80.47)	0.454	ns

s: significant at 5% level, ns: non-significant

influenced the drying behavior of the material (Fig. 3). During the initial time span of approximately 30 minutes, both samples exhibited a constant drying rate. However, the sample with egg albumin showed enhanced moisture removal compared to the control sample during this phase. As the drying process progressed, both samples eventually transitioned into a long falling drying rate phase. After 330 minutes of drying, both samples had reached the falling drying rate phase, where the drying rate had significantly slowed down, and the moisture content decreased at a much slower rate compared to earlier stages of drying. Foam mat drying did not affect the drying trend of overripe banana slurry. However, foam-mat drying enhanced the drying rate by ~1.6 folds (6.20×10^{-3} vs. 3.85×10^{-3} kg H₂O/kg dw/min) compared to control, due to the porous foam structure facilitating moisture diffusion. Compared to freeze-drying, which is energy-intensive and slower (8–12 hours, Onwude et al., 2016), foam-mat drying is more cost-effective and faster. Furthermore, unlike spray drying it is suitable for viscous and high solids products. Thus, foam-mat drying offers a balance of drying efficiency and retention.

Chemical composition of control and optimized overripe banana powder

Control and optimized overripe banana powder were compared by estimating chemical composition as tabulated (Table 2). The optimized powder showed significantly lower moisture 3.26% than the control powder 7.81% and slightly higher fat content 0.73% vs. 0.69%. Protein was significantly higher in the optimized powder which was 1.57% compared to the control powder (0.95%). Ash content showed no significant difference since it was 1.43% for optimized and 1.32% for control banana powder. The optimized

powder had significantly higher dietary fiber than control powder (15.16% vs. 12.12%) but almost similar carbohydrates values.

The optimized powder demonstrated a significant reduction in moisture content compared to the control powder due to the more efficient and rapid foam mat drying process of overripe banana. This drying method led to an even more porous internal structure of the mat, attributed mainly to the opening of finer pores and the formation of new pores facilitated by the movement of moisture. In contrast, the control samples (without foam mat) tended to become denser, tougher, and often developed a leathery surface during drying, as observed by (Sankat & Castaigne, 2004). The similar fat content of both foam mat-dried and control overripe banana powder was due to the chemical nature of the foaming agent which was chiefly proteinaceous in nature. Foam mat drying did not significantly affect the ash and carbohydrate contents of the overripe banana powder. However, the protein content increased in the foam mat-dried powder, likely due to the contribution of protein from egg albumin, as reported by Kumar et al. (2022).

CONCLUSION

The study optimized the foaming agent and foam-mat drying process for producing overripe banana powder as a natural sweetener for the processed food industry. Egg albumin at 7.5% was identified as the optimal foaming agent based on physico-functional parameters, including porosity, flowability, rheology, and color. The resulting powder serves a dual purpose: valorizing overripe bananas, otherwise destined for waste, and offering a shelf-stable, naturally sweet ingredient suitable for diverse food applications. Foam-mat drying with 7.5% egg albumin yields a nutrient-rich powder suitable for use in extrudates,

infant foods and energy beverages. The process is scalable due to its capacity to handle the bulk with relatively short drying time. The powder's high water absorption index (WAI) and moderate water solubility index (WSI) facilitate its incorporation into various food systems. Future research should explore optimization for other banana cultivars, particularly indigenous varieties, and evaluate the integration of advanced drying methods for enhanced drying rate. Additionally, the use of plant-based foaming agents could support the development of vegan-friendly products, for enhanced consumer need.

Note : Norola A. and Arora B. contributed equally in this research

ACKNOWLEDGEMENT

Authors are grateful to the Director, ICAR-Indian Institute of Agricultural Research, New Delhi, India for providing divisional fund and facilities to conduct this research.

REFERENCES

- Al-Dairi, M., Pathare, P. B., Al-Yahyai, R., Jayasuriya, H., & Al-Attabi, Z. (2023). Postharvest quality, technologies, & strategies to reduce losses along the supply chain of banana: A review. *Trends in Food Science & Technology*, 134, 177–191. <https://doi.org/10.1016/j.tifs.2023.03.003>
- Arora, B., Singha, P., & Rizvi, S. S. H. (2021). Supercritical fluid extrusion: Die design and physicochemical properties of milk protein extrudates. *Innovative Food Science and Emerging Technologies*, 68, Article 102637. <https://doi.org/10.1016/j.ifset.2021.102637>
- Farid, E., Mounir, S., Siliha, H., El-Nemr, S., & Talaat, E. (2023). Effect of soy protein isolate concentration and whipping time on physicochemical and functional properties of strawberry powder. *Journal of Food Measurement and Characterization*, 17(5), 4529–4540.
- Fatemeh, S. R., Saifullah, R., Abbas, F. M. A., & Azhar, M. E. (2012). Total phenolics, flavonoids and antioxidant activity of banana pulp and peel flours: Influence of variety and stage of ripeness. *International Food Research Journal*, 19(3), 1041–1046.
- Hardy, Z., & Jideani, V. A. (2020). Functional characteristics and microbiological viability of sfoam-mat dried Bambara groundnut (*Vigna subterranea*) yogurt from reconstituted Bambara groundnut milk powder. *Food Science and Nutrition*, 8(10), 5238–5248. <https://doi.org/10.1002/fsn3.951>
- Igual, M., Chiş, M. S., Socaci, S. A., Vodnar, D. C., Ranga, F., Martínez-Monzó, J., & García-Segovia, P. (2021). Effect of *Medicago sativa* addition on physicochemical, nutritional and functional characteristics of corn extrudates. *Foods*, 10(5), Article 928. <https://doi.org/10.3390/foods10050928>
- Kamali, R., Dadashi, S., Dehghannya, J., & Ghaffari, H. (2022). Numerical simulation and experimental investigation of foam-mat drying for producing banana powder as influenced by foam thickness. *Applied Food Research*, 2(1), Article 100075. <https://doi.org/10.1016/j.afres.2022.100075>
- Karim, A. A., & Wai, C. C. (1999). Characteristics of foam prepared from starfruit (*Averrhoa carambola* L.) puree by using methyl cellulose. *Food Hydrocolloids*, 13(3), 203–210. [https://doi.org/10.1016/S0268-005X\(98\)00086-1](https://doi.org/10.1016/S0268-005X(98)00086-1)
- Ketelaars, A. A. J., Pel, L., Coumans, W. J., & Kerkhof, P. J. A. M. (1995). Drying kinetics: A comparison of diffusion coefficients from moisture concentration profiles and drying curves. *Chemical Engineering Science*, 50(7), 1187–1191. [https://doi.org/10.1016/0009-2509\(94\)00494-C](https://doi.org/10.1016/0009-2509(94)00494-C)
- Khodifad, B. C., & Kumar, N. (2020). Foaming properties of custard apple pulp and mathematical modelling of foam mat drying. *Journal of Food Science and Technology*, 57(2), 526–536.
- Kumar, P. S., Keran, D. A., Pushpavalli, S., Shiva, K. N., & Uma, S. (2022). Effect of cellulose and gum derivatives on physicochemical, microstructural and prebiotic properties of foam-mat dried red banana powder. *International Journal of Biological Macromolecules*, 218, 44–56. <https://doi.org/10.1016/j.ijbiomac.2022.07.071>

- Ng, Y. V., Tengku Ismail, T. A., & Wan Ishak, W. R. (2020). Effect of overripe banana in developing high dietary fibre and low glycaemic index cookie. *British Food Journal*, 122(10), 3165–3177. <https://doi.org/10.1108/BFJ-12-2019-0934>
- Nishad, J., Selvan, C. J., Mir, S. A., & Bosco, S. J. D. (2017). Effect of spray drying on physical properties of sugarcane juice powder (*Saccharum officinarum* L.). *Journal of Food Science and Technology*, 54(3), 687–697.
- Onwude, D. I., Hashim, N., Janius, R. B., Nawi, N. M., & Abdan, K. (2016). Modeling the thin layer drying of fruits and vegetables: A review. *Comprehensive Reviews in Food Science and Food Safety*, 15(3), 599–618.
- Raghuramulu, N., Nair, K. M., & Kalyanasundaram, S. (2003). *A manual of laboratory techniques* (2nd ed.). National Institute of Nutrition, Indian Council of Medical Research.
- Raharitsifa, N., Genovese, D. B., & Ratti, C. (2006). Characterization of apple juice foams for foam-mat drying prepared with egg white protein and methylcellulose. *Journal of Food Science*, 71(3), E142–E151. <https://doi.org/10.1111/j.1365-2621.2006.tb15627.x>
- Ranganna, S. (2007). *Handbook of analysis and quality control for fruit and vegetable products* (2nd ed.). Tata McGraw-Hill.
- Rohilla, S., & Mahanta, C. L. (2022). Foam mat dried tamarillo powder: Effect of foaming agents on drying kinetics, physicochemical and phytochemical properties. *Journal of Food Processing and Preservation*, 46(12), Article e17164.
- Sankat, C. K., & Castaigne, F. (2004). Foaming and drying behaviour of ripe bananas. *LWT - Food Science and Technology*, 37(5), 517–525.
- Sankat, C. K., Castaigne, F., & Maharaj, R. (1996). The air-drying behaviour of fresh and osmotically dehydrated banana slices. *International Journal of Food Science and Technology*, 31(2), 123–135.
- Shaari, N. A., Sulaiman, R., Rahman, R. A., & Bakar, J. (2018). Production of pineapple fruit (*Ananas comosus*) powder using foam mat drying: Effect of whipping time and egg albumen concentration. *Journal of Food Processing and Preservation*, 42(2), Article e13467.
- Thippeswamy, B., Joshi, A., & Sethi, S. (2021). Foam mat drying of fruits: Concept, opportunities and limitations. *Biotica Research Today*, 3(1), 35–37. <https://bioticainternational.com/ojs/index.php/biorestoday/article/view/679>
- Thuwapanichayanan, R., Prachayawarakorn, S., & Soponronnarit, S. (2008). Modeling of diffusion with shrinkage and quality investigation of banana foam mat drying. *Drying Technology*, 26(11), 1326–1333. <https://doi.org/10.1080/07373930802330979>
- Thuy, N. M., Tien, V. Q., Tuyen, N. N., Giau, T. N., Minh, V. Q., & Tai, N. V. (2022). Optimization of mulberry extract foam-mat drying process parameters. *Molecules*, 27(23), Article 8570.
- Vani, B., & Zayas, J. F. (1995). Foaming properties of selected plant and animal proteins. *Journal of Food Science*, 60(5), 1025–1028. <https://doi.org/10.1111/j.1365-2621.1995.tb06285.x>
- Watharkar, R. B., Chakraborty, S., Srivastav, P. P., & Srivastava, B. (2021). Foaming and foam mat drying characteristics of ripe banana [*Musa balbisiana* (BB)] pulp. *Journal of Food Process Engineering*, 44(8), Article e13726. <https://doi.org/10.1111/jfpe.13726>
- Zayas, J. F. (1997). Foaming properties of proteins. In J. F. Zayas (Ed.), *Functionality of proteins in food* (pp. 260–309).

(Received : 28.10.2024; Revised : 4.5.2026; Accepted : 10.5.2026)

