Foam mat drying of Indian blackberry (Syzygium cuminii L.) fruit pulp: Optimization of process parameters and its powder characteristics

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Posted Date: January 11th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2273109/v2

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Additional Declarations:
No competing interests reported.

Tables 1 to 6 are available in the Supplementary Files section.
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Abstract
Foam-mat drying of Indian black-berry pulp (*Syzygium cumini* L.) was carried out using different foaming aids, to determine the effects of concentration of maltodextrin (MD), soy protein isolate (SPI) and carboxymethylcellulose (CMC) on foaming characteristics e.g. foam expansion (FE), foam stability (FS) and foam density (FD). Optimization of product ingredients were performed using three levels of MD (3.0, 5.0, and 7.0 %), SPI (0.5, 1.0, and 1.5 %) and CMC (0.0, 1.0, and 2.0 %) using Box-Behnken method of response surface design. The optimum solutions of the process parameters were obtained at 5.47% of MD, 1.02% of SPI and 1.06% of CMC with response functions of 93.93% FE, 91.60% FS and 481.71 kg/m$^3$ FD. The optimised foamed jamun pulp was dried using hot air-drying method at temperature of 50, 60 and 70°C. The drying rate and effective moisture diffusivity (8.978×10$^{-11}$ to 1.246×10$^{-10}$ m$^2$/s) increased with increase in drying temperature. The powder characteristics of dried jamun pulp including bulk density (0.15 to 0.12), flowability: HR (1.27 to 1.13) and CI (21.28 to 12.26 %), total anthocyanin content (61.06 to 35.63 mg/100g) and total phenolic content (278.49 to 195.78 mg GAE/100g) were reduced as the drying air temperature increased from 50 to 70° C, however water solubility index (58.55 to 74.28 %) and hygroscopicity (12.43 to 14.22 g/100g) of powder increased. The dried powder had a porous microstructure and yield medium brightness to their colour.

**Keywords:** Jamun pulp, Foam mat drying, Optimization, Flowability, Total anthocyanin content, Total phenolic content, Hygroscopicity, Water solubility index
1. Introduction

Indian blackberry (*Syzygium cumini* L.) belongs to the family *Myrtaceae*, an underutilized potentially important indigenous minor fruit in India and south-east Asian countries. The jamun fruit has a great economic importance as it has potential as an alternative medicine to treat various diseases. It has promising therapeutic value due to its various phytochemicals like glycoside, jambolin, jambosine, anthocyanins, tannins, flavonoids, gallic acid, ellagic acid etc. and minerals like Ca, Mg, K, Na, S and P etc. The presence of anthocyanin content delivers purple to deep blue colour to the fruit and is responsible for high antioxidant potential [1]. This extensive range of health promoting factors make it popular being utilised as a nutraceutical. The nutritive and bioactive content of fruits is influenced by their variety, stage of ripeness, climate, farming practices, and post-harvest management and processing. It is cheaply available, widely used as a traditional medicine plant, whose parts (leaf, bark, root and fruit) have been pharmacologically recognized to possess antidiabetic (hypoglycaemic), antibacterial, antiviral, antimicrobial, antiallergic, antipyretic, anti-inflammatory, gastroprotective, anticancer and anti-HIV activities[2]. Despite being the second largest producer of jamun in the world, India’s production mainly remains unorganised with significant post-harvest loss of this fruit every year. Due to the perishability and the seasonal availability of the jamun fruit, there is no such method developed for long term storage. To enhance the shelf life of jamun, development of different processing technology for fresh fruit storage or production of value-added products should require.

Considering the nutraceutical and therapeutic significance of jamun, there was felt necessary to investigate it scientifically using novel techniques of dehydration while preserving its nutritional standards and enhancing the shelf life by developing marketable viable commodity to ensure its accessibility throughout the year. Furthermore, because of the possible health advantages connected with its phenolic components, jamun has attracted the curiosity and major attention of the scientific research community and industrialised food manufacturers as a potential source of raw matter for the production of a wide range of food stuffs. Moreover, it is also utilized for the making of jelly [3], wine preparation [4, 5] and pulp [6] etc. Due to the seasonal availability and perishability, numerous research studies have conducted the dehydration of jamun fruit by various drying methods, like spouted bed drying [7], spray-drying [8] and freeze drying[9]. The production of powder from the jamun pulp is practically not possible using conventional drying since it contains higher proportion of low molecular weight sugar leading to its viscous nature. Even after long time of drying, the pulp becomes sticky and leather like. So, it is very difficult to convert in powder forms due to the problems of stickiness[10].

Foam-mat drying technique is one of the optimistic and consolidated effective dehydration methods for maintaining bioactive compounds in dehydrated fruit products. This method entails combining fruit and vegetable juice or pulp with a foaming and stabilizer additives to create a stable foam uniformly spread on a tray and air dried at temperatures varying from 50-80 °C, after which the dehydrated sample is crushed into a powder form [11]. The maximum surface area to volume ratio and porous structure of foam increases the mass transfer efficiency, reducing drying time and improving the nutritive and functional quality of dried product[12]. This method is one of the most cost effective and suitable technique for any heat sensitive, high sugar containing sticky fruit pulp, which are difficult to be dried by conventional methods of drying[13]. Foam mat dried products are relatively stable against physical, chemical, microbiological spoilage and have high preservation of all sensory attributed (colour, aroma and taste) related to other drying techniques. Tavares et al. [14] had reported that jamun powder obtained through foam mat drying using foaming agent (10.0% w/w Emustab, 2.5% w/w Super Liga Neutral and 20.0% maltodextrin) has a high concentration of bioactive components (anthocyanins, tannins, flavonols, and other phenolic compounds) and can be utilized to improve the quality of different food products. Many fruits and vegetables powder like mango, banana, apple, bael, pineapple, custard apple, mandarin, tamarind, papaya, tomato etc. have been successfully developed through foam mat drying [11-18]. Therefore, the objective of the present investigation is to study the foaming behaviour of jamun pulp to produce powder with optimization of process parameters using RSM, study the drying characteristics at different temperature with powder characteristics.

2. Material and methods

2.1 Raw material and preparation of fruit pulp

Fully ripe fresh jamun fruit (var. Ram jamun) was procured from the local market of Bhubaneswar, Odisha, India in the first week of July month, 2021. These fruits were collected at proper maturity stage. It was cleaned with
100 ppm chlorinated water and shade dried for 1-2 hours. Then the fruit was passed through a pulper machine (50 kg/h capacity) to extract the pulp, seed and pomace. After pulping of fruit, it was passed through a muslin cloth (60 cmx60 cm) to get clarified pulp with total soluble solid content of 11-12°B. It was heat treated at 80 °C for 10 min. Then the pulp was cooled at room temperature and packaged in 2 litre MPP packets and stored in refrigerated condition(4–5°C) until further use.

2.2 Foaming experiment
The samples were prepared by adding water in stored pulp (1:1 w/w) based on preliminary trials and was mixed with different levels of foaming agent i.e., MD (3.0%, 5.0% and 7.0% w/w), SPI (0.5%, 1.0% and 1.5% w/w) and CMC (0.0%, 1.0% and 2.0% w/w). Again, it was mixed with a fixed amount of Methyl Cellulose (MC) (1.0% w/w) to get a final blended sample. Then this mixture was whipped for 5-6 minutes by electric blender (Model HL1655, Philips India Ltd.). Once the sample accomplished the foam structure, then it was carefully transferred to measuring cylinder to find the foaming properties. After measuring the foaming properties, the foamed jamun pulp was spread uniformly on the trays for drying. The details procedure of the preparation of jamun pulp and foam mat dried powder is shown in Fig. 1.

2.3 Experimental Design
In this research study, Response Surface Methodology (RSM) was employed in the experimental data with the help of statistical tool (Design Expert software version 10.0.1, Statease Inc, Minneapolis, MN) for different optimization parameters and produce response surface plots for the development of jamun pulp powder. Based on preliminary trials, the Box Behnken Design (BBD) technique was implemented for creating the experimental design on foamed samples with three independent variables, such as MD (A), SPI (B), CMC (C) at three levels (-1, 0, 1). To assess their impact on the dependent parameters (FE, FS and FD), these independent parameters were chosen along with their levels which are given in Table 1. In BBD, the number of experiments (N) needed is expressed by the relationship, N = 2k (k-1) + C0, where C0 is the number of central points and k is the number of factors. So, the design consists of a total 17 runs of different combination involving five replicates of central point. The dependent response functions were fitted to the second order polynomial equation (Equation (6)).

2.4 Foaming characteristics
2.4.1 Foam expansion
The foam expansion of jamun pulp was measured to get the percentage rise in the volume of pulp after foaming. During whipping operation, foam expansion is an important parameter to indicate that the ability of air incorporation into the pulp foam structure. It was measured by the difference between the volume of pulp before (initial volume) and after foaming (final volume) according to the following eq. (1) [17].

\[
\text{Foam expansion, FE} \% = \frac{V_1 - V_0}{V_0} \times 100
\]

Where,
\(V_0 = \text{Initial volume of the pulp (cm}^3\)\)
\(V_1 = \text{Final volume of the pulp (cm}^3\)\)

2.4.2 Foam stability
The foam obtained jamun pulp was poured into the 100 ml of a measuring cylinder and without any disturbance it was left at ambient temperature (28 ± 5° C) for 2h. Thereafter, in every 30 minutes, the liquid drained from the foam as foam drainage volume due to gravity was directly measured. The following formula eq. (2) was used to find the foam stability of jamun pulp foam [18].

\[
\text{Foam stability, FS} \% = \frac{V_t}{V_0} \times 100
\]

Where,
\(V_t = \text{The volume of foam measured in every 30 minutes (cm}^3\)\)
\(V_0 = \text{Initial volume of foam (cm}^3\)\)
2.4.3 Foam Density
The density of foamed sample was calculated as per the procedure given by Ng and Sulaiman[18] with some modifications. After foaming, the jamun foam was gradually poured into a 100 ml standard measuring cylinder without collapsing of the foam structure. The mass of the foam and its volume was noted after each measurement. The experiments were done in triplicate for each experiment and the foam density was calculated as per the following formula eq. (3).

\[
\text{Foam density, } FD \text{ (g/cm}^3) = \frac{M_f}{V_f}
\]

Where,
\[M_f = \text{Mass of the foam sample (g)}\]
\[V_f = \text{volume of the foam (cm}^3)\]

2.5 Drying experiment
The drying studies were carried out in a laboratory scale hot air dryer. The optimized foamed pulp was uniformly spread over a rectangular steel plate of dimension 33 x 22.5 x 2 cm and kept for drying in a oven at set temperatures of 50°C, 60°C and 70°C. The foam thicknesses were maintained fixed as 4 mm. The air velocity in oven was maintained constant at a value of 1.0 m/s. The weight of the samples after every 10 minutes drying was noted by using a digital electric balance for the first 1 hour and then after every 15 and 30 minutes. Drying was carried out up to three consecutive constant weight of the product was recorded. The final dried jamun pulp flakes were removed from plate with the help of spatula and these flakes were crushed using a pestle and mortar to obtain powder product. The powdered samples were immediately packed in air tight glass containers for further analysis.

2.6 Drying characteristics
2.6.1 Moisture ratio
Moisture content present of jamun pulp during foam-mat drying was estimated in terms of moisture ratio (MR) using the following formula.

\[
MR = \frac{M - M_e}{M_i - M_e}
\]

Where,
\[M \text{ (kg water/kg dry solid)} = \text{The moisture content at any time ‘}t’\]
\[M_e \text{ (kg water/kg dry solid)} = \text{The equivalent moisture content}\]
\[M_i \text{ (kg water/kg dry solid)} = \text{The initial moisture content as determined by AOAC [19]}\]

2.6.2 Effective moisture diffusivity
The moisture diffusivity \((D_{eff})\) of foamed jamun pulp was evaluated by using the Fick’s law of diffusion and assuming foamed jamun pulp spread on plate as a slab geometry. The simplified equation is expressed as eq. (5) [20].

\[
MR = \frac{8}{\pi^2} \exp \left( -\pi^2 \frac{D_{eff} t}{(2L)^2} \right)
\]

Where,
\[D_{eff} \text{ Effective moisture diffusivity (m}^2/s)\]
\[2L \text{ The thickness of foam-mat sample (m)}\]
\[t \text{ Drying time (s)}\]

2.7 Statistical analysis
The analysis of variance (ANOVA) and regression analysis were used to calculate the statistical significance of model terms. To assess the model’s adequacy, lack-of-fit and \(R^2\) (coefficient of determination) values were used. The importance of all the polynomial model terms was statistically determined by obtaining F-values at 5% levels of probability. The objective of this research was to find the optimum levels of three variables that would result in the maximum foam expansion and stability as well as presence of higher number of bioactive compounds in jamun pulp powder.
\[ Y = \beta_0 + \sum_{i=1}^{4} \beta_i x_i + \sum_{i=1}^{4} \beta_{ii} x_i^2 + \sum_{j=i+1}^{4} \beta_{ij} x_i x_j \]  
(6)

Where,
- \( Y \) = Response function parameters
- \( \beta_0, \beta_i, \beta_{ii} \) and \( \beta_{ij} \) = Regression coefficients
- \( x_i, x_j \) and \( x_{ij} \) = Independent variables in coded form

2.8 Physico-chemical properties of jamun powder

2.8.1 Colour measurement

Colour of the pulp and foam-mat dried jamun powder were determined by CR-20 (Konica, Milonta, INC, Japan) Colorimeter. Prior to analysing the sample, a white coloured tile was used to calibrate the instrument. Obtained results were expressed in the form of L’, a’ and b’ where L’ value represents the lightness of colour (0= black, 100= white) a’ value represents greenness to redness and b’ value represents yellowness to blueness. Samples were analysed in triplicate form and the average value of each parameters was recorded.

2.8.2 Bulk and tapped Density

The bulk density of powder sample was measured by pouring 10g of the sample into a 50ml of measuring cylinder and the volume occupied by the cylinder was their bulk density. For determination of tapped density, equal amount of the powder was taken and tapping of cylinder 15 times on a mat made up of a rubber type material from a height of approximately 20 cm. The final volume of powder sample was noted for further analysis. The bulk and tapped density were determined by its mass and volume measured for each sample [21].

2.8.3 Flowability

The flow characteristics of jamun powder was evaluated on the basis of the value of Carr Index (CI) and Hausner ratio (HR). These two terms were calculated on the basis of bulk and tapped density values [20]. The CI and HR value were measured by the following formula. The flow behaviour pattern of any powder characteristics are specified on the basis of CI and HR given in Table 2 [21].

\[
CI = \frac{T.D - B.D}{T.D} 
\]  
(7)

\[
HR = \frac{T.D}{B.D} 
\]  
(8)

2.8.4 Total anthocyanin content (TAC)

Total anthocyanin content of jamun pulp powder was evaluated by pH-differential method [22]. Two buffer solutions (potassium chloride buffer, pH 1 (0.025 M) and sodium acetate buffer, pH 4.5 (0.4 M)) was used in this method. UV-Visible spectrophotometer (Systronics, India) was used for spectral measurement at 510 nm and 700 nm. The TAC was calculated as Cyanidin 3-glucoside (Cyd 3-glu) per kg FW, using a molecular weight of 449.2 g/mol and an extinction coefficient (e) of 26,900L/cm mol.

\[
Absorbance (A) = (A_{510nm} - A_{700nm}) \text{pH1.0} - (A_{510nm} - A_{700nm}) \text{pH 4.5} 
\]

\[
TAC \text{ (mg/100g)} = \frac{A \times MW \times DF \times 1000}{e \times 1} 
\]  
(9)

Where,
- \( A \) = Absorbance value,
- \( MW \) = Molecular weight (449.2),
- \( DF \) = Dilution factor,
- \( e \) = Molar absorptivity (26,900)

2.8.5 Total phenolic content (TPC)

Total phenolic content of dried samples was calculated by the Folin-Ciocalteu method. To determine TPC, the method explained by Abd El-Salam and Morsy [23] was adopted and the results were as expressed mg Gallic acid equivalents (GAE)/100g.

2.8.6 Hygroscopicity
The hygroscopicity of the jamun powder sample was determined by the process described by Samyor et al. [24] with slight modification. Foamed-dried jamun powder of 2 g was placed in a petri plate and placed inside sealed desiccator at 28 ± 5°C containing saturated solution of ammonium chloride. Saturated solution of ammonium chloride helps to maintain constant relative humidity. The sample weights were taken every day until a steady-state mass was obtained. Hygroscopicity (HG) was calculated as per the following formula eq. (10).

\[
\text{Hygroscopicity} \% = \left( \frac{c+M}{d-M} \right) \times 100
\]  

Where,

- \( M \) = Initial moisture content of the sample
- \( c \) = The increased weight of the sample
- \( d \) = Initial weight of the sample

2.8.7 Water solubility index

Water solubility index (WSI) of the foam mat dried jamun samples were calculated by following the method reported by Wong et al. [25]. Sample of 2 g weight was added with 25 ml distilled water and taken in a centrifuge tube, kept it in water bath (30°C) for 30 min. After that the sample was centrifuged at 5000 rpm for 15 min. Then the obtained supernatant liquid was slowly taken out from centrifuge tube to a petri plate and kept it in hot air oven for drying at 105°C until a constant weight was observed. The remaining sediment weight was noted down. The following formula was used to determine WSI (eq. 11).

\[
\text{WSI} \% = \frac{\text{weight of dissolved solids in supernatant, g}}{\text{weight of dry sample, g}} \times 100
\]  

2.8.8 FTIR analysis

Fourier Transform Infrared Spectroscopy may identify the chemical structures and linkage of molecules through the generation of an infrared absorption spectrum. Properly dried jamun powder samples (2g) non-foamed as well as foamed were placed on a base plate of diamond crystal of universal ATR- FTIR to classify its functional groups [24]. The infrared absorption spectrums obtained from FTIR Spectrometer (Model PerkinElmer spectrum Version 10.4.3, fixed with the KBr optics and a LiTa03 detector of MIR source and the frequency varies from 4000 to 450 cm\(^{-1}\)) were analysed. Each experiment was performed with scanning the sample eight times with four resolutions.

2.8.9 Surface morphology of powder using scanning electron microscope

Scanning Electron Microscope (Hitachi S3400N) was used to describe the morphology of both foamed and non-foamed jamun pulp powder sample dried at 60°C in hot air oven. The powder was placed using double-sided adhesive carbon tape before being coated with a thin layer of gold (approximately 15 nm) using sputter-coating machine. Then the microscope was operated at 15 kV and representation images were captured at magnification of about 100X.

3.0 Results and Discussion

3.1 Effect of foaming agents on foaming behaviour of jamun pulp

The effect of foaming agents i.e., maltodextrin (3.0, 5.0, 7.0 %), soya protein isolate (0.5, 1.0, 1.5 %), CMC (0.0, 1.0, 2.0 %) on foaming behaviour of jamun pulp foam and their optimization were performed. Quadratic equation models were developed for the response variables e.g., Foam expansion, Foam stability and Foam Density with respect to the independent variables. The 17 combinations of BBD design of experiments with coded and uncoded values of the parameters and their corresponding response values were given in Table 3. Foam expansion values increased with increase in maltodextrin composition from 3.0 to 7.0 %. The FE is maximum at 7.0% MD; however, the foam stability was lower. The no CMC (0.0%) condition gave the lowest stability of the foamed pulp i.e., around 32.16 to 35.16 %. However, addition of CMC in 0.5 or 1.0% had increased the foam stability to above 90%. Similarly, lowest foam density was observed at the levels of 5% MD, 1.0% SPI and 1.0% CMC 471 to 499 kg/m\(^{3}\).

Table 4 represents the results of the ANOVA in terms of model significance, linear, quadratic, and interaction effects. The fitted polynomials models for FE, FS, and FD were significant, while the lack of fit value was insignificant, suggesting that the produced models were suitable. The predicted model’s goodness of fit was
further demonstrated by the higher coefficient of determination ($R^2$) values of 0.98, 0.98, and 0.98 for the FE, FS, and FD, respectively. The results also reveal that process variables, including MD and CMC, have a significant influence on the three foam responses.

3.1.2 Effect of ingredients on foam expansion
Foam Expansion (FE) of jamun pulp found to vary between 32.20 to 110.50% (Table 3). The model F value of 63.71 (Table 4) suggests that the model is significant at $P<0.001$. The coefficients of the model terms (linear, square and interaction terms) are given in Table 4 and explained that CMC concentration had negative impact on foam expansion. Maltodextrin concentration had positive effect on FE of foamed jamun pulp. The $R^2$ and adjusted $R^2$ values are 0.98 and 0.97 respectively indicated goodness of fit of the model. The linear terms of MD and CMC had significant effects on FE at 1% level of significance, while SPI had non-significant effect. The quadratic term of A$^2$ was significant, showing non-linear difference in FE because of change in proportion of MD ($P<0.001$). The interaction terms of MD and SPI is also significant ($P<0.05$), indicating the influence of combined effects on FE. Fig.2 shows the effects of MD, SPI and CMC on the foam expansion of jamun pulp. A higher dose of foaming agent i.e. MD and CMC produces a high FE, but, a high dose of SPI also shows a negative impact on the foam expansion as well as foam stability due to the generation of larger bubbles [26,27]. While foaming, as the foaming agents are moving from the aqueous phase to the air-liquid interface, the surface tension is decreased as the concentration of foaming agents increased which resulted in increase in FE of jamun pulp.

3.1.3 Effect of ingredients on foam stability
Foam stabilizer plays an important role to retain the foam in stable form [20]. To accomplish a successful foam drying process, the concentration of foaming aids should be optimized taking both FE and FS into account. From the result (Table 3), the minimum FS (32.16%) of jamun pulp at uncoded value (3, 1, 0 %) was about 2.95 times lesser than highest foam density (95.02%) at uncoded value (5, 1, 1 %) and the FS average value was 70.56 %. It was observed that the model is highly significant because of model F value of 70.43 ($P<0.001$). The coefficient of regression ($R^2$) and adjusted $R^2$ value of the model are 0.98 and 0.97 respectively which indicated goodness of fit of the model. The linear terms of C had significant effect on FS at $P < 0.001$ (Table 4) while there is no significant effect observed for A and B. The coefficient of C is positive, showing higher FS obtained with the increase in CMC concentration. Non-linear variation was observed significant due to quadratic terms of A$^2$, B$^2$ and C$^2$ ($P<0.001$). There was no significant effect was observed in interaction terms. Fig.3 shows that the stability of the foam increases as CMC increases. Initially FS increased with increase concentration of MD and SPI then it was decreased after certain time. This could be because proteins are present in MD and SPI, which acted as an excellent stabiliser by lowering the surface energy level between bubbles when foams were being continuously formed. The size of the bubbles and their formation are directly impacted by the foaming agent concentration, which may also have influenced the FS [28]. The mixture of CMC as foam stabilizer enhanced the FS by reducing the foam drainage volume. So, it was reported that CMC had a key role in averting foam breakage. Similar results are also reported in muskmelon foam mat drying [20] and bael pulp foam mat drying [29].

3.1.4 Effect of ingredients on foam density
Foam Density generally varies due to the incorporation of variation of foaming aids, whipping speed and its duration in the foam mat drying method. Though we fixed the time and speed of whipping, here the foam stabilizer and pulp content affect the density of the foam. The minimum FD (471 kg/m$^3$) of jamun pulp was observed at uncoded parameter of 5.0, 1.0, 1.0 % and maximum FD (792 kg/m$^3$) at uncoded parameter of 3.0, 1.0 and 2.0 % of MD, SPI and CMC respectively. Based on literature, density of foam values between 300-600 kg/m$^3$ was found appropriate for foam mat dehydration technique [26]. The F value was found to be 67.97 from the statistical analysis showed that the model was significant ($P<0.001$). The $R^2$ and adjusted $R^2$ value of the model was 0.98 and 0.97 respectively (Table 4). The linear terms of A (MD) and C (CMC) had a significant effect on FD at 1% level of significance while B (SPI) had insignificant effect. The coefficients of process variable (Table 4) described that MD had adverse effect, whereas positive effect induced by CMC on FD which shows that FD decrease with an increase of MD concentration but increased with increase in CMC concentration (Fig. 4). When MD concentration was increased, there was a noticeable decrease in foam stability and density. Foam loses its viscosity and forms huge bubbles when it has a high concentration of foaming agent and a low concentration of foam stabiliser. As a result, when tiny bubbles of gravity are added, foam collapses by enlarging its bubbles [28]. Similar results were also reported by Abbasi and Azizpour [11] and Krasaekoopt and Bhatia [30]. The quadratic term of
all $A^2$, $B^2$ and $C^2$ had a significant effect (P<0.001) of non-linear difference in FD due to alter in proportion of MD, SPI and CMC. The interaction terms had no significant effect on FD. Low density foam provides a larger surface area to the medium of drying air, which speeds up the process of removing water during drying [31].

Optimization of the foaming behaviour of jamun pulp was achieved following numerical optimization technique with maximizing the FE and FS and minimizing the FD values. The optimized conditions were obtained as 5.47% of MD concentration, 1.02% of SPI concentration and 1.06% of CMC concentration when the response functions were FE of 93.93%, FS of 91.60%, and FD of 481.71 kg/m$^3$. The desirability function value at optimized condition was found to be 0.89.

3.2 Drying of foamed jamun pulp

The foamed jamun pulp prepared under the optimized condition, was dried in a hot air dryer at 50, 60 and 70°C temperature. The drying times to achieve the moisture content of dried powder from within 13.2% to 10.5% (db) were recorded to be 570, 480 and 450 min for 50, 60 and 70°C temperature respectively (Fig. 5). The fastest drying rate was observed at 70°C (Fig 5) as compared to 50 and 60 °C. The drying characteristics (Fig. 5 and 6) are similar to the results of foam mat drying of banana [17, 32], Khodifad et al. [33] and Omolola et al. [34] both noticed a decrease in moisture content and moisture ratio with rising temperature in foam mat drying of custard apple and banana pulp. The rapid transformation of water into vapour may be caused by an increase in heat between air voids. The porous construction and sufficient surface area may have contributed to the enhanced moisture migration via the capillary with rising temperature. According to Djaeni et al. [35], increased pulp surface area results in a higher moisture removal rate. Stable foam causes an increase in porous structure, a faster drying rate, and a reduction in drying time [36].

3.2.1 Effective moisture diffusivity

The average values of effective moisture diffusivities of foamed jamun pulp were found to be 8.978×10$^{-11}$, 1.084×10$^{-10}$, 1.246×10$^{-10}$ m$^2$/s at temperatures of 50, 60, 70 °C respectively. The effective moisture diffusivity increased with increase in drying air temperature due to the fact that the foaming aids enhanced the movement of water molecules. The drying temperature, increased surface area, and enhanced pore size all contributed to faster moisture evaporation from the foamed sample [33]. The increased pore space and surface area of the foamed pulp may have contributed to a reduction in drying time and an increase in $D_{eff}$ [37] at higher temperature.

3.3 Powder characteristics of foamed jamun pulp

3.3.1 Bulk density and Tapped Density

One of the key factors influencing the quality of powder is density. Bulk density is a parameter used to describe the powder product’s quality for economic and practical reason [38]. The bulk density of optimized foam-dried jamun powder was found to be varied between 0.128 and 0.154 kg m$^{-3}$ whereas the tapped density ranged from 0.146 to 0.193 kg m$^{-3}$ (Table 5). Similar kinds of results were also obtained in case of banana [17], blueberry [39] and fig [28] foam mat drying. The increase in moisture evaporation, which causes structural fragmentation and breakage and form air voids, may be the cause of the density drop observed with temperature from 50 to 70 °C [38].

3.3.2 Flowability

The flowability of powder is highly influenced by physical factors such as particle size distribution, shape, bulk density, moisture content, interparticle forces, and so on. Powder flow characteristics were measured by the CI and HR values. As per the standard value, CI values of less than 15% and HR values of less than 1.18 show good flowability [20]. The CI values and HR values were found to be in the range of 12.26±0.30 to 21.28±1.91 and 1.13±0.003 to 1.27±0.03 % respectively. It was observed that the flowability values increased as the drying temperature increased. The foam dried jamun powder had acceptable flowability properties depending on the CI and HR values. The increase value in flowability may be due to the reduction in moisture content. The air entrapment in foaming operation with the addition of foaming and stabilising agent help to increase the glass transition temperature of sugars, gives the sample its free-flowing in nature and reduce its hygroscopicity [40]. The increase value in flowability with higher temperature of drying may be due to the reduction in moisture
content. Similar results were also reported in foam mat dried powder of ripe banana [17] and muskmelon powder [20].

3.3.3 Total anthocyanin content
The total anthocyanin content (TAC) of dehydrated jamun powder was found to be 61.06, 53.49 and 35.63 mg/100g at 50, 60 and 70°C respectively (Table 5). The TAC was reduced with increase in the drying air temperature. The higher temperature in foam mat drying resulted in negative impact and thus reducing the TAC of the sample [41]. Mussi et al. [7] had reported that the range of air temperature (60-80°C) might be a significant factor responsible for the anthocyanin degradation. Abbasi and Azizpour [11] had found highest anthocyanin content retained in sour cherry dry powder at moderate temperature (65°C) using the foam mat drying technique. In the present investigation however, total anthocyanin was highest (61.06±4.68) at the lowest temperature of drying i.e. 50 °C. The variation of TAC between 50 and 60°C were statistically non-significant, however at 70°C it was significantly (p<0.05) reduced as compared to the lower temperatures.

3.3.4 Total phenolic content
The phenolic content (TPC) of foam mat dried jamun powder at 50, 60 and 70 °C was found to be 278.49, 230.96 and 195.78 respectively (Table 5). TPC was observed to be decreased with an increase in drying temperature. The reduction in TPC for increase in temperature was noticeable due to heat sensitive component and susceptible to oxidation due to structural disruption in powder [42]. Similar result was obtained by Samyor et al. [24] reported that the TPC of the foam mat dried passion fruit powder was reduced considerably with increase in drying air temperature from 40-60°C. The statistical analysis showed, there was significant difference (p<0.05) in variation of TPC with drying air temperature from 50 to 70 °C and it was in a decreasing trend.

3.3.5 Water solubility index (WSI)
The powder's solubility is a key indicator of its capacity to remain uniformly mixed with water. WSI analyses the quantity of soluble substances in the powder. WSI of jamun powder dried at 50 to 70°C found to be ranged between 58.55 to 74.28 %. The WSI values of jamun powder were adjacent to those of foam mat dried ripe banana powder [17] and pineapple powder [38]. Increase in drying air temperature were observed to result in higher WSI of jamun powder. Possible causes of the increase in solubility of powder with increased temperature of drying may be due to higher rate of moisture removal and porous structure helps in breaking of molecular bonds of sugar molecules [38] during solution with water.

3.3.6 Hygroscopicity
The hygroscopicity of jamun powder ranged from 12.43 to 14.22 g/100g (Table 5) with drying temperature varying from 50 to 70°C. It was observed that increasing temperature increased the dried jamun powder's hygroscopicity, however the change is almost non-significant (p<0.05). Fruit powder usually contains mono and di-saccharides in the pulp, which is the major cause of its hygroscopicity. Having larger surface area than complex sugars, simple sugars enable the hydroxyl group to react with water molecules more [43]. Similar outcomes were shown when sugar-rich fruit was used e.g., dried mango powder [44]. Similarly, Salahi et al. [45] have also reported increasing hygroscopicity of cantaloupe pulp powder due to faster reduction of moisture content of powder with increase in drying temperature and increase in the water gradient between the powder and the surrounding air during drying.

3.3.7 Colour
Table 6 shows the change in colour of the powder at different temperatures in terms of L, a and b values. The observed L value of powder ranged from 43.00±0.79 to 51.73±0.33, a value ranged from 19.50±0.30 to 23.46±0.72 and b value ranged from -1.56±0.09 to 9.03±0.13 at a temperature between 50-70°C. The lightness value represents a measurement of colour along the light-dark axis and dried jamun powder was lighter in colour with increasing temperature. The redness (a value) and blueness (b value) of powder was also reduced with increasing drying temperature from 50 to 70 °C. Similar observations were obtained by Watharkar et al. [17] for foam dried ripe banana powder and muskmelon powder [20]. However, lime juice that has been foam dried exhibits a decreasing lightness as drying temperature increased [46]. When the drying temperature is increased, the reducing sugar may bind with an amino group of protein, resulting in the Maillard reaction and the breakdown
of the total anthocyanin content may be the cause of changing of colour towards lighter and less redness or blueness of the foam dried jamun powder.

### 3.3.8 FTIR analysis

The FTIR spectra of jamun powder was assessed to identify the presence of functional groups and structure clarification in the frequency region of 4000-400 cm\(^{-1}\). The obtained total of 10 peaks of jamun powder are represented in Fig. 7 which depicts the intensity of the major peaks. The FTIR analysis of both foamed and non-foamed dried jamun powder where the spectral stretching range varies from 513.52 to 3299.94 cm\(^{-1}\) and 458.56 to 3294.34 cm\(^{-1}\). Band ≡C-H stretching, N-H symmetric and O-H stretching were present mainly due to the presence of phenolic group compounds such as alkynes, amides and carboxylic acids respectively. Moreover, esters, ketones, alkyl halides alcohols, ether and many aromatic compounds were found in the obtained spectrum of both foamed and non-foamed jamun powder. Peaks were obtained more prominently in optimized foamed dried sample than the non-foamed dried jamun powder.

### 3.3.9 Scanning electron microscopy (SEM)

In terms of morphological characteristics, the powder obtained after foaming (Fig. 8(a)) denotes a puffy and perforated surface, whereas the powder obtained without foaming (Fig. 8(b)) was thicker and fractured. Shrinkage was observed in the non-foamed sample which may be attributed due to the application of heat during the dehydration process. The porous nature of sample was linked with their lower bulk density. The formation of porous structures in powder may be owing to the entrapment of air into the foam. Similar finding was also obtained in foam mat freeze drying of blueberry juice powder with small openings and bulky structure using bovine serum albumin protein [36]. Several reports were discussed about a comparable result in the case of foamed dried of mango pulp powder [47], ripe banana pulp powder [17] and muskmelon foam powder [48].

### 4.0 Conclusion

Foaming of jamun pulp was enhanced with addition of SPI and MD as foaming agent and addition of CMC was found to be effective in giving more stabilised foam with better foaming capacity as well as better drying and powder behaviour. The optimized ingredient compositions were found out to be 5.47% of MD, 1.02% SPI and 1.06% CMC for achieving 93.93% of foam expansion, 91.60% of foam stability and 481.71 kg/m\(^3\) of foam density. The effective moisture diffusivity of the jamun foam ranged from 8.978×10\(^{-11}\) to 1.246×10\(^{-10}\) m\(^2\)/s. The porous nature of the powder was confirmed with its light weight, low bulk and tapped density. The dried jamun powder also demonstrated the highest quality in terms of solubility and flowability. The Total anthocyanin content, total polyphenol contents as well as the colour values (L, a, b) of powder were affected with increase in drying temperature from 50 to 70 °C. The FTIR analysis of both foamed and non-foamed dried jamun powder, where the spectral stretching range varies from 513.52 to 3299.94 cm\(^{-1}\) and 458.56 to 3294.34 cm\(^{-1}\) respectively, (band ≡C-H stretching, N-H symmetric and O-H stretching) showing the presence of phenolic group compounds such as alkynes, amides and carboxylic acids. The surface microstructure observed through SEM suggested a puffy and perforated surface of foam mat dried powder, whereas, the powder obtained without foaming was more compact and fractured. The foam mat dried Indian blackberry or jamun powder from the present investigation can be utilized for further innovative product developments or used as such as a nutritionally reach and bioactive components packed fruit juice powder.

### Abbreviations

- % Percentage
- °C degree Celsius
- °B degree Brix
- AOAC Association of Official Analytical Chemists
- FTIR Fourier infrared spectroscopy
- RSM Response Surface methodology
- BBD Box-Behnken Design
- MPP Metalised Polyester Poly
- var. variety
- GAE gallic acid equivalent
- ppm parts per million
Acknowledgement
The authors acknowledge the All-India Co-ordinated Research Project on Post Harvest Engineering and Technology, Indian Council of Agricultural Research, Department of Agricultural Processing and Food Engineering, College of Agricultural Engineering and Technology, Odisha University of Agriculture and Technology, Bhubaneswar, India for their financial supports with laboratory facility for conducting the study. Also, the authors are thankful to Central Instrumentation Facility, Odisha University of Agriculture and Technology, Bhubaneswar, India for providing modern laboratory facilities for conducting this investigation.

Conflict of Interest
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.

Authors’ contribution
I Sahu planned, conducted the experiments and written the manuscript. M Mohapatra assisted in planning of experiments, statistical analysis, written and corrected the manuscript. M Panda guided and assisted in determination of powder characteristics. R Nayak helped in conducting the biochemical analysis. U S Pal guided in interpreting the technical data. K Rayaguru helped in analysis of the data and facilitating the research work. S K Dash guided and supported in overall accomplishment of the research work.

Guideline statement
The authors confirm that all procedures of the experiments, including the collection of jamun fruit from plant materials and processing of the fruit pulp, complied with relevant institutional, national, and international guidelines and legislation.

Data availability statement
The datasets used and analysed during the current study available from the corresponding author on reasonable request.

References


**Figure 1**

Process flow chart of preparation of jamun powder using foam mat drying
Figure 2

Response surface plots showing the effect of MD, SPI and CMC on FE

Figure 3

Response surface plots showing the effect of MD, SPI and CMC on FS
Response surface plots showing the effect of MD, SPI and CMC on FD

Drying rate, g water/g dry matter-min

Moisture content, % (db)

Figure 4

Figure 5
Drying rate as a function of drying temperature and moisture content

Figure 6

Moisture ratio as a function of drying temperature and time

Figure 7

FTIR spectra of a) foamed and b) non-foamed dried jamun pulp
Figure 8

Photomicrograph of jamun pulp powder (a) foamed and (b) non-foamed powder sample

Supplementary Files

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- TableFoammatdryingofjamunpulp1.docx