

Influence of Drying Temperature on the Quality Attributes and Bioactive Retention of *Syzygium cumini* (Jamun) Pulp Powder

Anjali Gautam^{1,2}, Manisha Kaushal^{2*}, Nisha Sharma^{3*}, Devina Vaidya², Anil Gupta², Dimple Tanwar¹, Jyoti Mehta⁴, Kiran Bisht⁵

¹School of Bioengineering, Faculty of Applied Sciences and Biotechnology, Shoolini University of Biotechnology and Management Sciences, Solan, Himachal Pradesh, India

²Department of Food Science and Technology, Dr Yashwant Singh Parmar University of Horticulture and Forestry Nauni, Solan

³Department of Microbiology, School of Life & Applied Sciences, Maya Devi University, Dehradun, 248011, Uttarakhand, India

⁴School of Biotechnology, Faculty of Applied Sciences and Biotechnology, Shoolini University of Biotechnology and Management Sciences, Solan, Himachal Pradesh, India

⁵Department of Biosciences, Graphic Era (Deemed to be University), Dehradun, 248002, Uttarakhand, India

***Corresponding author:**

Dr Manisha Kaushal: manishapht@gmail.com

Dr Nisha Sharma: sharma.nisha11685@gmail.com

40 Graphical Abstract



Jamun pulp was mechanically dehydrated and milled into fine powder. The standardized powder showed significantly higher phenolics, ascorbic acid, and antioxidant activity than commercial fruit juice powders. These findings indicate that dehydration at 55°C yields a bioactive-rich Jamun powder suitable for functional food and nutraceutical applications.

48 Abstract

The present study was conducted to develop Jamun (*Syzygium cumini* L.) pulp powder with the objective of preserving its bioactive phytochemicals and nutritional quality. Jamun pulp was dehydrated using controlled mechanical drying at four different temperatures (45°C , 50°C , 55°C , and 60°C), followed by pulverization into fine powder. Among the tested conditions, drying at 55°C was identified as the optimum temperature, yielding the highest drying efficiency (12.43%) and retaining the maximum total anthocyanin content (998.32 mg/100 g). The standardized mechanically dried Jamun pulp powder exhibited significantly higher levels of total phenolics, ascorbic acid, and antioxidant activity compared to commercially available fruit juice powders. Additionally, the powder maintained a low moisture content, which enhanced its shelf stability without compromising its physicochemical properties. The effective preservation of bioactive constituents under controlled drying conditions highlights the importance of optimized processing in minimizing nutrient degradation. Overall, the findings demonstrate that mechanical dehydration at 55°C is an efficient method for producing bioactive-rich Jamun pulp powder, which can serve as a natural antioxidant source and a promising functional ingredient for health-oriented food formulations and nutraceutical applications.

Keywords: Jamun Pulp, Drying, Powder, Anthocyanins, Scanning Electron Microscopy, FTIR

1. Introduction

Syzygium cumini (L.) Skeels, commonly known as jamun or black plum, is a tropical fruit valued for its rich content of bioactive compounds, particularly anthocyanins, phenolics, flavonoids, and vitamin C that contribute to its vigorous free radical scavenging activity and functional food potential (Shavronskaya et al., 2023). These natural compounds are known for their potent antioxidant, antidiabetic, and anti-inflammatory properties, making jamun an excellent candidate for developing functional foods and nutraceutical ingredients. However, the fruit is highly perishable due to its high moisture content and soft texture, which limits its availability and market potential in fresh form (Feng et al., 2023). The fruit has a deep purple to black colour due to the presence of anthocyanin pigments, which are known for their antioxidant and health-promoting effects (Kaur, 2024).

Despite its high nutritional value, the post-harvest utilization of jamun is limited because the fruit is highly perishable, has a short harvesting season, and undergoes rapid spoilage after picking. Therefore, to increase its shelf life and ensure year-round availability, processing techniques such as drying can be effectively employed (Kanauija et al., 2025). Drying is a traditional and widely used preservation method that reduces the moisture content of the product, thereby preventing microbial growth and enzymatic spoilage. Drying is one of the most effective methods to extend the shelf life of jamun by reducing its moisture content and inhibiting microbial spoilage (Giri et al., 2025). Converting jamun pulp into a powder form not only enhances its stability but also provides a convenient ingredient for use in various food formulations, such as beverages, yoghurts, bakery products, and ice creams (Ratti et al., 2024). Among the various factors influencing the drying process, temperature plays a crucial role in determining the quality attributes (such as colour, texture, solubility, and rehydration ability) as well as the retention of bioactive compounds (Yikilkan et al., 2025). While higher drying temperatures can shorten the drying time and improve process efficiency, they may also cause thermal degradation of heat-sensitive nutrients, such as anthocyanins and vitamin C. Conversely, lower temperatures help preserve bioactive compounds but may lead to longer drying times, higher energy costs, and potential microbial risks (Yin et al., 2025). Converting jamun pulp into powder form through drying enhances storage stability, reduces packaging and transportation costs, and provides a convenient ingredient for use in various food formulations such as smoothies, candies, yoghurts, bakery products, and health supplements (Rafiquzzaman et al., 2025).

Moreover, jamun powder can serve as a natural colorant and functional additive due to its anthocyanin content. However, the drying temperature has a significant influence on the quality and retention of bioactive compounds in fruit powders (Swaminathan et al., 2015). High drying temperatures can cause degradation of heat-sensitive compounds, such as anthocyanins, vitamin C, and phenolics, leading to a loss of color, flavor, and antioxidant activity. On the other hand, very low temperatures may prolong drying time, increase energy consumption, and result in powders with poor physical characteristics, such as reduced flowability, solubility, and rehydration capacity (Gamal et al., 2023). Understanding how different drying temperatures affect these bioactive compounds helps in developing an optimized drying process that retains the maximum nutritional and functional qualities of the product (Wojdyło et al., 2020).

The present study focused on evaluating the effect of different drying temperatures on the physicochemical characteristics, colour attributes, and bioactive compound retention of *Syzygium*

cumini pulp powder. The outcomes of this study provide promising insights for the development of bioactive-enriched *Syzygium cumini* (jamun) powder standardized by its improved shelf stability, superior sensory attributes, and enhanced nutritional quality. The optimized drying process not only aids in the preservation of heat-sensitive phytochemicals such as anthocyanins, phenolics, and vitamin C but also ensures desirable physicochemical properties, including colour, solubility, and flowability. Consequently, the resultant jamun powder holds significant potential as a functional ingredient in the formulation of value-added food products, beverages, nutraceuticals, and dietary supplements aimed at promoting health and wellness.

2. Materials and methods

2.1 Raw Material

Jamun fruits were procured from the Local market of Solan (Himachal Pradesh) and Chandigarh in the month of July-August, 2022, while wild jamun fruits (var- Ra- jamun) were procured from district Bilaspur (HP) from an altitude of 1800 m in the month of June-July, 2022.

2.2 Optimization of conditions for the preparation of jamun powder

The experiment was conducted to optimize the drying parameters for Jamun pulp to achieve maximum drying efficiency and anthocyanin retention. The goal was to develop a scientifically standardized process for producing high-quality, nutrient-rich Jamun powder. Pulp was prepared and passed through a pulper for the extraction of pulp. The extracted pulp was homogenized, heated, and filled in pre-sterilized glass bottles, followed by processing at $90 \pm 2^\circ \text{C}$ for 25 minutes. The pulp was then used for standardizing the conditions of powder preparation by drying it in a mechanical dehydrator at different temperatures (45°C , 50°C , 55°C , and 60°C), which was subsequently pulverized into a fine powder. The conditions were optimized on the criteria of drying yield and total anthocyanin content.

2.2.1 Powder Yield (%)

Yield of fruit powder was estimated by dividing the dried material by the fresh weight of fruit expressed in terms of per cent with the formula given below:

$$\text{Yield (\%)} = \frac{\text{Weight of dried material}}{\text{Fresh weight of fruit}}$$

2.2.2 Flow properties of powder

The powder flow properties, or flowability, determine the powders potential to flow in a desired manner in a specific instrument or equipment. The flowability is affected by various factors, including particle size, surface texture, moisture content, and sugar content. The fruit powders were evaluated for their flow properties by determining their bulk Density, tapped Density, Carr index, Hausner ratio, and angle of repose, following standard procedures (Suhag et al., 2024).

2.2.3 Bulk Density and Tapped Density

The bulk density and tapped density of Jamun pulp powder were determined using a modified method described by (Sarabandi et al., 2018). To measure bulk density, 20 g of the powder sample was carefully transferred into a 50 mL graduated cylinder. The cylinder was handled gently to avoid compaction, and the initial volume occupied by the powder was recorded. Bulk density was then calculated as the ratio of the powders mass to this measured volume. For tapped density, the same cylinder containing the sample was tapped 100 times on a laboratory bench from a height of approximately 10 cm. This tapping allowed the particles to settle more closely together, reducing

the powder volume. The tapped density was calculated by dividing the mass of the powder by the reduced volume after tapping. These measurements help in understanding the flow characteristics, packing behavior, and handling properties of the Jamun pulp powder, which are essential for processing, packaging, and product formulation.

$$\text{Bulk Density} = \frac{\text{Mass of powder}}{\text{Bulk Volume}}$$

Where, Mass of powder = W (in grams); Bulk volume = Vb (in mL or cm³)

Tapped density

Tapped density refers to the mass of the powder divided by the volume after tapping (usually after 100, 500, or 1250 taps).

$$\text{Tapped Density} = \frac{\text{Tapped Volume}}{\text{Mass of powder}}$$

Where, Mass of powder = W; Tapped volume = Vt

2.2.4 Hausner ratio and Carr compressibility

Carr Index and Hausner Ratio were calculated from bulk and tapped Density, which determines the flowability and Compressibility of powders. The scale of flowability according to the US Pharmacopeia is given in **Table 1**. The following formula was used:

$$\text{Hausner Ratio} = \frac{\text{Tapped Density (TD)}}{\text{Bulk Density (BD)}}$$

$$\text{Carr's Index (\%)} = \frac{\text{Tapped Density} - \text{Bulk Density}}{\text{Tapped Density}} \times 100$$

Table 1. Classification Scale for Powder Flowability

Carrs Compressibility (%)	Flow Behaviour	Hausner Ratio
Up to 10%	Exceptional flow	1.00–1.11
11–15%	Good flow properties	1.12–1.18
16–20%	Moderate / Fair flow	1.19–1.25
21–25%	Adequate / Passable	1.26–1.34
26–31%	Poor flowability	1.35–1.45
32–37%	Very poor flow	1.46–1.59

Above 38%	Extremely poor flow	>1.60
-----------	---------------------	-------

2.2.5 Colour measurement

The colour characteristics of the samples were evaluated using a Lovibond Colour Tintometer (Model PFX-I Series spectrophotometer). This instrument provided colour readings in both RYBN units and the standard CIE (Commission Internationale de l'Éclairage) colour space parameters, namely L^* , a^* , and b^* . The L^* value indicates the lightness of the sample on a scale of 0 to 100, where 100 represents pure white and 0 represents pure black. The a^* coordinate reflects the colour transition from green (negative values) to red (positive values), while the b^* coordinate represents the shift from blue (negative values) to yellow (positive values). Each sample was analysed in triplicate following the procedure outlined in (Adit et al., 2024) to ensure accuracy and reproducibility. In addition, chroma (C^*) and hue angle (h°), which describe colour intensity and the overall colour tone, respectively, were calculated using the formulas provided by (IAOAC, 2012). These parameters help in understanding the visual quality and consistency of the Jamun pulp powder.

$$h^\circ = \tan^{-1} \frac{b^*}{a^*}$$
$$C = \sqrt{(a^*)^2 + (b^*)^2}$$

Where L^* (darkness-lightness), a^* (red–green), and b^* (yellow–blue) are parameters of colour measurement.

2.2.6 Moisture content (%)

Moisture content was determined using a KI 250 (b) moisture analyzer based on the loss-on-drying principle. In this procedure, the instrument first records the initial weight of the sample, then heats it under controlled conditions to remove moisture. Once the sample is fully dried, the analyzer automatically measures the final weight. The difference between the initial and final weights represents the amount of moisture lost, allowing the moisture content to be accurately calculated.

2.2.7 Water activity (a_w)

A computer digital water activity meter (Rotronic Hygropalm) was used to measure the water activity (a_w) of the sample at room temperature. The sample was filled in a standard cuvette up to the rim and placed below the water activity meter sensor, which gives a direct reading of the sample's water activity according to (IAOAC, 2012).

2.2.8 pH

pH is defined as the negative logarithm of the molar concentration of hydrogen ions; it is the free hydrogen ion activity. The pH meter (ELTOP-3030 pH meter) was calibrated with buffer solutions of 4.0, 7.0, and 9.0. The pH of fruit pulp was taken directly with the pH meter according to (IAOAC, 2012). For powders and tablets, the pH was taken by reconstituting the sample. 1g sample was mixed using a magnetic stirrer in 10 ml of distilled water, and was kept for 1 hour before taking the reading in the pH meter.

2.3 Total soluble solids (TSS)

The total soluble solids of the fruit powder sample were prepared by mixing 1 g of the sample in 10 mL of distilled water and letting it stand for 1 hour. The total soluble solids were measured

using a hand refractometer (Model ERMA) of 0-32°B, 28-62°B and 58-92°B ranges. Three replications were taken for each sample, and the mean value was reported.

2.4 Titratable acidity (%)

Titratable acidity was determined by titrating a known volume of the sample against a standard solution of NaOH, using phenolphthalein as an indicator. For powder and tablet, the samples were prepared by weighing a known amount of sample and making up the volume with distilled water before using the filtrate to determine the titratable acidity. The titratable acidity was expressed as a percentage according to IAOAC, 2012 as per the given formula:

Titratable acidity (%)

$$= \frac{\text{Titre value} \times \text{Normality of alkali} \times \text{Volume made up} \times \text{Eq. weight of dominant acid} \times 100}{\text{Weight of sample} \times \text{Volume of aliquot} \times 1000}$$

2.5 Antioxidant activity (%)

Antioxidant activity (free radical scavenging) was measured, where 3.9 mL of 6×10^{-5} mol/L DPPH (2, 2-diphenyl-1-picrylhydrazyl) was used as a source of the free radical, was put into a cuvette with 0.1 mg of powder (sample extracted in methanol), and the absorbance was measured at 515 nm after 30 minutes, and methanol was used as a blank (Ranganna, 2009). Antioxidant activity was calculated using the following equation:

$$\text{Antioxidant activity (\%)} = \frac{\text{Ab(B)} - \text{Ab(S)}}{\text{Ab(B)}} \times 100$$

Where, Ab (B) = Absorbance of blank Ab (S) = Absorbance of sample

2.6 Total ash (%)

Total ash content was determined using a standard gravimetric procedure. A known quantity of the sample was placed into pre-weighed silica crucibles. The oven-dried samples (previously used for moisture determination) were first heated gently on a hot plate until most of the organic matter was charred and visible fumes were no longer produced. Following this initial carbonization, the crucibles were transferred to a muffle furnace and ashed at 550°C for 5 hours, ensuring complete oxidation of the remaining organic matter. The process continued until a clean, carbon-free white ash with a constant weight was obtained. The ash content was calculated based on the weight of the residue and expressed as a percentage on a fresh weight basis according to the method described in (Nagendra et al., 2023), as shown below.

$$\text{Ash (\%)} = \frac{\text{Weight of ash}}{\text{Weight of the sample taken}} \times 100$$

2.7 Total phenols (mg/100g)

The total phenolic content of the samples was estimated using the Folin–Ciocalteu colorimetric method, with catechol serving as the standard phenolic compound. Approximately 1 mg of the sample was placed in a clean mortar and homogenized with 1 mL of methanol to ensure efficient extraction of phenolic compounds. The mixture was then centrifuged using a Revolutionary

Research Centrifuge for 20 minutes at 5000 rpm to obtain a clear supernatant. From the resulting extract, 1 mL of an aliquot was transferred into a test tube, followed by the addition of 5 mL of 10% Folin–Ciocalteu reagent. After allowing the reaction mixture to stand for 10 minutes, 4 mL of 7% sodium carbonate solution was added to develop the characteristic blue coloration. The tubes were then incubated in a water bath maintained at 30–40°C for 40 minutes to facilitate complete colour development, after which they were cooled to room temperature. The absorbance of the samples was measured at 765 nm using a UV–VIS spectrophotometer (Model Shimadzu, Japan). Phenolic concentration was calculated based on the standard calibration curve prepared from catechol solutions ranging between 8 and 32 µg/mL. These measurements help in assessing the antioxidant potential and bioactive quality of the Jamun pulp powder, as phenolic compounds play a key role in imparting health benefits and stability to the product.

2.8 Ascorbic acid (mg/100g)

The ascorbic acid content was estimated using the AOAC method with 2,6-dichlorophenol indophenol dye. The sample was extracted in 3 percent meta-phosphoric acid and was titrated with dye to the pink color endpoint (Ranganna, 2009). The results were expressed as mg per 100 g of sample and calculated by using the formula given below:

$$\text{Ascorbic acid (mg/100g)} = \frac{\text{Titre value} \times \text{Dye factor} \times \text{Volume made up}}{\text{Aliquot of extract taken} \times \text{Weight of sample taken}} \times 100$$

2.9 Anthocyanins

Total anthocyanins present in all samples were determined by the spectrophotometric method given by (Ranganna, 2009). The procedure involves the extraction of anthocyanins with 8%t ethanolic HCl and measuring their optical Density at 535 nm in a UV-Vis spectrophotometer (Model UV-1650 P,C Shimadzu, Japan).

2.10 Equilibrium relative humidity (%)

The equilibrium relative humidity (ERH) of the powder samples was determined using the standard static gravimetric method. Approximately 5 g of the sample was evenly spread on pre-weighed petri dishes and placed inside desiccators containing sulfuric acid (H₂SO₄) solutions of different concentrations. These solutions generated a wide range of controlled relative humidity conditions, covering 0–100% RH. The samples were allowed to equilibrate for 24-hour intervals, during which the gain or loss in weight was recorded. This process was continued until each sample reached a constant weight, indicating moisture equilibrium with the surrounding environment. Once equilibrium was achieved, the moisture equilibrium data were plotted against the respective relative humidity levels to determine the ERH of the samples, following the procedures described in (Ranganna, 2009; Nagendra et al., 2023). The ERH experiments were carried out at ambient laboratory temperatures (18.5–31.5°C). To assess the stability and moisture sensitivity of the product, the critical and danger points for each sample were evaluated using the weight equilibrium method outlined by (Jiang et al., 2025; Wink et al., 1946). These parameters provide valuable insights into the storage behaviour, shelf life, and moisture-related quality changes in the Jamun pulp powder.

2.11 Fourier Transform Infrared (FTIR) Spectroscopy

FTIR analysis of the samples was performed using the potassium bromide (KBr) pellet method, following standard procedures. Approximately 2 mg of the finely dried sample was thoroughly mixed with spectroscopic-grade KBr and compressed into a transparent pellet suitable for infrared measurement. The spectra were obtained using a Perkin Elmer Spectrum 400 FT-IR/FIR

Spectrometer (USA), ensuring high accuracy and sensitivity. The infrared spectra were recorded over the 4000–450 cm^{-1} wavenumber range with a resolution of 0.4 cm^{-1} , allowing for precise identification of functional groups. The characteristic absorption bands observed in the spectra were interpreted according to the guidelines and classifications described in (Stuart et al., 2005). This analysis helped in identifying the major functional groups present in the Jamun pulp powder, offering insights into its structural, biochemical, and compositional characteristics.

2.122 Scanning electron microscopy (SEM) analysis

The particle size and morphology of jamun powder were analyzed using a digital Scanning Electron Microscope (SEM – JSM 6100 (JEOL)) equipped with a digital image processor instrument. Analysis was performed at the magnification range of 150X to 1000X and an accelerating voltage of 15 KV.

3. Result and Discussion

Jamun fruits have a high titre of vitamins and bioactive compounds like anthocyanins along with an appreciable amount of moisture content, thereby, to increase the shelf life and easy handling process, the fruit is converted into powders. Thus, the pulp procedure standardized was used for the preparation of jamun powder by conducting drying studies at different temperatures i.e., 45, 50, 55, 60, and 65°C in a mechanical dehydrator.

3.1 Dehydration characteristics of jamun powders

The dehydration characteristics of jamun powder prepared from pulp extracted by the hot extraction method with 0.2 percent citric acid presented in (Figure 1).

Dehydration characteristics of jamun pulp showed that, irrespective of the temperature of drying in comparison to the total period of drying, the rate of dehydration was fast during the initial period of drying. At 45°C temperature, about 50 percent (fwb) of the moisture was removed within the first 5.0 hours of drying, thereafter, the rate of drying slowed down. It took about 13 hours to dry the jamun pulp to a powder of about 8.25 per cent moisture content at 45°C drying temperature. Earlier (Nan et al., 2018), also stated that the rate of moisture removed is slowest during the falling rate period of drying than that of the constant rate period. Similarly, the drying characteristics (fwb) at 50°C. Showed that 50 per cent of the moisture from the pulp was reduced in the first 4 hours, and thereafter the drying slowed down, which took an overall time period of 10 hours from jamun pulp to dry to a moisture content of 8.03 per cent.

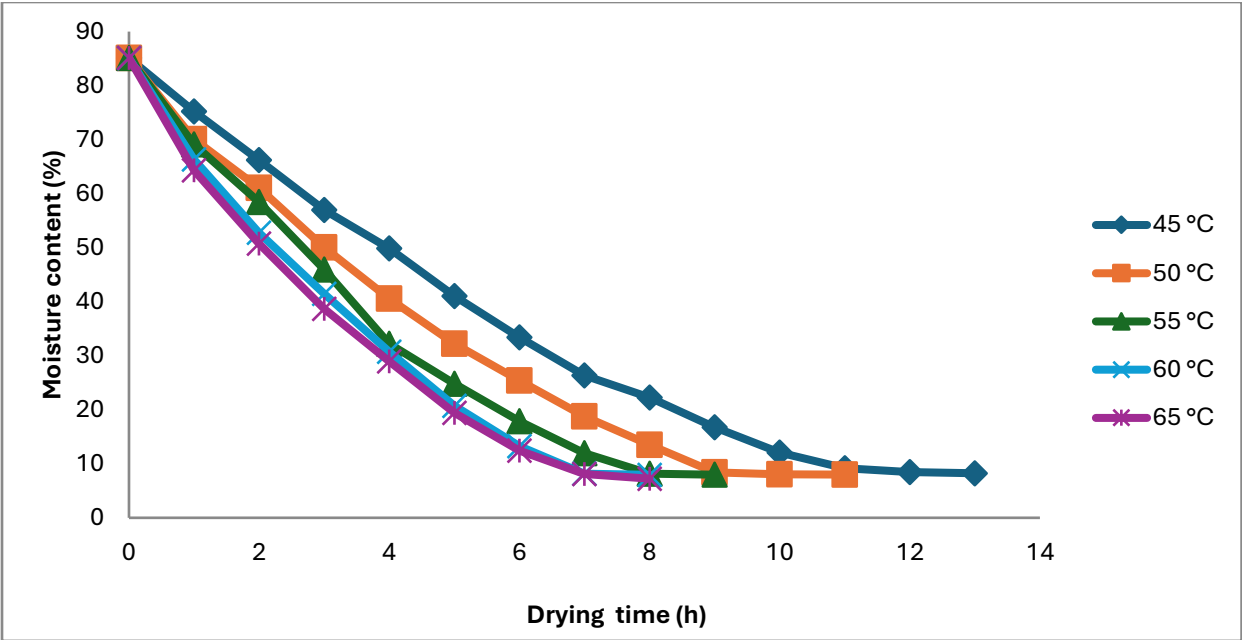


Figure 1. Drying behavior of jamun pulp at different temperatures

The dehydration characteristics of jamun pulp at 55°C showed that, during the total drying period, the rate of dehydration was fast during the initial 3 hours, during which 49.47% of the moisture was lost. Thereafter, the rate of drying slowed down, and it took 8.0 hours for the jamun pulp to reach a moisture content of 7.98%. At a 60°C drying temperature, it took approximately 7 hours to dry the jamun pulp to a powder with a moisture content of about 7.90%. Similarly, the drying characteristics (fwb) and moisture content of the pulp showed that at a 65°C temperature, 50 percent moisture was reduced in the first 2.0 hours and took about 6 hours to reduce the moisture content to 7.35 percent.

Dehydration characteristics shows that with the similar tray load and moisture content, the dehydration time taken for drying of jamun pulp at 45°C temperature for 13 hours with a powder yield of 8.71 per cent and the dehydration ratio as 11.48 while at 50°C temperature the time take to dry the similar quantity of pulp was 10 hours with powder yield of 9.90 per cent with dehydration ratio of 10:10. At drying temperature 55°C, 60°C and 65°C, the drying time taken was 8, 7 and 6 hours respectively with powder yield as 12.43, 10.91 and 10.54 percent respectively. On the basis of anthocyanin content, drying of jamun pulp at 55°C resulted in maximum anthocyanins as 998.32 mg/100g, as against 954.29 mg/100g at 65°C. The amount of anthocyanin content at drying temperatures of 45°C, 50°C, and 60°C was observed as 981.06, 989.39, and 960.28 mg/100g. Exposure to higher drying temperatures (60 and 65°C) leads to decreased anthocyanin content, while temperatures like 45 and 50°C may also reduce the amount of total anthocyanins due to prolonged heat treatment, leading to the destruction of anthocyanin content during the drying process. Thus, on the basis of total anthocyanin content, the drying temperature of 55 °C is hereby optimized as shown in (Table 2).

Table 2. Dehydration characteristics of jamun powders at different temperature conditions

Temperature (°C)	Drying time (h)	Dehydration Ratio	Yield (%)	Moisture (%)	Total anthocyanin content (mg/100g)
45	13	11.48	8.71	8.25	981.06
50	10	10.10	9.90	8.03	989.39
55	8	8.04	12.43	7.98	998.32
60	7	9.16	10.91	7.90	960.28
65	6	9.48	10.54	7.35	954.29

3.2 Colour characteristics of jamun powder

Colour is an important quality attribute in the food industry, which influences the consumer preference and acceptability of the product. The data presented in (Table 3 and Figure 2) represent the colour values (L^* , a^* , b^*) of jamun powder at different temperatures, namely 45, 50, 55, 60, and 65 °C. The colour values of jamun powder were reported to be 42.82 for L^* , 18.37 for a^* , and 41.43 for b^* at 45 °C drying temperature, 42.80 for L^* , 19.45 for a^* , and 43.45 for b^* at 50 °C, and 44.70 for L^* , 20.74 for b^* , 44.41 for a^* , at 55 °C. The L^* , a^* , b^* values were recorded as 40.30, 19.38, 45.42, respectively, at 60°C while 40.18, 19.03, 45.43, respectively at 65°C. The values were contrary to the values reported by (Shishir et al., 2014). The values a^* and b^* observed were in accordance with the values reported by (Wadia et al., 2020). However, the L^* values observed were higher.

Table 3. Colour characteristics of jamun powder at different temperatures

Properties	Temperature (°C)				
	45°C	50°C	55°C	60°C	65°C
L^* (Lightness)	42.82	42.80	44.70	40.30	40.18
a^* (Redness- Greenness)	18.37	19.45	20.74	19.38	19.03
b^* (Yellowness- Blueness)	41.43	43.45	44.41	45.42	45.43
ΔE	62.34	64.01	66.33	63.73	63.56

Thus, from the above results, it was concluded that drying of jamun pulp at 55°C temperature was standardized on the basis of a higher amount of total anthocyanin content (998.32 mg/100g) and colour value of the extracted powder. Thus, 55°C temperature for drying of jamun pulp was selected for further studies.

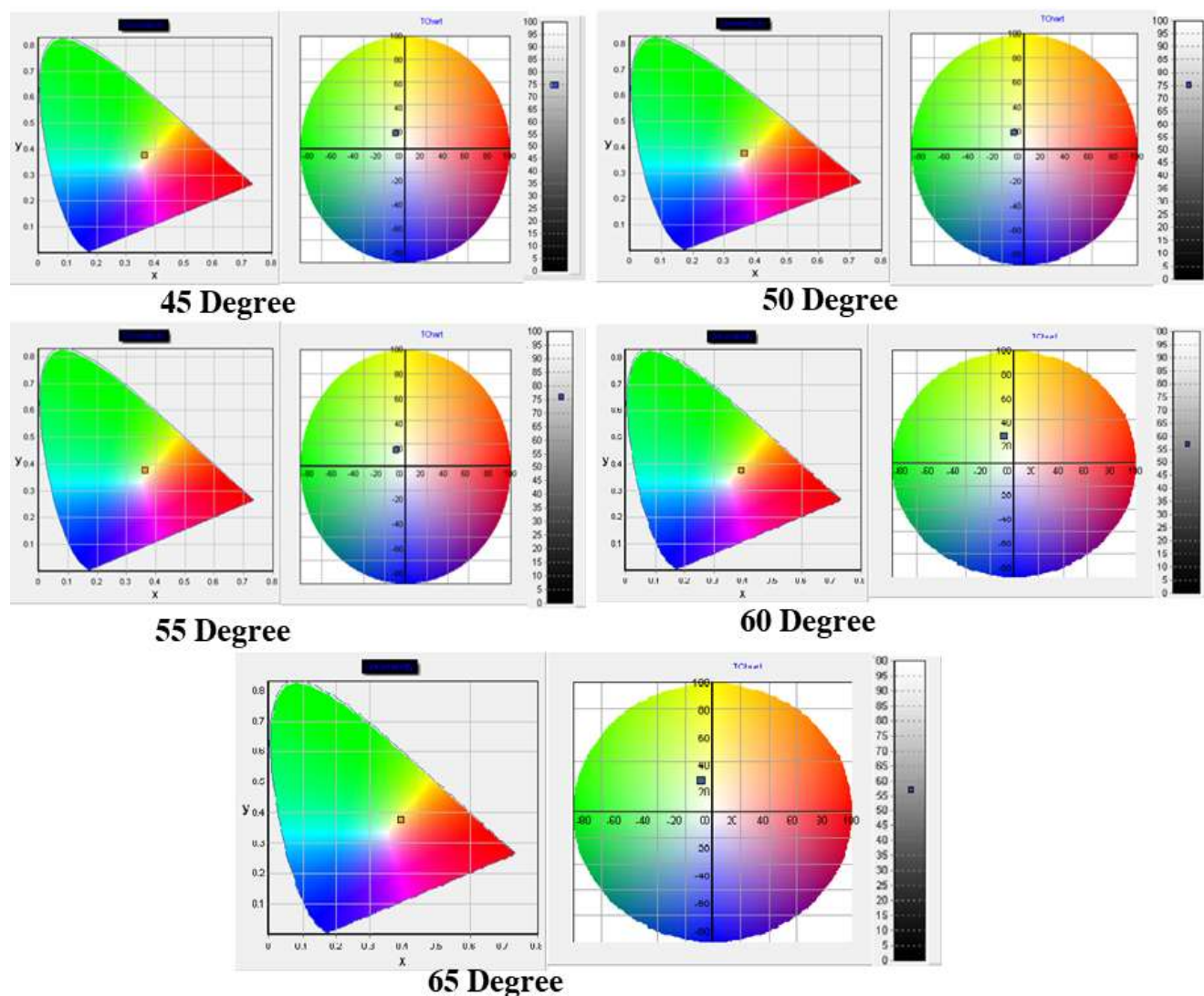


Figure 2. CIE color model readings of jamun powder dried at 45, 50, 55, 60, 65. °C

3.3 Flow properties of jamun pulp powder

The flow properties of jamun pulp powder dried at 55°C depicted the bulk Density and tapped Density as 0.66 ± 0.02 g/mL and 0.73 ± 0.03 g/mL, respectively (**Table 4**). The bulk Density of powder influences the arrangement of particles, and the powder with lower bulk Density will collapse easily when dispersed. The tapped Density of a powder is determined as the volume occupied after tapping, and it influences the powder's packing conditions (Caliskan et al., 2013; Akar et al., 2019). The water absorption index and water solubility index of jamun powder were 2.88 ± 0.05 and 0.57 ± 0.03 , respectively. High water absorption capacity determines the hydrophilic nature and high hydrogen bonding of protein molecules (Bellissent-Funel et al., 2016), and the high value of water solubility index in the finer fraction may be due to an emulsion formed, which restricts the separation of particles adequately after centrifugation and leaching of water-soluble components (Xiao et al., 2025). The lower the bulk Density, the higher the porosity in jamun pulp

powder, as 13.81 ± 0.08 percent. The bulk Density and tapped Density influence the Carr index and Hausner ratio, which are in inverse relationship with the powder compressibility and flowability. The Carr index was determined as (good), with the Hausner ratio as 1.25 (Passable), according to the values calculated and the classification given by Jebitta et al. (2016). The jamun pulp powder was determined to be moderately passable.

The inter-particle force, such as Van der Waal forces and the moisture content of the powder, influences the cohesiveness of the powder, the higher the moisture content, the less flowable the powder (Li et al., 2004). The flowability is also due to the particle adhesion, which is influenced by the sugar content in the powders, since the sugar content is higher in jamun pulp powder, thus the flowability of the powder was reduced (Pombo et al., 2020). The powders were further used for the extraction of anthocyanins.

Table 4. Different Flow properties of jamun powder

Parameters	Mean $\pm$ S.E*
Powder yield (%)	12.43 ± 0.22
Bulk Density (g/mL)	0.66 ± 0.02
Tapped Density (g/mL)	0.73 ± 0.03
Water absorption index (g/g)	2.88 ± 0.05
Water solubility index (g/g)	0.57 ± 0.03
Carr index (%)	Good
Porosity (%)	13.81 ± 0.08
Hausner ratio	1.25 (Passable)

S.E*= Standard error

3.4 Chemical characteristics of jamun powder

The chemical characteristics of jamun powder (**Table 5**) revealed the moisture content and water activity as 7.98 ± 0.18 per cent and 0.36 ± 0.04 , respectively, which were similar to the values observed by (Luke et al., 2005). The TSS, pH, and titratable acidity of jamun powder were observed to be $67.40^\circ\text{B} \pm 0.08$, 3.70 ± 0.12 , and 9.53 ± 0.10 percent, respectively. The ascorbic acid, total phenols, and anthocyanin content were recorded as 18.43 ± 0.27 , 1025.83 ± 0.80 , and 998.83 ± 0.72 mg/100g, respectively. The data reported were in accordance with the values given by Rao et al. (2011) and Verma et al. (2018) in guava powder.

The moisture content of the powder is reduced during drying, which is responsible for significant changes in the chemical characteristics of the fruit powders compared to the fresh fruit (Kucharska et al., 2025). Removal of moisture content concentrated the bioactive compounds manifold, thus resulting in an overall increase in the compounds. Further, the titratable acidity of the fruit powders increased during dehydration, as the drying temperatures increased the molecular vibrations, which prevent hydrogen bond formation, resulting in free H^+ ions contributing to the increased acidity (Moldovan et al., 2021). The increase in total phenols, anthocyanin content, and antioxidant activity during drying may be attributed to the release of bound phenolic acids at high temperatures, which have a positive correlation with radical scavenging activity (Babaei et al., 2025; Zhang et al., 2025). Decrease in ascorbic acid was probably due to its heat, light, and oxygen-sensitive nature as well as the dilution effect exerted by the addition of foaming agent (Yin et al., 2022). Moreover, the extracted jamun powder contained a significant amount of macro minerals,

including sulfur (6.90 ppm), phosphorus (8.89 ppm), copper (0.28 ppm), zinc (0.78 ppm), and iron (14.09 ppm).

Table 5. Various chemical characteristics of jamun powder

Parameters	Mean $\pm$ S.E*
Moisture (%)	7.98 $\pm$ 0.18
Water activity (a_w)	0.36 $\pm$ 0.04
TSS ($^{\circ}$ B)	67.40 $\pm$ 0.08
pH	3.70 $\pm$ 0.12
Titrateable acidity (% citric acid)	9.53 $\pm$ 0.10
Ascorbic acid (mg/100g)	18.43 $\pm$ 0.27
Total phenols (mg/100g)	1025.83 $\pm$ 0.80
Antioxidant activity (% DPPH)	86.79 $\pm$ 0.02
Anthocyanins (mg/100g)	998.32 $\pm$ 0.73
Minerals (ppm)	
Phosphorus	8.89
Sulphur	6.90
Copper	0.28
Zinc	0.78
Iron	14.09

S.E*= Standard error

3.5 Equilibrium Relative Humidity (ERH) Study of Jamun Powder

ERH data in jamun powder revealed that at 30.00 percent relative humidity, the powder had a moisture content of 5.52 percent. Data presented in **Table 6** further indicates that the powder exposed to 50.00 per cent relative humidity exhibited considerable changes in the colour and texture within 11 days of exposure.

Table 6. Measurement of the Equilibrium relative humidity (%) of jamun powder with time

Relative humidity (%)	Equilibrium moisture content (%)	No. of days to reach equilibrium	Remarks
0	1.438	14	Normal colour and texture
10	3.541	13	Normal colour and texture
20	4.536	13	Normal colour and texture
30	5.525	13	Normal colour and texture
40	6.410	13	Normal colour and texture
50	7.464	11	Normal colour and texture
60	8.768	10	Dark colour and soft texture
70	9.531	9	Dark colour and soft texture
80	14.43	7	Dark colour and lump formation
90	19.77	7	Lump formation with an off odour

100	28.04	5	Mould growth with an off odour
-----	-------	---	--------------------------------

Thus, the critical point and danger point (5% lower relative humidity than the crucial point) for jamun powder were recorded at relative humidities of 50.00% and 45.00%, respectively. At 40.00 per cent relative humidity, there was no change in the powder colour and flowability, while there was darkening of the powder when stored at relative humidity beyond 50.00 per cent. The product exposed to 80.00% relative humidity exhibited considerable changes in colour and texture within 7 to 9 days of exposure. Thus, the critical point (characterized by dark color and lumps formation in the powder) and danger point (5% lower relative humidity than the critical point) for the powder were calculated at 55% relative humidity. When the product was stored at 100 percent relative humidity, mould growth appeared after 5 days of storage. Henceforth, different fractions of jamun powder fall in the category of hygroscopic substances. Thus, it is evident that jamun powder should be stored in a relative humidity of 55 percent. The relationship between equilibrium moisture content and the number of days required for the powders to reach equilibrium is presented in (figures 3 and 4).

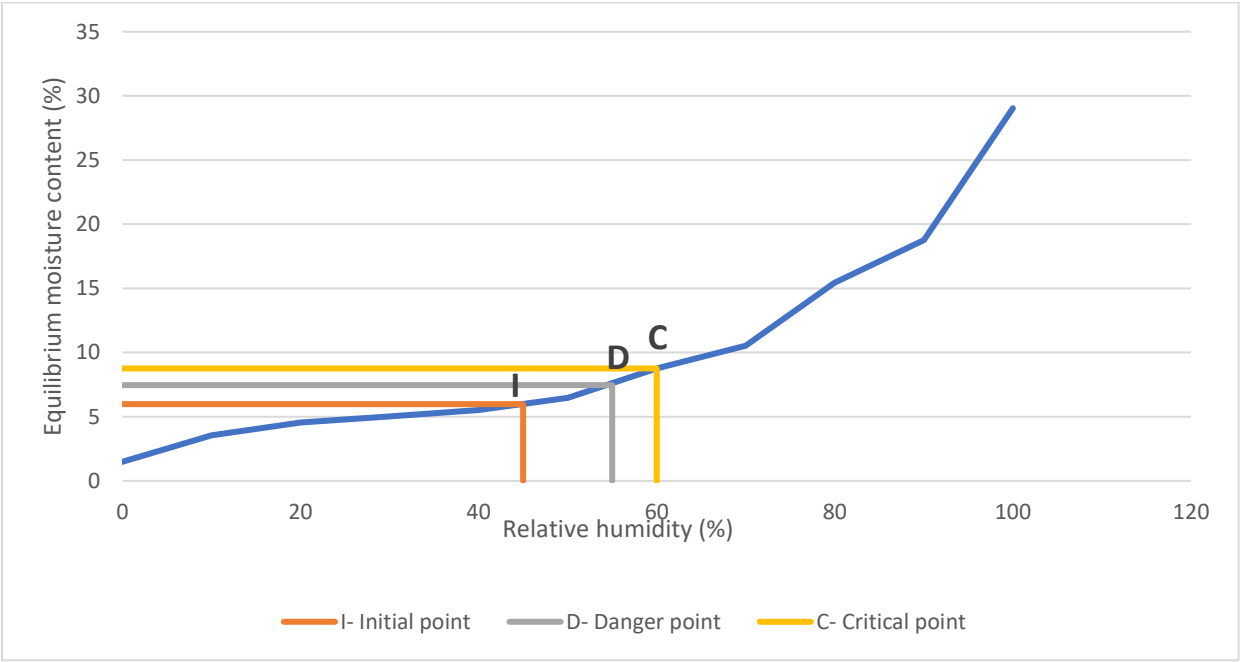


Figure 3. Humidity moisture equilibrium curve for jamun powder

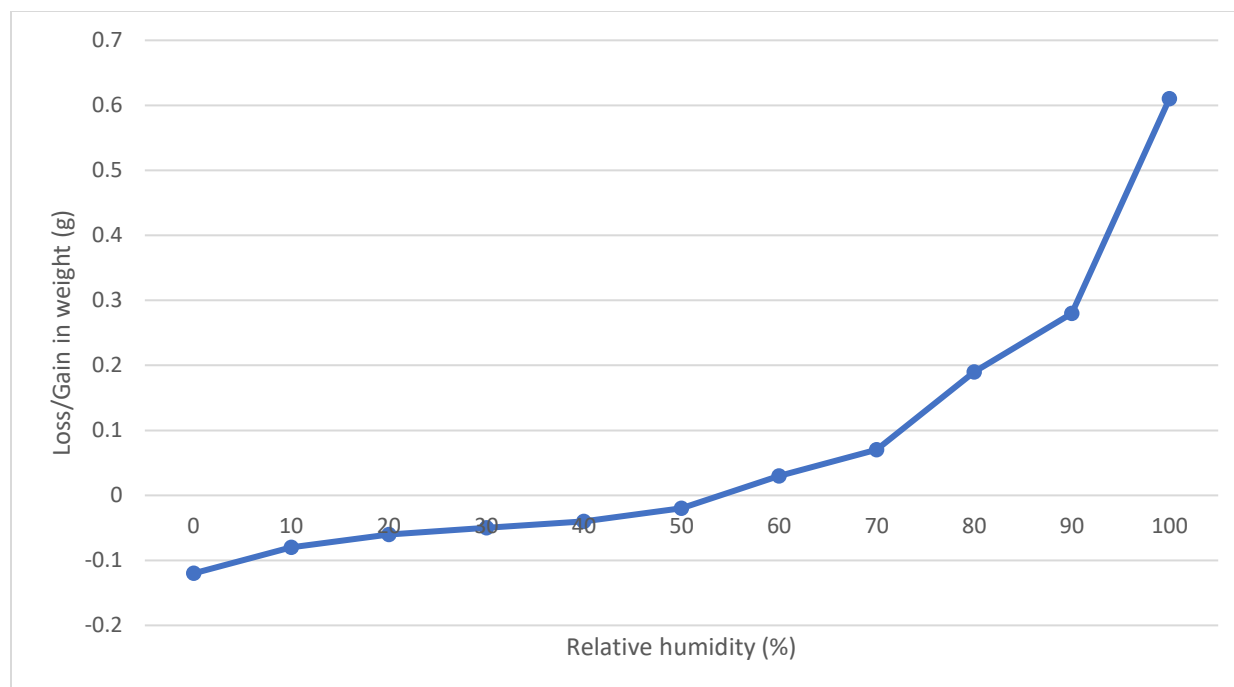


Figure 4. Graphical interpolation isotherm for jamun powder

The moisture-humidity relationship of the product indicated three key stability points

- Initial Point: At 45% relative humidity, the sample reached an equilibrium moisture content of 5.98%.
- Danger Point: At 55% relative humidity, the equilibrium moisture content increased to 7.46%, indicating the onset of potential quality deterioration.
- Critical Point: At 60% relative humidity, the equilibrium moisture content rose further to 8.76%, marking the threshold beyond which the product becomes highly susceptible to spoilage or structural changes.

The jamun powder was stored in glass vials for conducting the storage study, both under ambient and refrigerated conditions. There was a non-significant change in moisture content, phenols, and anthocyanin content during 6 months of storage. Thus, it was concluded that six months of storage of jamun powder under refrigerated conditions retained its maximum quality characteristics, and therefore, it was further used for anthocyanin extraction.

3.6 FTIR spectroscopy of jamun powder

Analysis of the fingerprint region of spectra revealed the presence of tri-substituted alkenes and anhydrides (Stuart, et al., 2005). An infrared spectrum of jamun powder is presented in the (figure 5). Revealed the peaks, whereas their intensities indicated the presence of a significant amount of phytochemicals in jamun powder (Table 7). The FTIR analysis of jamun powder showed the presence of hydroxyl group of alkenes and aromatic groups which signifies the compound anthocyanin (cyanidin) in particular, with the absorption ranging from 2258 (N=C=O) Isocyanate

class, 2228-2191 (C=C) Alkyne class, 2094 (C-H) aromatic compound, 1938 (C=C=C) Aldehyde class and 1045 (CO-O-CO) anhydride, respectively. FTIR spectra show the presence of the cyanidin compound of anthocyanin in jamun powder dried at 55°C.

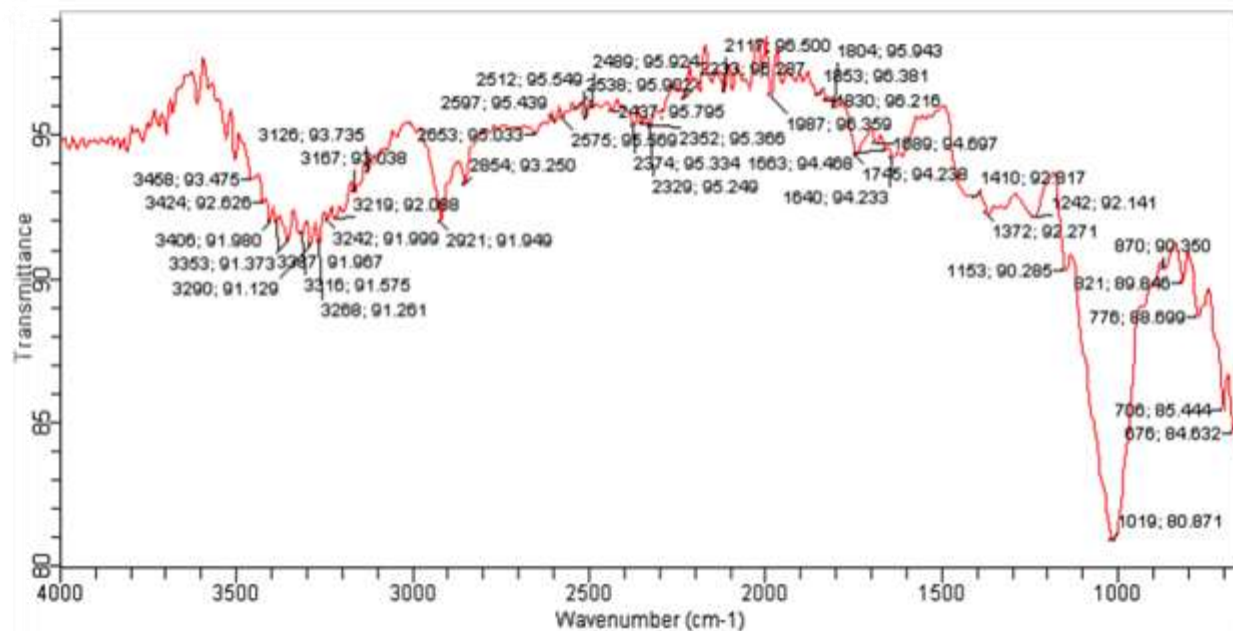


Figure 5. FTIR spectra of Jamun powder

Table 7. FTIR analysis of jamun powder

Absorption (cm⁻¹)	Appearance	Group	Compound class
2258	Strong, broad	N=C=O	Isocyanate
2228	Weak	C≡C stretching	Alkyne
2191	Weak	C≡C stretching	Alkyne
2094	Weak	C-H bending	Aromatic compound
1938	Medium	C=C=C	Allene
2853	Medium	C-H stretching	Aldehyde
1045	Strong, broad	CO-O-CO	Anhydride

3.7 SEM analysis of jamun powder

The external surface characteristics of the best treatment obtained at 55 °C were analyzed at different magnifications using SEM, depicted in **(Figure 6a-e)**. The morphology of the surface revealed a smooth and shriveled appearance of the particles in the jamun powder dried at 55 °C, which could be attributed to the shrinkage of particles after moisture loss. The surface was quite uneven, with a large number of grooves; however, no hollow pores or agglomerates were observed, even at 1000x magnification. This indicates that the drying temperature was optimal and did not alter the surface morphology of the powder. The lack of hollow pores also validates the flow

characteristics of the powder. Similar interpretations of surface morphology were given by (Azian et al., 2004; An et al., 2016).

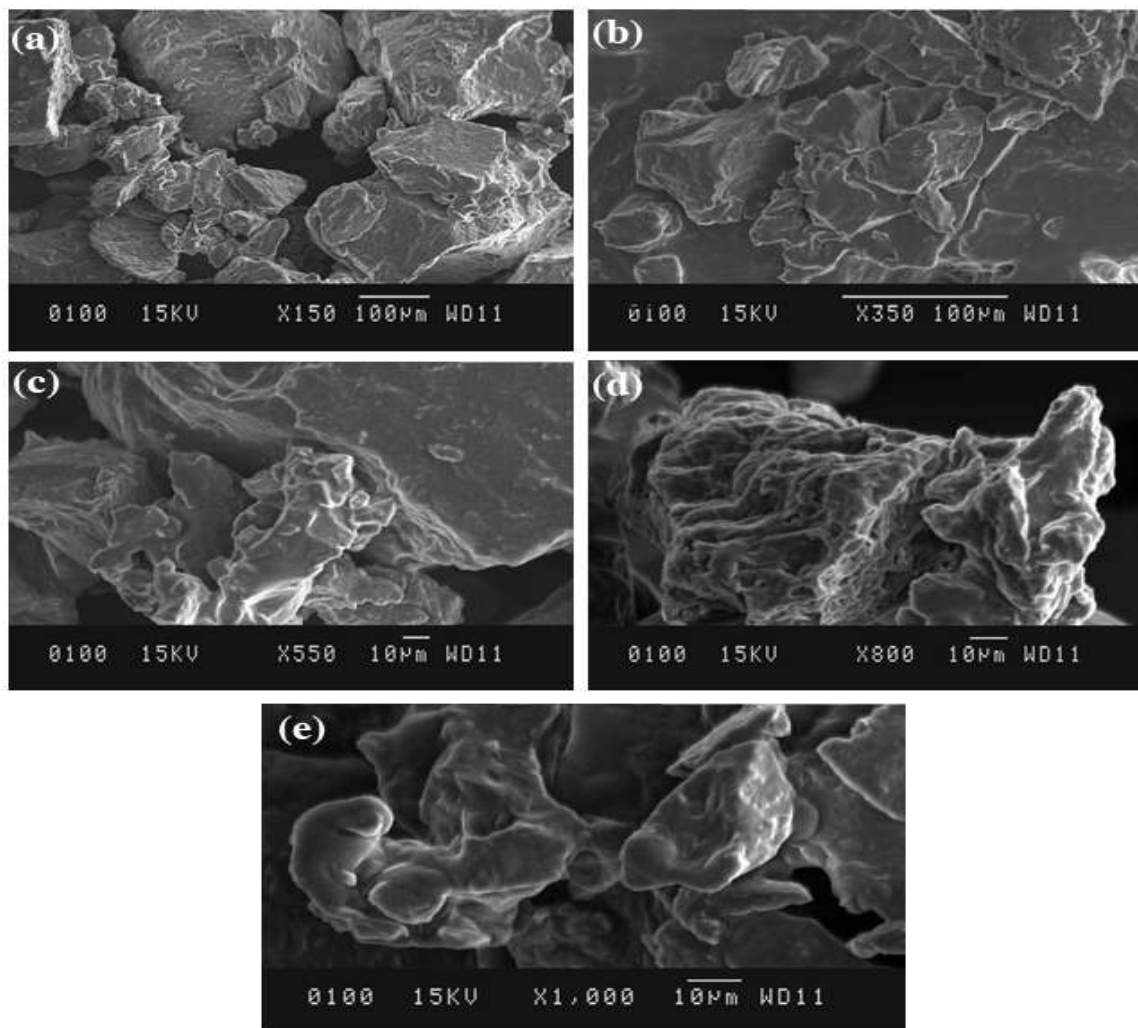


Figure 6. SEM analysis of jamun powder at 55°C at different magnifications viz., (a) 150, (b) 350, (c) 550, (d) 800 and (e) 1000

Conclusion

Mechanical drying of Jamun pulp at 55°C was identified as the optimal condition for producing high-quality Jamun powder. Drying at this temperature yielded superior results based on higher drying efficiency, as well as enhanced retention of total anthocyanins, total phenolics, ascorbic acid, and antioxidant activity. These optimized conditions ensured the production of premium-quality Jamun powder. The final characteristics of the powder were largely influenced by the drying process. By carefully controlling temperature and drying duration, it was possible to remove

moisture efficiently without compromising the nutritional integrity or sensory attributes of the fruit. Key physicochemical properties, including bulk density, moisture content, particle size distribution, and water activity, were thoroughly evaluated. The powder exhibited desirable features such as high bulk density, low moisture content, and fine particle size, making it suitable for incorporation into a wide range of food products. Furthermore, the powder demonstrated good storage stability, with minimal changes in color, flavor, or nutrient composition over time. Overall, the findings indicate that Jamun powder has strong potential as a functional and nutritious ingredient for the food and nutraceutical industries. Future research may focus on exploring alternative drying technologies, profiling the specific bioactive compounds responsible for its health benefits, and assessing its applications in functional foods and nutraceutical formulations.

Acknowledgment

The authors would like to heartily acknowledge Dr Y.S. Parmar of the University of Horticulture and Forestry, Nauni, Solan, and Shoolin University for providing the necessary research facilities during the study.

Author's Contribution

Conceptualization: Anjali Gautam, Manisha Kaushal; Data Curation: Anjali Gautam, Manisha Kaushal, Devina Vaidya; Experimentation: Anjali Gautam; Investigation & Supervision: Manisha Kaushal Software and Formal analysis: Dimple Tanwar, Kiran Bisht; Writing original draft: Nisha Sharma, Anjali Gautam; Review, Editing & Writing: Nisha Sharma, Devina Vaidya, Anil Gupta, Dimple Tanwar, Jyoti Mehta, Kiran Bisht.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data are available within this manuscript. There is no associated data.

Ethical Statement

Not applicable

Consent to participate

Not applicable

Consent to publish

Not applicable

Funding statement

None

References

- 549 AOAC. Official methods of analysis. 19th ed. Washington (DC): Association of Official
550 Analytical Chemists; 2012. p. 11–18.
- 551 Adit S, Kishor R, Priti A, Nepoliyan G, Giriya S, Saru G, et al. Utilization of cassava flour and
552 addition of gluten for the preparation of noodles. *Int J Food Agric Nat Resour*. 2024;5(2):28–37.
- 553 Akar G, Barutçu Mazi I. Color change, ascorbic acid degradation kinetics, and rehydration
554 behavior of kiwifruit as affected by different drying methods. *J Food Process Eng*.
555 2019;42(3):e13011.
- 556 An K, Zhao D, Wang Z, Wu J, Xu Y, Xiao G. Comparison of different drying methods on Chinese
557 ginger (*Zingiber officinale* Roscoe): Changes in volatiles, chemical profile, antioxidant properties,
558 and microstructure. *Food Chem*. 2016;197:1292–300.
- 559 Azian MN, Mustafa Kamal AA, Azlina MN. Changes of cell structure in ginger during processing.
560 *J Food Eng*. 2004;62:359–64.
- 561 Babaei Rad S, Mumivand H, Mollaei S, Khadivi A. Effect of drying methods on phenolic
562 compounds and antioxidant activity of *Capparis spinosa* L. fruits. *BMC Plant Biol*.
563 2025;25(1):133.
- 564 Bellissent-Funel MC, Hassanali A, Havenith M, Henchman R, Pohl P, Sterpone F, et al. Water
565 determines the structure and dynamics of proteins. *Chem Rev*. 2016;116(13):7673–97.
- 566 Caliskan G, Dirim SN. Effects of different drying conditions and maltodextrin addition during
567 spray drying of sumac extract. *Food Bioprod Process*. 2013;91(4):539–48.
- 568 Feng S, Bi J, Laaksonen T, Laurén P, Yi J. Texture of freeze-dried intact and restructured fruits:
569 formation mechanisms and control technologies. *Trends Food Sci Technol*. 2023;143:104267.
- 570 Gamal El R, Song C, Rayan AM, Liu C, Al-Rejaie S, ElMasry G. Thermal degradation of bioactive
571 compounds during drying of horticultural and agronomic products: a comprehensive overview.
572 *Agronomy*. 2023;13(6):1580.
- 573 Giri AD, Gaharwal AM, Deshmukh KY, Mahalle SP, Patil BN, Khairkar NA. Studies on different
574 drying methods and packaging materials on the storability of jamun pulp powder. *Plant Arch*.
575 2025;25:2634–42.
- 576 Jiang N, Gomez L, Grotewold E. Extraction and quantification of total anthocyanins and
577 characterization of specific anthocyanins from maize. *Cold Spring Harb Protoc*. 2025;5:108577.
- 578 Kanaujia A, Barman K, Belwal P, Yadav N, Kushwaha S, Kushwaha A. Effect of 6-
579 benzylaminopurine treatments on post-harvest quality and storage life of jamun (*Syzygium cumini*
580 Skeels) fruit. *Arch Curr Res Int*. 2025;25(5):70–83.
- 581 Kaur D, Yousuf B, Qadri OS. *Syzygium cumini* anthocyanins: recent advances in biological
582 activities, extraction, stability, characterization, and utilization in food systems. *Food Prod Process*
583 *Nutr*. 2024;6:34–44.

- 584 Kucharska-Guzik A, Guzik Ł, Charzyńska A, Michalska-Ciechanowska A. Influence of freeze
585 drying and spray drying on physical and chemical properties of powders from *Cistus creticus* L.
586 extract. *Foods*. 2025;14(5):849.
- 587 Howard LK, Ereifej L. Effect of ascorbic acid and dehydration on phenolics, antioxidant capacity,
588 anthocyanins, and color in fruits. *J Agric Food Chem*. 2005;53:44–54.
- 589 Moldovan C, Frumuzachi O, Babotă M, Menghini L, Cesa S, Gavan A, et al. Optimized drying
590 process for recovery of bioactive compounds from autumn fruits of *Berberis vulgaris* L. and
591 *Crataegus monogyna* Jacq. *Antioxidants*. 2021;10(10):1579.
- 592 Nagendra P, Srinivasa BM. Estimation of ascorbic acid content in selected fruits grown in Mandya
593 district, Karnataka. *Int J Multidiscip Res*. 2023;5:2156–60.
- 594 Fu N, Huang S, Xiao J, Chen XD. Producing powders containing active dry probiotics using spray
595 drying. *Adv Food Nutr Res*. 2018;85:211–62.
- 596 Pombo JCP, de Medeiros HHBR, Pena RDS. Optimization of spray drying process for developing
597 cupuassu powder. *J Food Sci Technol*. 2020;57(12):4501–13.
- 598 Li Q, Rudolph V, Weigl B, Earl A. Interparticle van der Waals force in powder flowability and
599 compactibility. *Int J Pharm*. 2004;280(1):77–93.
- 600 Rafiquzzaman M, Hossain MA, Dwip RR, et al. Freeze-dried instant juice powders from guava,
601 amla, and jamun: physicochemical properties and consumer acceptance. *Food Sci Nutr*.
602 2025;13:70374.
- 603 Ranganna S. Handbook of analysis and quality control for fruit and vegetable products. 4th ed.
604 New Delhi: Tata McGraw-Hill; 2009. p. 1112.
- 605 Rao GN, Nagender A, Satyanarayana A, Rao DG. Preparation, chemical composition, and storage
606 studies of quamachil (*Pithecellobium dulce* L.) aril powder. *J Food Sci Technol*. 2011;48:90–5.
- 607 Ratti C. Freeze drying for food powder production. In: Handbook of food powders. 2024. p. 37–
608 56.
- 609 Jebitta SR, Ramanathan M, Rajkumar P. Physical and nutritional evaluation of freeze-dried jamun
610 pulp powder under different storage conditions. *Indian J Nat Sci*. 2016;7:976–97.
- 611 Sarabandi K, Peighambaroust SH, Sadeghi Mahoonak AR, Samaei SP. Effect of carriers on
612 microstructure and physical characteristics of spray-dried apple juice concentrate. *J Food Sci*
613 *Technol*. 2018;55(8):3098–109.
- 614 Shavronskaya DO, Noskova AO, Skvortsova NN, Adadi P, Nazarova EA. Encapsulation of
615 hydrophobic bioactive substances for food applications. *J Food Process Preserv*. 2023;3:e5578382.
- 616 Shishir MRI, Taip FS, Aziz NA, Talib RA. Physical properties of spray-dried pink guava powder.
617 *Agric Agric Sci Procedia*. 2014;2:74–81.

- 618 Stuart BH. Infrared spectroscopy: fundamentals and applications. Hoboken (NJ): John Wiley &
619 Sons; 2005.
- 620 Suhag R, Kellil A, Razem M. Factors influencing food powder flowability. *Powders*.
621 2024;3(1):65–76.
- 622 Santhalakshmy S, Don Bosco SJ, Francis S, Sabeena M. Effect of inlet temperature on
623 physicochemical properties of spray-dried jamun juice powder. *Powder Technol*. 2015;274:37–
624 43.
- 625 Verma M, Rai GK, Kaur D. Effect of extraction solvents on phenolic content and antioxidant
626 activity of Indian gooseberry and guava. *Int Food Res J*. 2018;25(2):762–8.
- 627 Wadia C, Champawat PS, Jain SK. Influence of foam thickness, whipping time, and drying
628 temperature on guava powder during foam-mat drying. *J Pharmacogn Phytochem*. 2020;9(5):720–
629 7.
- 630 Wink WA. Determining moisture equilibrium curves of hygroscopic materials. *Ind Eng Chem*
631 *Anal Ed*. 1946;18(4):251–2.
- 632 Wojdyło A, Lech K, Nowicka P. Effects of drying methods on bioactive compound retention and
633 color of red-fleshed apple snacks. *Molecules*. 2020;25(23):5521.
- 634 Xiao T, Ma X, Hu H, Xiang F, Zhang X, Zheng Y, et al. Advances in emulsion stability:
635 mechanisms, emulsifiers, and food applications. *Food Chem*. 2025;29:102792.
- 636 Yikilkan Y, Redha AA, Kaba B, Pasazadeh H, Koca I. Production of chokeberry pulp powder by
637 convective and freeze-drying foam-mat techniques. *Sustain Food Technol*. 2025;3:1329–40.
- 638 Yin N, Luo J, Wang C, Xiong Y, Sun Y, Yuan E, et al. Effects of hot air drying temperature on
639 chemical composition and bioactivity of *Houttuynia cordata*. *Foods*. 2025;14:1962.
- 640 Yin X, Chen K, Cheng H, Chen X, Feng S, Song Y, et al. Chemical stability of ascorbic acid in
641 commercial products. *Antioxidants*. 2022;11(1):153.
- 642 Zhang P, Zhang J, Li L, Gu T, Chen S, Wang J, et al. Release of bound phenolics by liquid
643 fermentation with *Bacillus subtilis*. *Foods*. 2025;14(3):499.
- 644