

RESEARCH ARTICLE

Drying Kinetics and Efficiency of Vacuum-assisted Drying of *Phyllanthus emblica* (Amla) Slices at Moderate Temperature

Keerthana R^{1*}, Karthiayani A¹, Nithyalakshmi V¹, Mathanghi S K²

¹Department of Food Process Engineering, College of Food and Dairy Technology, Tamil Nadu Veterinary and Animal Sciences University, Chennai, Tamil Nadu, India

² Department of Food Processing Technology, College of Food and Dairy Technology, Tamil Nadu Veterinary and Animal Sciences University, Chennai, Tamil Nadu, India.

ABSTRACT

This study investigated the drying behaviour and efficiency of vacuum-assisted drying of *Phyllanthus emblica* (amla) slices under controlled pressure and temperature conditions. Fresh amla slices (1-2 mm thick) were pre-dried at 60 °C for 90 min and subsequently vacuum-dried at '-600 mm Hg' and 60, 65, 70, and 75 °C. The effects of temperature on moisture reduction, drying rate, moisture ratio, and energy efficiency were evaluated. Drying curves exhibited a continuous decline typical of the falling rate period without a constant rate period, confirming that internal diffusion dominated moisture migration. Increasing the drying temperature significantly reduced total drying time from 5.5 h at 60 °C to 4 h at 75 °C, achieving final moisture contents of 11.47-12.41 % (d.b.). The drying rate peaked within the first 0.5 h (0.530-0.926 g g⁻¹ h⁻¹) and decreased progressively as moisture content decreased. Moisture ratio curves demonstrate a faster approach to equilibrium at higher temperatures, demonstrating enhanced diffusivity under vacuum. Drying efficiency improved from 13.97 % at 60 °C to 19.63 % at 75 °C, indicating better utilisation of thermal energy at elevated temperatures. Among packaging materials, polypropylene exhibited superior moisture barrier properties compared with low-density polyethylene during storage. Overall, vacuum-assisted drying produced shelf-stable amla slices with minimal thermal degradation, offering strong potential for the development of high-quality, functional, and nutraceutical food products.

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INTRODUCTION

Drying is one of the oldest and most effective techniques for preserving fruits and vegetables by reducing moisture content to safe levels, thereby preventing microbial growth. When performed under controlled temperature and humidity conditions, drying not only extends shelf life but also helps preserve the product's nutritional and

sensory attributes (Sehrawat *et al.*, 2016). The growing consumer demand for natural, minimally processed, and health-oriented foods has driven research towards developing drying methods that retain nutritional quality, colour, and texture. Traditional dehydration methods, including sun and hot-air drying, are cost-effective but often result in

*Corresponding author mail: keerthanainiya62@gmail.com



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undesirable changes in flavour, texture, and colour due to prolonged exposure to high temperatures and oxygen. In contrast, advanced techniques such as freeze drying, vacuum drying, and fluidised bed drying offer improved product quality through controlled process parameters (Hayashi, 1989). The efficiency and final product quality depend primarily on the drying method and the conditions applied during dehydration (Vega-Mercado *et al.*, 2001). However, distinguishing between conventional and emerging drying processes can be challenging, as most innovations build upon established methods (Mujumdar and Huang, 2007).

The drying of heat-sensitive fruits poses unique challenges due to the potential degradation of thermolabile compounds, such as ascorbic acid and polyphenols. Excessive drying temperatures and long exposure times can also cause shrinkage and discolouration, affecting consumer acceptability (Ramachandran *et al.*, 2024). Low-temperature drying under reduced pressure, such as vacuum drying, has therefore gained attention for minimising oxidative and thermal damage while improving energy efficiency. Under vacuum, water evaporates at lower temperatures due to reduced boiling point (Afolabi, 2014), allowing the retention of heat-labile bioactive and colour pigments. Moreover, the oxygen-free environment suppresses enzymatic browning and lipid oxidation (Reis, 2014).

Indian gooseberry (*Phyllanthus emblica* L.), commonly known as amla, is an abundant source of vitamin C (600 -700 mg per 100 g) and phenolic compounds (Sidhu and Zafar, 2020). It is widely recognised in Ayurveda for its therapeutic and rejuvenating properties and is extensively used in processed products such as powders, candies, juices, and pickles (Goraya and Bajwa, 2015). However, the fruit's high moisture content and strong astringency limit its fresh consumption and make it highly perishable. Efficient dehydration techniques are therefore essential to extend its shelf life and retain its bioactive composition. Studies on other tropical tree fruits, such as tamarind (*Tamarindus indica* L.), have shown a wide range in vitamin C and related biochemical characteristics, emphasising the importance of preserving these labile components during post-harvest processing (Mayavel *et al.*, 2024).

Several studies have explored the drying of amla

using hot-air and freeze-drying systems, but limited research exists on vacuum-drying kinetics and their influence on the physical and sensory properties of the dried fruit. Understanding the moisture-loss pattern, drying efficiency, and changes in texture and colour during vacuum drying is crucial to optimise process parameters and ensure superior product quality.

Hence, the objective of the present study was to investigate the drying behaviour of *Phyllanthus emblica* slices under vacuum-assisted drying at different temperatures, focusing on moisture content reduction, drying rate, drying efficiency, texture, and colour characteristics of the dried product. This work aims to provide insights into optimising vacuum-drying parameters for heat-sensitive fruits to improve retention of quality attributes and process efficiency.

MATERIALS AND METHODS

Experimental setup

Vacuum drying experiments were conducted using a laboratory-scale vacuum-assisted dryer developed for controlled dehydration studies. The system comprised a vertical cylindrical drying chamber constructed from stainless steel (SS 304), with an internal diameter of 25 cm, a height of 30 cm, and a wall thickness of 3 mm, yielding an internal volume of approximately 15 L.

Seven perforated stainless-steel trays (16 cm diameter each) were mounted vertically on a central rod with uniform spacing to allow even air circulation and consistent drying across layers. Heating was provided by a 1 kW ceramic band heater positioned around the chamber wall and a 750 W mica disc heater at the base, ensuring uniform heat transfer. The chamber temperature was continuously monitored using a platinum resistance temperature detector (RTD; accuracy ± 1 °C) connected to a temperature controller, enabling precise temperature regulation throughout the drying process.

The system was connected to a double-stage rotary vane vacuum pump (4.6 CFM, 500 W motor) capable of maintaining a vacuum level of -600 mm Hg (≈ 21.3 kPa absolute pressure). Chamber pressure was monitored via a glycerine-filled Bourdon tube vacuum gauge (range: -760 to

0 mm Hg). The entire assembly was externally insulated with ceramic wool (thermal conductivity $\approx 0.17 \text{ W m}^{-1} \text{ K}^{-1}$) to minimise heat losses, enclosed by a stainless-steel cover for safety and durability.

A 10 mm thick transparent polycarbonate lid was fitted with a silicone gasket and four locking clamps to ensure airtight sealing. The lid housed a vacuum release valve, a pressure control valve, a pressure gauge, and a pressure control valve. Before each trial, the chamber was tested for vacuum integrity using the pressure rise method to confirm negligible leakage ($< 3 \text{ mm Hg min}^{-1}$).

Raw material preparation

Fresh fruits of *Phyllanthus emblica* (var. Chakaiya) were sourced from a local market in Chennai, India. Fruits were sorted to ensure uniform ripeness, colour, and size, and were free from mechanical or microbial damage. The fruits were washed under running tap water to remove adhering dirt and impurities, deseeded using an amla deseeder, and sliced into uniform pieces (1-2 mm thickness) using a stainless-steel knife.

Pre-drying treatment

Before vacuum drying, sliced amla samples were pre-dried in a tray dryer at 60°C for 90 minutes under forced convection to reduce surface moisture and improve sample handling. This step helped prevent sticking and ensured uniform moisture distribution before vacuum drying. The pre-dried samples were cooled to room temperature and immediately loaded into the vacuum dryer trays to minimise moisture regain from ambient air.

Vacuum drying procedure

Vacuum drying was carried out at four temperatures ($60, 65, 70,$ and 75°C) under a constant vacuum pressure of ' -600 mm Hg ' (21.3 kPa). Approximately $1.0 \pm 0.05 \text{ kg}$ of amla slices was loaded into the chamber for each run, evenly distributed across the trays.

Drying was continued until the weight change between consecutive readings (30 min interval), indicating attainment of equilibrium moisture content. Total drying time ranged from 4.0 to 5.5 hours, depending on the drying temperature.

After completion, the chamber was slowly vented to atmospheric pressure to avoid structural damage to the dried samples. The dried slices were

cooled to room temperature, then packed in low-density polyethylene (LDPE) and polypropylene (PP) pouches and sealed using an impulse hand sealer for storage and subsequent analysis.

The sequence of operations involved in the vacuum drying process is shown in Figure 1.

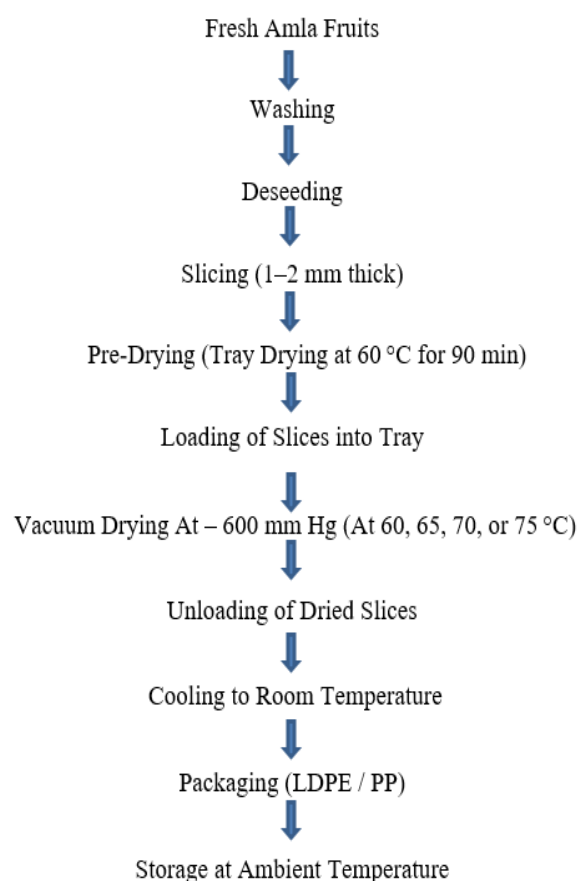


Figure 1. Illustration of the vacuum drying process

Determination of moisture content

The moisture content of the amla samples was determined using the oven-drying method, as per the Association of Official Analytical Chemists (AOAC, 2000). Approximately 5 grams of amla slices were accurately weighed into clean, dry crucibles. The crucibles were placed in a hot air oven and dried at 105°C for 24 hours. After drying, the crucibles were immediately covered, cooled in a desiccator to room temperature, and then weighed.

Moisture content (%) was determined by measuring the weight difference before and after drying, as described in Equation 1. The moisture content on a dry basis (d.b.)

was calculated using the following formula:

$$\text{Moisture content (dry basis, \%)} = \frac{W_1 - W_2}{W_2} * 100 \quad (1)$$

where W_1 and W_2 represent the initial and final weights (g) of the sample, respectively.

Determination of drying rate

The drying rate of amla during the vacuum-assisted drying process was calculated by applying Equation 2, given by Parveen and Pandian (2020)

$$Y = \frac{W_w}{t} \quad (2)$$

Where, Y denotes the drying rate (g/h), W_w is the weight loss during drying (g), and t is the drying time (h).

Determination of drying efficiency

The drying efficiency (η_d) was calculated as the ratio of the heat energy required to evaporate water to the total heat supplied by the dryer (Soysal *et al.*, 2006; Billiris *et al.*, 2014), using Equation 3.

$$\eta_d = \frac{Q_w}{Q_g} * 100 \quad (3)$$

where Q_w is the energy required for drying (kJ), and Q_g is the total heat supplied. The total energy requirement, Q_w , was estimated using Equation 4.

$$Q_w = W_{bd}C_p * (T_d - T_a) + M_{tw}C_w(T_d - T_a) + M_w * \lambda \quad (4)$$

Where, W_{bd} denotes the mass of bone-dry sample (kg), C_p and C_w denotes the specific heat capacities of product and water ($\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$) respectively, T_d and T_a denotes the drying and ambient air temperatures ($^\circ\text{C}$) respectively, M_{tw} denotes the total water in the

sample (kg), M_w denotes the water removed during drying (kg), and λ denotes the latent heat of vaporisation of water (kJ kg^{-1}).

Statistical analysis

All experiments were conducted in triplicate, and results were expressed as mean $\pm$ standard error (SE). Statistical significance was analysed using one-way ANOVA at a confidence level of $p \leq 0.05$

RESULTS AND DISCUSSION

Moisture content of vacuum-dried amla slices

The initial moisture content of fresh amla was 88.49 ± 0.61 % (w.b.), consistent with earlier reports for high moisture fruits such as amla (Murthy and Joshi, 2007; Shree, 2022). After vacuum drying at -600 mm Hg, a significant ($p \leq 0.01$) reduction in moisture content was observed with increasing temperature (Table 1). The final moisture decreased from 12.41 ± 0.07 % d.b. at 60 $^\circ\text{C}$ to 11.47 ± 0.12 % d.b. at 75 $^\circ\text{C}$, indicating an inverse correlation between drying temperature and moisture level. This trend can be attributed to the greater temperature gradient and vapour pressure difference established between the product surface and the surrounding drying air at higher temperatures, which enhances moisture migration and evaporation (Zeng *et al.*, 2024).

During storage for 3 months, all samples showed a gradual increase in moisture content, indicating partial moisture uptake from the ambient air. The rise was more evident in low-density polyethylene (LDPE) packaging than in polypropylene (PP). At 60 $^\circ\text{C}$, the moisture content increased from 12.41 % d.b. to 15.83 % d.b. in LDPE and from 13.85 % d.b. to 14.17 %

Table 1. Moisture content (Mean $\pm$ SE)[@] of dried amla slices at different drying temperatures

Sample Type	Drying Temperature ($^\circ\text{C}$)	Moisture content (% db.)	MC (% db) After 3 Months - LDPE	MC (% db) After 3 Months - PP
Dried amla slices	60	12.410 ± 0.069^c	15.830 ± 0.051^c	13.846 ± 0.058^c
Dried amla slices	65	11.946 ± 0.109^b	14.513 ± 0.101^b	13.640 ± 0.101^c
Dried amla slices	70	11.576 ± 0.092^a	14.216 ± 0.069^a	13.086 ± 0.118^b
Dried amla slices	75	11.466 ± 0.116^a	14.170 ± 0.072^a	12.723 ± 0.054^a
F value		25.810**	106.158**	34.253**

@ Average of 3 trials

** Highly Significant ($p \leq 0.01$)

* Significant ($0.01 < p \leq 0.05$)

NS - Non Significant ($p > 0.05$)

d.b. in PP, while at 75 °C, the values rose from 11.47 % d.b. to 14.17 % d.b. (LDPE) and 12.72 % d.b. (PP). The higher gain in LDPE can be explained by its greater water vapour transmission rate (WVTR), which allows moisture exchange with the external environment. PP films, in contrast, exhibit superior barrier properties and lower permeability, effectively restricting water migration and maintaining the structural integrity of the dried product (Kumar et al., 2022).

The observed patterns align closely with previous findings. Kumar and Sagar (2012) reported that

vacuum-dried amla slices attained a final moisture content of approximately 9-11 % d.b., significantly lower than those produced by solar or cabinet drying, confirming the efficiency of vacuum drying. Minj et al., (2018) also demonstrated a consistent reduction in moisture from 2.69 % to 2.22 % d.b. as the drying temperature increased from 50 °C to 70 °C. Similarly, Reshmi et al., (2018) observed that oven-dried amla slices had lower residual moisture and higher dehydration ratios than sun-dried samples, while Shree (2022) described the typical falling-rate drying



(a) Fresh sample



(b) Pre-dried sample



(c) Vacuum dried at 60 °C



(d) Vacuum dried at 65 °C



(e) Vacuum dried at 70 °C



(f) Vacuum dried at 75 °C

Figure 2. Visual comparison of *Phyllanthus emblica* (amlam) slices at different stages of vacuum drying at 60-75 °C under – 600 mm Hg.

behaviour of amla, dominated by internal diffusion mechanisms.

Drying behaviour and kinetics

The visual changes in amla slices during vacuum drying at different temperatures are shown in Figure 2.

Effect of drying time on moisture content

The variation in moisture content of amla slices during vacuum drying at different temperatures (60–75 °C) under a pressure of '– 600 mm Hg' is shown in Figure 3. A steady reduction in moisture content was observed as drying time increased, regardless of temperature, exhibiting a typical drying curve with an initial rapid moisture removal, followed by a gradual decrease until equilibrium was reached. At 60 °C, the initial moisture content of 179.34 % d.b. decreased progressively to 12.3 % d.b. after 5.5 h of drying. When the temperature was increased to 65 °C, the drying time required to reach a similar final moisture level (11.96 % d.b.) reduced to 5 h, while further increases to 70 °C and 75 °C resulted in total drying durations of 4.5 h and 4 h, achieving final moisture contents of 11.57 % and 11.38 % d.b., respectively. Thus, the overall drying time decreased by approximately 9%, 18%, and 27% when the temperature was raised from 60 to 65, 70, and 75 °C, respectively.

The observed trend can be attributed to the enhanced vapour-pressure gradient and internal moisture diffusivity at higher temperatures, which accelerate water migration from the interior of the product to the surface. During the early stages of drying, moisture is primarily lost through surface evaporation when free water is abundant, and there is a brief transient heating stage. As drying progresses, the surface becomes less saturated, and internal diffusion of bound water through cellular capillaries becomes the rate-limiting step, characterising the falling-rate period (Murthy and Joshi, 2007). The dominance of this falling-rate period in the present study aligns with the general drying behaviour of high-moisture fruits such as amla and mango, where internal diffusion mechanisms govern most of the drying process.

The decrease in total drying time with increasing temperature is consistent with earlier findings for amla dried under cabinet conditions at 50–70 °C, where higher temperatures produced shorter drying durations and lower final moisture contents (Minj *et al.*, 2018). Similar behaviour has been observed during vacuum drying of mango pulp, where increasing the chamber plate temperature from 65 °C to 75 °C significantly reduced the drying

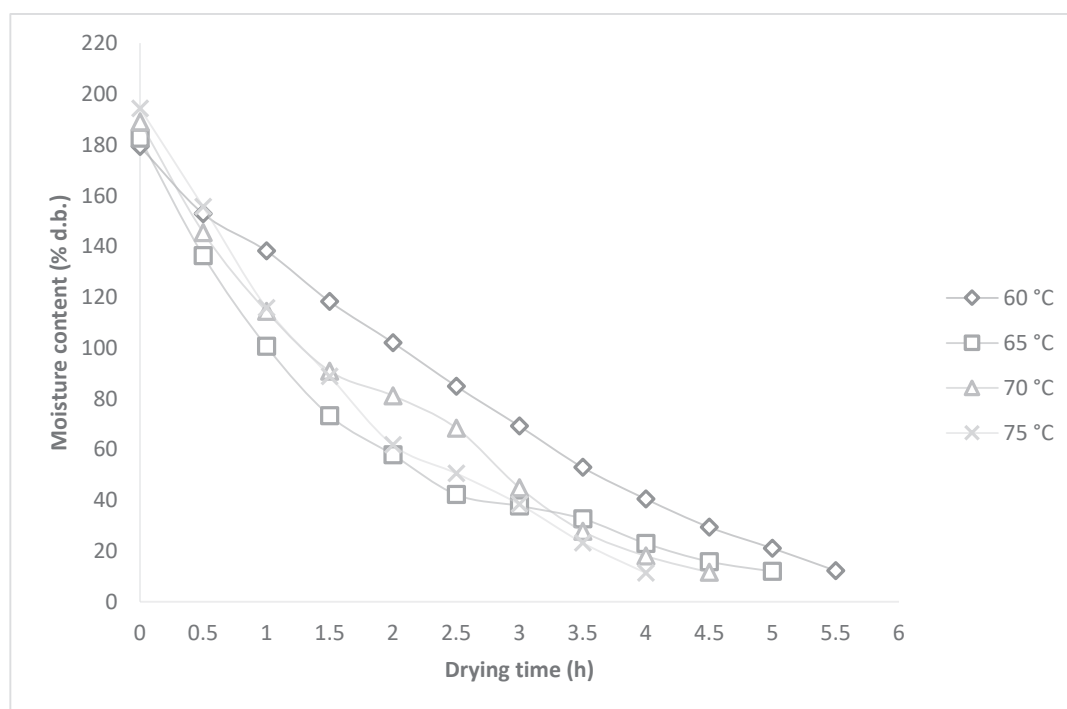


Figure 3. Effect of drying time on moisture content

time owing to the rise in effective moisture diffusivity (Jaya and Das, 2003). These reports corroborate the present observations that elevated temperatures promote rapid moisture removal due to increased internal vapour generation and greater driving force for diffusion.

In the current study, all drying curves showed a characteristic continuous decline in the falling rate phase, without a constant rate period, until the samples approached an equilibrium moisture content of approximately 11-12 % d.b. Such a moisture path corresponds closely to that reported for amla dried in fluidised-bed and tray dryers, where the equilibrium moisture content of 13 ± 1 % d.b. was reached within 150-240 min, depending on operating temperature and airflow (Murthy and Joshi, 2007). Comparable final moisture ranges have also been reported for pear slices dried in vacuum-assisted infrared systems, with final values between 10.08 and 11.79 % d.b., and for amla fruits processed in solar dryers, achieving 2- 4 % (w.b.) within 7-16 h (Shree, 2022; Topuz *et al.*, 2023).

Effect of drying time on drying rate

Across all temperatures, the drying rate time profiles (Figure 4) exhibited a brief initial acceleration

to a peak followed by a continuous decline. At 60 °C, the drying rate rose to a maximum of $0.530 \text{ g g}^{-1} \text{ h}^{-1}$ at 0.5 h and declined to $0.304 \text{ g g}^{-1} \text{ h}^{-1}$ at 5.5 h. Raising the temperature to 65 °C increased the mass transfer rate, with a peak of $0.926 \text{ g g}^{-1} \text{ h}^{-1}$ at 0.5 h and a final rate of $0.341 \text{ g g}^{-1} \text{ h}^{-1}$ at 5.0 h. At 70 °C, the peak was $0.871 \text{ g g}^{-1} \text{ h}^{-1}$ (0.5 h) and the final rate $0.394 \text{ g g}^{-1} \text{ h}^{-1}$ at 4.5 h, while at 75 °C the peak reached $0.780 \text{ g g}^{-1} \text{ h}^{-1}$ (0.5 h) and the end value was $0.457 \text{ g g}^{-1} \text{ h}^{-1}$ at 4.0 h. The higher peaks at 65-70 °C relative to 60 °C indicate a stronger temperature-driven vapour pressure gradient under vacuum. Once available surface water is exhausted, capillary flow gives way to diffusion/vapour transport through cell walls and pores, as shown by falling drying rate curves after the initial peak (Murthy and Joshi, 2007).

These results agree with previous studies on cabinet and solar dried amla, where the drying rate is initially high and decreases continuously with time, with greater initial rates at higher temperature (e.g., 6.78 to 0.55 min^{-1} at 60 °C; 8.19 to 0.72 min^{-1} at 70 °C) (Minj *et al.*, 2013; Prajapati and Sheorey, 2023; Shree, 2022).

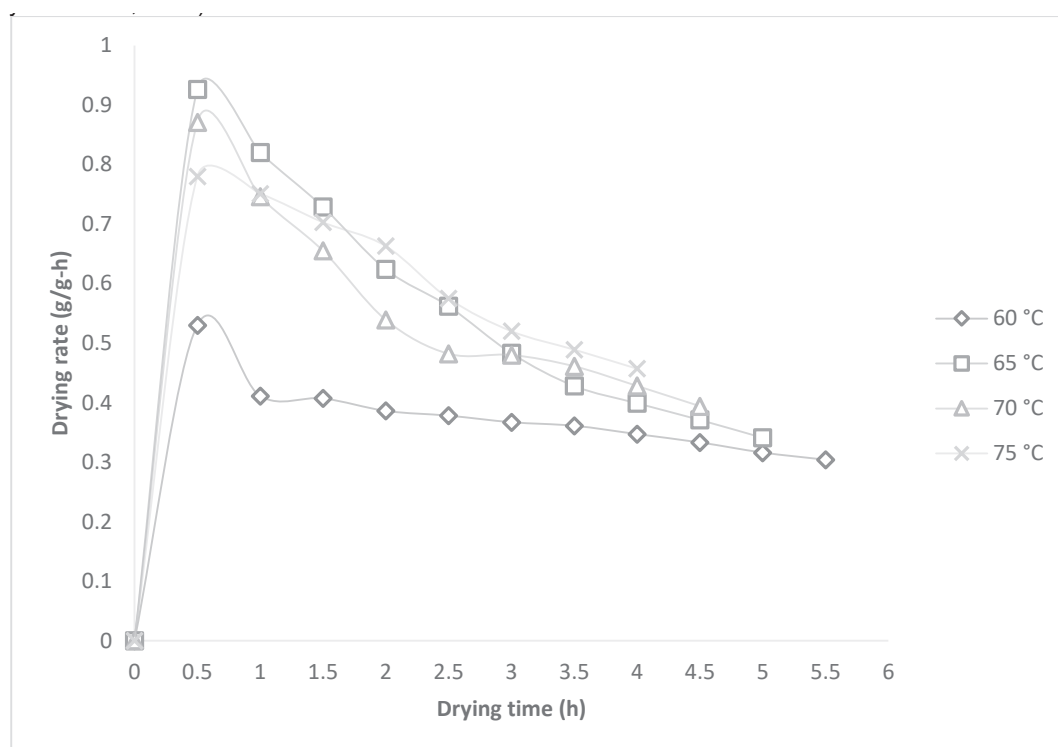


Figure 4. Effect of drying time on drying rate

Overall, the present results confirm that vacuum drying follows the characteristic behaviour of high moisture plant materials. Higher temperatures increase the initial drying rate and shorten the falling rate period, while the applied vacuum (-600 mm Hg) enhances drying by lowering the boiling point and reducing external resistance. This leads to a quick rise in the drying rate, followed by a gradual, diffusion-controlled rate.

Effect of drying time on moisture ratio

The variation in moisture ratio with drying time for vacuum-dried amla slices at temperatures ranging from 60 °C to 75 °C under a pressure of ' -600 mm Hg' is shown in Figure 5. The moisture ratio (MR) decreased gradually with drying time at all temperatures, exhibiting the exponential type decay expected for fruit tissues under vacuum. At 60 °C, MR declined from 1.000 to 0.841 (0.5 h), 0.634 (1.5 h), and 0.341 (3.0 h), approaching 0.053 (5.0 h) and reaching 0.000 at 5.5 h. Increasing the temperature to 65 °C, MR fell to 0.729 (0.5 h), 0.359 (1.5 h), and 0.121 (3.5 h), reaching 0.000 by 5.0 h. At 70 °C, the decay was steeper with MR values of 0.754 (0.5 h), 0.447 (1.5 h), 0.188 (3.0 h), and 0.036 (4.0 h), reaching 0.000 at 4.5 h. The fastest reduction occurred at 75 °C, where MR decreased to 0.787 (0.5 h), 0.423 (1.5 h), and 0.148 (3.0 h),

reaching 0.000 at 4.0 h. Collectively, these curves confirm that under -600 mm Hg vacuum, the time required to attain $MR = 0$ (i.e., practical equilibrium under the test conditions) shortened from 5.5 h to 4.0 h as temperature increased from 60 to 75 °C ($\approx 27\%$ reduction).

The sharp initial drop in moisture ratio indicates a substantial vapour pressure difference and low external resistance under vacuum, promoting rapid evaporation of easily accessible surface water. As drying continues, moisture movement inside the material slows down because it must diffuse through cell walls and internal spaces, leading to the long falling-rate phase typical of high-moisture plant materials. The steeper MR time curves at higher temperatures indicate that greater heat input increases the effective moisture diffusivity, speeding internal moisture movement and reducing the time to reach equilibrium. These behaviours are in line with oven-dried amla results, where MR declines exponentially over time and higher air temperatures show a faster decline (Raaf *et al.*, 2022). They also agree with vacuum vs low-pressure superheated steam drying of amla flakes, where 75 °C achieved $\approx 20\%$ shorter times to equilibrium than 65 °C at similar pressures due to a larger thermal driving force and higher diffusivity

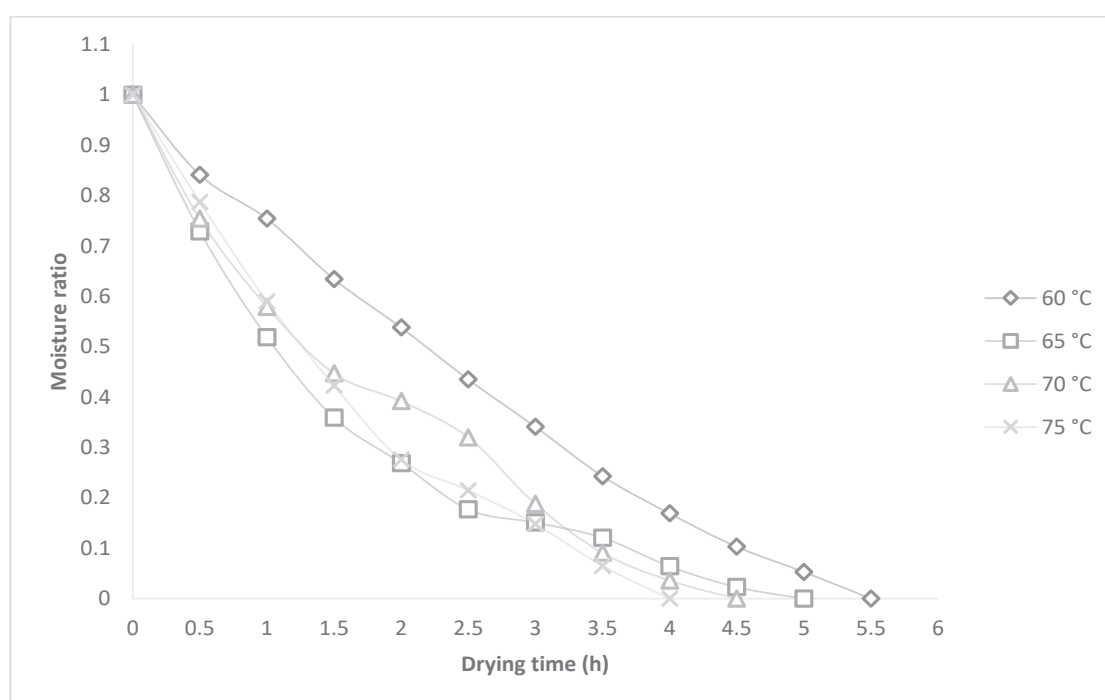


Figure 5. Effect of drying time on moisture ratio

(Methakhup *et al.*, 2005). In high-sugar fruit pulps and date types, similar temperature-dependent steepening of MR curves and shorter drying periods have been reported; transport is influenced by compositional and morphological variables (e.g., sugars, tissue thickness) (Amellal and Benamara, 2008). Studies on oven-dried amla have also reported an initial rapid drying phase followed by a diffusion-controlled stage. Higher drying temperatures and thinner slices consistently shorten the time required to attain lower moisture ratios (Raaf *et al.*, 2021).

Effect of moisture content on drying rate

The variation in drying rate with moisture content for vacuum-dried amla slices at temperatures ranging from 60 °C to 75 °C under a pressure of '-600 mm Hg' is shown in Figure 6. In all cases, a continuous decline in drying rate was observed as the moisture content decreased, indicating that the entire process occurred predominantly in the falling-rate period. At 60 °C, the drying rate was highest (0.530 g g⁻¹ h⁻¹) at a moisture content of around 152.86 % d.b., and it gradually declined with

increasing moisture loss, reaching 0.304 g g⁻¹ h⁻¹ at a terminal moisture content of 12.3 % d.b. Similarly, at 65 °C, the maximum drying rate of 0.926 g g⁻¹ h⁻¹ was recorded at 136.34 % d.b., followed by a steady decline through the mid-moisture range (100.62-42.22 % d.b.) and finally near 0.341 g g⁻¹ h⁻¹ at 11.96 % d.b. At 70 °C, the drying rate initially reached 0.871 g g⁻¹ h⁻¹ at 145.44 % d.b., decreasing progressively to 0.394 g g⁻¹ h⁻¹ at 11.57 % d.b., while at 75 °C, the rate started at 0.780 g g⁻¹ h⁻¹ at 155.36 % d.b. and reduced steadily to 0.457 g g⁻¹ h⁻¹ when the final moisture content approached 11.38 % d.b. These curves display the characteristic inverse relationship between drying rate and moisture content commonly observed in fruit matrices: the higher the moisture, the greater the availability of free water for evaporation; the lower the moisture, the greater the internal mass-transfer resistance. The overall decline in drying rate with decreasing moisture content indicates that water removal from amla slices was primarily governed by internal diffusion rather than surface (Murthy and Joshi, 2007).

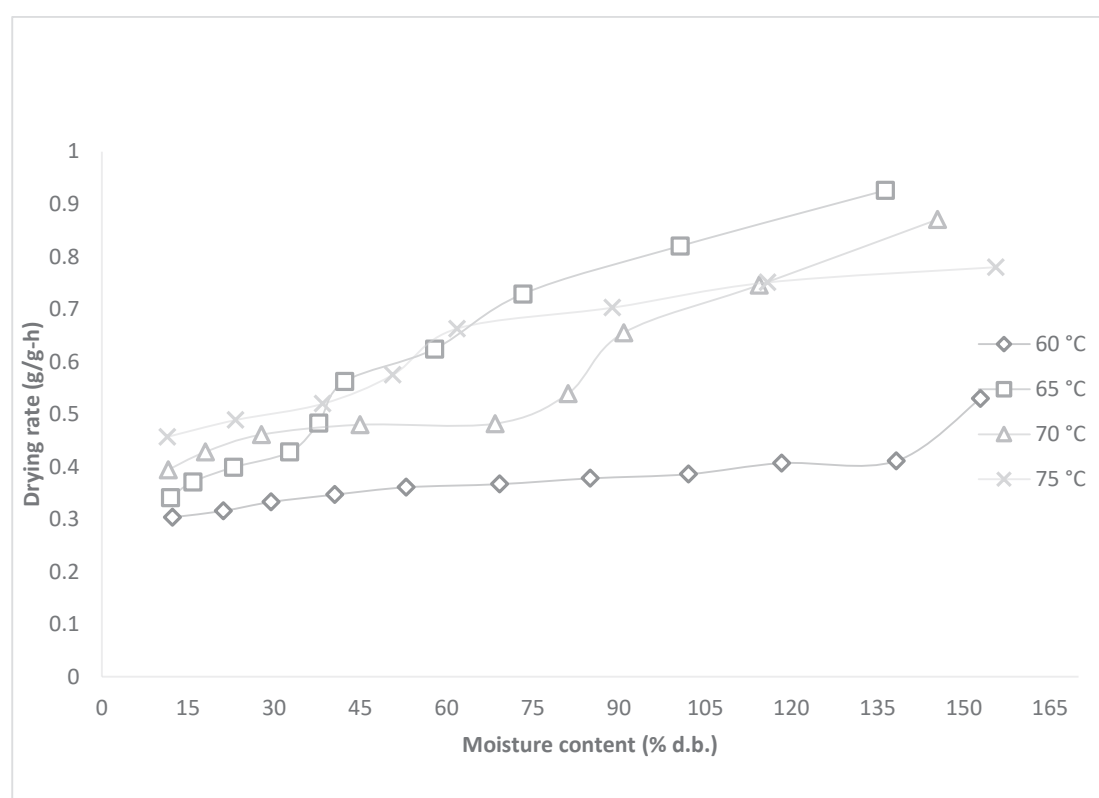


Figure 6. Effect of moisture content on drying rate

A comparison across the four temperatures shows that higher temperatures produced both higher initial rates and shorter overall drying durations, highlighting the positive effect of temperature on moisture migration kinetics. The rise in temperature from 60 °C to 65 °C nearly doubled the peak drying rate (0.530 to 0.926 g g⁻¹ h⁻¹), while further increases to 70 °C and 75 °C maintained high initial rates, though with slightly reduced maxima, likely due to increased tissue shrinkage and reduced surface permeability at the highest temperature. Such behaviour has also been observed in temperature-sensitive fruit matrices, where excessive heating leads to local structural collapse, restricting internal moisture flow despite the elevated thermal driving force (Amellal and Benamara, 2008).

The present observations are in strong agreement with findings from cabinet-dried amla, where the drying rate decreased consistently with falling moisture content, and higher set temperatures yielded faster rates overall (Minj *et al.*, 2013). Comparable results were also reported for vacuum-dried radish slices, where the drying rate increased with temperature but declined steadily as moisture content decreased, with no constant-rate period observed (Lee and Kim, 2008). In both studies, the relationship between drying rate and moisture content reflected diffusion-controlled

behaviour typical of agricultural materials. Similarly, Shree (2022) observed that in solar and open-sun drying of amla, the drying rate decreased as the moisture content dropped.

Drying efficiency

The drying efficiency of the vacuum drying system increased progressively with increasing temperature from 60 °C to 75 °C, as illustrated in Figure 7. At 60 °C, the efficiency was 13.97 %, increasing to 15.42 % at 65 °C, 17.68 % at 70 °C, and reaching a maximum of 19.63 % at 75 °C.

Various studies have reported similar effects of temperature and vacuum pressure on the drying efficiency of food products. Suryanto *et al.*, (2021) observed that applying vacuum pressure significantly enhanced drying efficiency by approximately 11-12 % in coffee and cocoa beans compared with atmospheric conditions. The overall drying efficiency of vacuum-based systems in their study ranged from 31 to 36. Although the efficiency values in the present work (13.97–19.63 %) are lower, they are reasonable for a vacuum dryer operating on a laboratory scale.

Similarly, Prajapati and Sheorey (2023) reported that a natural-convection cabinet solar dryer for gooseberries (amla) achieved drying efficiencies of 38.61–43.75 %, whereas open-sun drying under the same conditions yielded only 12.5–14.1 %, illustrating the benefit of regulated drying temperature and

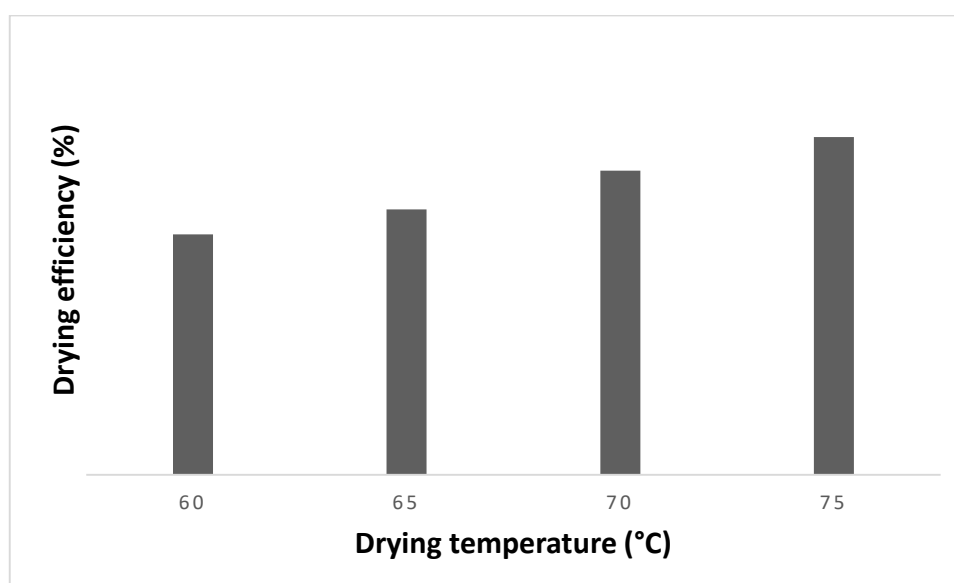


Figure 7. Drying efficiency of vacuum-assisted drying of *Phyllanthus emblica* (amla) slices at 60, 65, 70, and 75 °C under – 600 mm Hg.

enclosed air circulation. Furthermore, Djamila *et al.*, (2021) found similarly low efficiencies (6.74 - 7.42 %) in a rotary vacuum dryer for oyster mushrooms, attributing the losses to mechanical and chamber maintenance energy, where the chamber retained a significant portion of the heat input to maintain target temperature rather than directly contributing to moisture removal.

CONCLUSION

The present study demonstrated that vacuum-assisted drying at a reduced pressure of '600 mm Hg' provides an efficient and effective means of dehydrating *Phyllanthus emblica* (amla) slices while maintaining desirable moisture characteristics and process efficiency. The drying kinetics indicated that the process was primarily governed by the falling rate period, confirming that moisture migration occurred mainly through internal diffusion rather than surface evaporation. Increasing the drying temperature from 60 °C to 75 °C significantly shortened the total drying time from 5.5 h to 4 h, demonstrating that elevated temperatures under vacuum conditions enhance mass transfer without inducing severe thermal degradation.

Final moisture contents of 11.47-12.41% d.b. were achieved across all temperature levels, ensuring product stability and microbial safety. During storage, amla slices packed in polypropylene exhibited lower moisture regain than those in LDPE, establishing PP as a superior packaging material for long-term stability. The drying rate and moisture ratio profiles followed typical exponential decay patterns, with initial rapid moisture removal followed by a diffusion-controlled phase. Higher temperatures promoted faster attainment of equilibrium, attributed to increased water diffusivity and to vapour pressure gradients under vacuum. Drying efficiency improved steadily from 13.97 % at 60 °C to 19.63 % at 75 °C, showing more effective utilisation of thermal energy at higher process temperatures.

Overall, the findings confirm that vacuum-assisted drying offers a promising alternative to conventional air or sun drying for heat-sensitive fruits such as amla. The combination of reduced pressure and controlled temperature minimises oxidative and thermal damage, making this approach particularly suitable for producing high-quality dried fruit ingredients for nutraceutical, confectionery, and functional food applications. Future work could

focus on mathematical modelling of drying kinetics, optimisation of energy consumption, and comparative evaluation with other advanced drying methods, such as freeze- or microwave-assisted vacuum drying, to further enhance process performance.

Credit authorship contribution statement

Keerthana R: Investigation, data curation, writing – original draft. Karthiayani. A: conceptualization, supervision, validation. Nithyalakshmi. V: conceptualization, supervision, validation. Mathanghi, S.K.: conceptualization, supervision, validation.

Conflict of interest

There is no conflict of interest by the authors.

Ethics Statement

No specific permits were required for field studies as no human or animal subjects were involved.

Consent for Publication

All authors have agreed to the publication of this content.

Data Availability

All the data are present in the graph.

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