International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 5, 2025
https://theaspd.com/index.php

Energy Performance Evaluation of a Biomass-Fired Dryer for Amla Processing

P. Murugan[1]**, S. Dhanushkodi**[2]**, K. Sudhakar**[3]
[1] Research Scholar, PRIST University, Vallam, Thanjavur – 613403, Tamilnadu, India
[2]PRIST University, Vallam, Thanjavur – 613403, Tamilnadu, India
[3] Energy Centre, National Institute of Technology, Bhopal, M. P., 462003 India
Corresponding author : pm1meproj@yahoo.com

Abstract
This study presents an energy performance evaluation of a biomass-fired dryer developed for the dehydration of Amla (Phyllanthus emblica) fruits. Amla is rich in vitamin C and bioactive compounds, but its high moisture content limits shelf life and post-harvest utilization. Drying is a vital method to preserve its quality and extend usability. In this investigation, locally available agricultural biomass such as rice husk, coconut shells, and sawdust was used as fuel in a direct-heated drying system. Key performance metrics, including moisture removal rate, drying efficiency, specific energy consumption (SEC), and thermal efficiency, were analyzed under varying operating conditions. The initial moisture content of Amla was reduced from approximately 84% to 12% (wet basis) at drying temperatures ranging from 60°C to 80°C. Results showed that fuel type, airflow rate, and drying temperature significantly affected drying performance. The specific energy consumption ranged from 4.2 to 6.5 MJ/kg of water removed, and thermal efficiency varied between 15% and 25%. The biomass dryer demonstrated consistent performance and energy savings when compared to conventional electric dryers. The findings highlight the feasibility of biomass as a sustainable energy source for rural-based fruit drying applications and suggest optimization strategies for improved dryer design and energy efficiency.
Keywords: *Amla drying; Biomass dryer; Energy analysis; Thermal efficiency; Specific energy consumption; Moisture removal rate; Sustainable drying;*

1. INTRODUCTION

India is a largest growing economy with agriculture as the backbone of the nation. Solar and biomass are the two main renewable sources of energy that are widely used in India .There are commercially important cash crops like Amla grown in different regions of India. All these products required careful drying before producing them to the market [1]. Various methods are employed to utilize renewable energy sources including drying, electricity and other applications. Appropriate use of renewable sources in drying provides a reduction of drying time and specific improvement of the product quality in terms of color, taste and texture in comparison to open sun drying. Amla (*Phyllanthus emblica*), commonly known as Indian gooseberry, is a highly valued fruit in Ayurvedic medicine and the functional food industry due to its rich content of vitamin C, polyphenols, and antioxidants [2]. Despite its nutritional and medicinal properties, Amla is highly perishable owing to its high moisture content (typically 80–85% wet basis), which promotes microbial spoilage and biochemical degradation during storage and transportation. To enhance shelf life and preserve its quality, dehydration is a widely adopted method in both small-scale and industrial processing sectors [3]. Conventional drying techniques, including electric and gas-based systems, are often energy-intensive and economically unviable in rural and decentralized settings. As a result, biomass-fired dryers have emerged as an energy-efficient and sustainable alternative, particularly in regions where biomass is readily available. Biomass resources such as rice husk, sawdust, coconut shells, and crop residues offer renewable, low-cost, and carbon-neutral fuel sources suitable for thermal applications like drying [4].

Energy performance assessment of such biomass dryers is essential to ensure optimal design, operational efficiency, and minimal environmental impact. Key metrics such as drying efficiency, thermal efficiency, specific energy consumption (SEC), and moisture removal rate provide valuable insight into the system's effectiveness under varying conditions of biomass type, fuel feed rate, and drying temperature. Although several studies have evaluated biomass drying technologies for agricultural products, limited data exist on performance analysis specific to Amla. Therefore, this study aims to fill that gap by experimentally analyzing a biomass-fired dryer designed for Amla dehydration. The study focuses on quantifying energy performance indicators and identifying the operational parameters that influence drying efficiency and fuel consumption [5].

Drying is one of the oldest and most effective preservation methods for agricultural products, and it plays a crucial role in post-harvest processing. For moisture-rich fruits like Amla (*Phyllanthus emblica*), drying not only extends shelf life but also improves transportability and reduces storage losses. Traditional sun drying, though cost-effective, is highly weather-dependent and susceptible to contamination. As a result, artificial dryers particularly those utilizing renewable energy sources are gaining popularity in agro-processing industries [6].

Biomass, derived from agricultural and forestry residues, is a promising alternative energy source for thermal drying applications. Reviewed various biomass drying systems and reported that they offer lower operational costs and reduced environmental emissions compared to fossil fuel-based dryers. Biomass such as rice husk, sawdust, coconut shell, and crop residues are commonly used due to their high calorific values and local availability [7]

The performance of a dryer is commonly assessed through parameters such as drying rate, specific energy consumption (SEC), thermal efficiency, and moisture removal rate. Jain and [8] demonstrated that biomass dryers, when optimized, can achieve thermal efficiencies of 20–35%. [9] Studied a biomass-fired batch dryer for spice drying and found that the SEC varied significantly depending on fuel type and moisture content of the product. Studies by [10] also emphasized the importance of controlling air flow rate and drying temperature to achieve uniform drying and reduce energy losses.

Amla drying has been explored using solar, electric, and hybrid dryers. [11] Studied solar drying of Amla slices and found considerable nutrient retention at controlled drying temperatures. However, electric dryers often incur high energy costs, making them less favorable in rural contexts. Few studies have explored biomass-based drying of Amla. A gap remains in understanding the thermodynamic performance and fuel optimization of such systems specifically for high-moisture fruits like Amla.

The growing interest in sustainable agriculture has increased demand for decentralized, energy-efficient drying systems. According to [12], energy efficiency is a critical factor, especially in small-scale operations where energy costs directly affect profitability. Integrating biomass energy for drying contributes to carbon reduction and supports circular economy models in agro-processing.

The present study aims to analyze the performance of the simple biomass dryer which utilizes wood and briquette to generate heat that is used to dry Amla. The comparison of energy and exergy efficiency of the biomass drier is also studied in this work

2. Experimental Setup

The experimental analysis was conducted using a custom-built, direct-type biomass-fired batch dryer designed for drying high-moisture agricultural products, specifically Amla (*Phyllanthus emblica*). The dryer consists of a combustion chamber fabricated from mild steel, where biomass fuel such as rice husk, sawdust, or coconut shell is burned to generate thermal energy. Hot air produced in the combustion zone is directed into a cylindrical drying chamber (1 meter in diameter and 1.2 meters in height) equipped with perforated trays to hold the Amla fruits. An axial fan (250 mm, 0.5 HP) circulates heated air uniformly through the drying chamber, while an exhaust chimney ensures proper ventilation and removal of combustion gases. The fuels used were locally sourced and air-dried prior to use. Their average calorific values were recorded as 13.5 MJ/kg for rice husk, 14.2 MJ/kg for sawdust, and 19.8 MJ/kg for coconut shell. The biomass feed rate was manually controlled and maintained between 2.0 and 2.5 kg/hr depending on the target drying temperature. Fresh Amla fruits were cleaned and their initial moisture content, measured using the oven-drying method at 105°C for 24 hours, was found to be approximately 84% (wet basis). About 2 kilograms of Amla were loaded per batch and spread evenly across the trays. Instrumentation included K-type thermocouples placed at key points inside the combustion chamber, at the inlet and outlet of the drying chamber, and within the sample material—to monitor temperature distribution. A hot wire anemometer measured airflow velocity, while a precision digital weighing balance (±0.01 g) was used to record the mass of the sample at 30-minute intervals during drying. The process continued until the final moisture content reached approximately 12% (wet basis). Performance metrics such as drying time, moisture removal rate, specific energy consumption (SEC), and thermal efficiency were calculated for each trial to evaluate the energy performance of the dryer system (Figure 1).

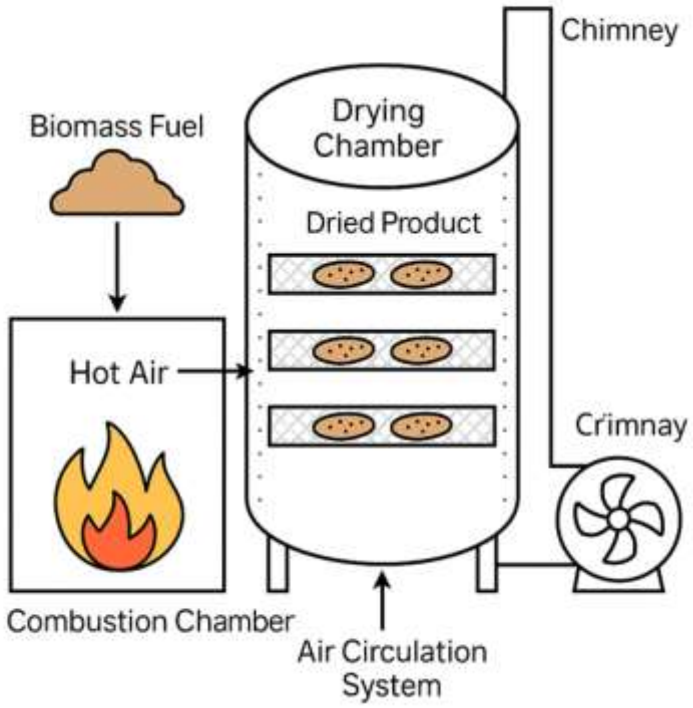


Figure 1. Experimental set up

3. Performance characteristics

The system performance and the drying characteristics of Amla such as moisture content, drying rate, and efficiency were calculated using the following equations.

Moisture content: The moisture in Amla were determined after each hour of drying. The moisture content after each hour in drying was determined by taking the initial weight and weight loss after each hour with the help of electronic balance

$$M_c = \frac{M_i - M_d}{M_i} \text{x}100$$

Drying Rate: The drying rate was formed by a decrease of the water concentration during the time interval between two subsequent measurements divided by this time interval.

$$R_d = \frac{M_i - M_d}{t}$$

Biomass heater combustion efficiency: Biomass heater combustion efficiency can be defined as the ratio of useful heat gain over the product of fuel consumption and calorific value. It can be expressed for natural convection mode.

$$\eta_g = \frac{m_f C_p (T_0 - T_i)}{FC.CV}$$

Drying chamber efficiency: It can be defined as the ratio of the difference between the drying chamber inlet and drying chamber outlet temperature to the difference between the drying chamber inlet and ambient temperature.

$$\eta_d = \frac{(T_1 - T_2)}{(T_1 - T_2)}$$

Overall system efficiency η_s is the ratio of the energy required to evaporate moisture from the product to the heat supplied to the dryer.The system drying efficiency is a measure of the overall effectiveness of a drying system. Energy consumed by the blower is taken into account for forced convection mode. System efficiency can be expressed as.

$$\eta_s = \frac{\phi x L(M_i - M_d)}{FC.CV(100 - M_i)}$$

Exergy efficiency
The exergy efficiency of the biomass dryer was evaluated using the following relation [27]

S.No	Parameter	Relation
1	The exergy outflow of the drying chamber (Ex_{dco})	mc $[(T_{dco}-T_a)-T_a \ln\frac{Tdco}{Ta}]$
2	The exergy Inflow of the drying chamber (Ex_{dci})	mc $[(T_{dci}-T_a)-T_a \ln\frac{Tdci}{Ta}]$
3	The exergy loss (Ex_{loss})	Ex_{dci}- Ex_{dco}
4	Drying chamber Efficiency (η_{dc})	$\frac{T1-T2}{T1-Ta}$
5	Exergy efficiency (η_{EX})	$\frac{Exdco}{Exdci}$

The biomass dryer can dry Amla from a moisture content of 9% w.b. reduced to 3% w.b.within 7 hours.The moisture content of the product decreases with a decrease in overall efficiency.

4. RESULTS AND DISCUSSION

4.1 Exergy Analysis with Respect to Drying Time

Exergy analysis provides insight into the quality of energy used in thermal systems by quantifying the useful work potential. In the biomass dryer used for Amla drying, exergy inflow primarily originates from the combustion of biomass, which produces high-temperature gases that transfer heat to the drying air. As drying progresses, the temperature of the drying chamber is maintained or slightly fluctuates, depending on fuel supply and airflow regulation. It generally increases during the initial drying period, when moisture content is high and drying rates are rapid, and gradually decreases in the falling-rate period as the surface moisture depletes and heat transfer efficiency drops [13].

With time, the exergy destruction caused by irreversibilities in combustion, heat transfer, and air leakage also varies. Typically, maximum exergy utilization is observed during the first 60–90 minutes, when the drying rate is high and the exergy outflow aligns closely with the inflow. As drying continues beyond this period, exergy efficiency drops due to reduced moisture availability and increased thermal losses [14]. Monitoring these inflow and outflow exergy values at 30-minute intervals allows estimation of exergy efficiency over the total drying duration, often ranging from 12% to 25%, depending on biomass type and system insulation (Figure 2).

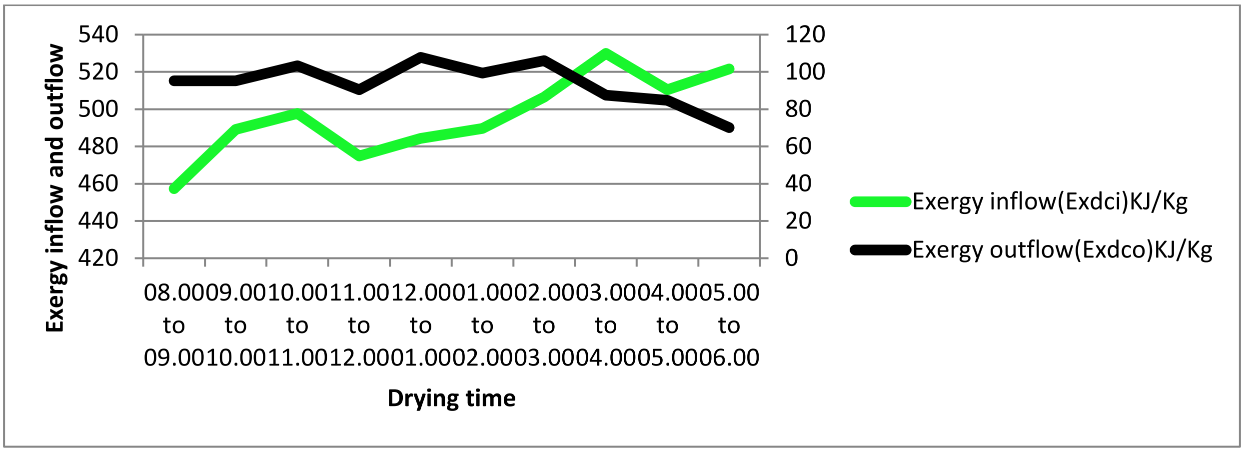


Figure 2. Exergy Analysis with Respect to Drying Time

4.2 Exergy loss with Respect to Drying Time

Exergy loss in a biomass drying system reflects the irreversibility of the energy conversion process and highlights the potential for efficiency improvement. In the case of Amla drying using a biomass-fired dryer, exergy losses occur due to incomplete combustion, heat transfer to ambient surroundings, frictional air flow losses, and thermal inefficiencies in the drying chamber. At the beginning of the drying process, typically within the first 30–60 minutes, the temperature difference between the hot air and the moist product is high, resulting in more effective heat and mass transfer [15]. During this stage, exergy is efficiently transferred to the product, and exergy loss remains relatively low. However, as drying progresses into the falling-rate period, the moisture content of Amla reduces significantly, leading to lower heat absorption by the product and higher exergy dissipation to the surroundings. Over time, particularly after 90–120 minutes of drying, the rate of useful energy utilization decreases while combustion and thermal losses remain relatively constant or even increase due to continued biomass burning. This imbalance causes a gradual rise in exergy loss. Exergy destruction becomes dominant during this later phase, especially if there is poor insulation, non-uniform airflow, or over-firing of biomass. Graphically, this results in an upward trend in exergy loss with respect to time, often peaking toward the end of the drying cycle [16]. Typically, in biomass dryers, 30–50% of the total exergy input may be lost due to system irreversibilities, especially if control mechanisms for fuel rate and drying temperature are absent. Monitoring exergy loss at regular intervals during the drying process not only helps identify inefficient operating zones but also aids in optimizing drying time and fuel consumption, ensuring energy-efficient and sustainable operation (Figure 3).

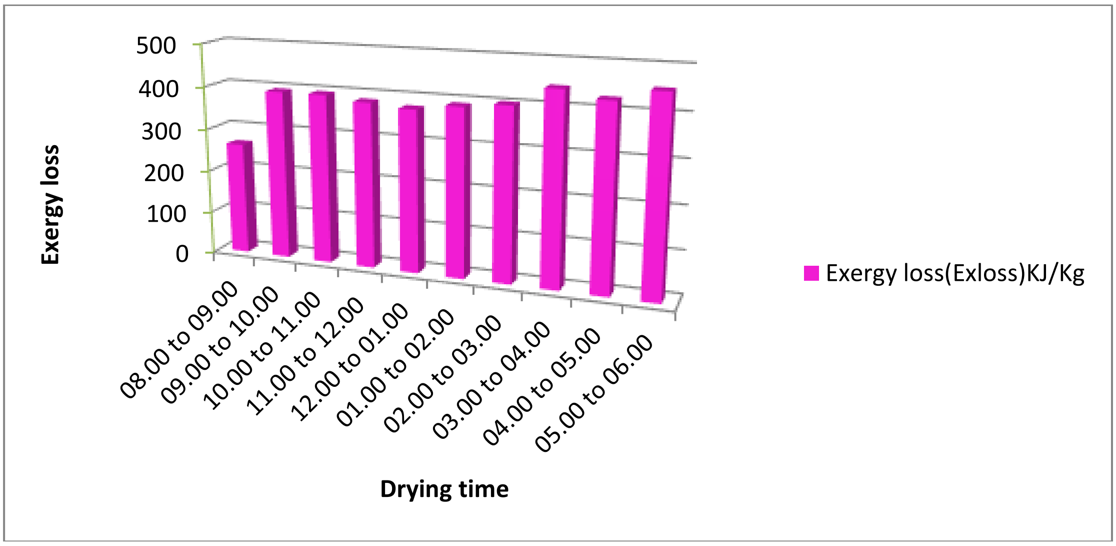
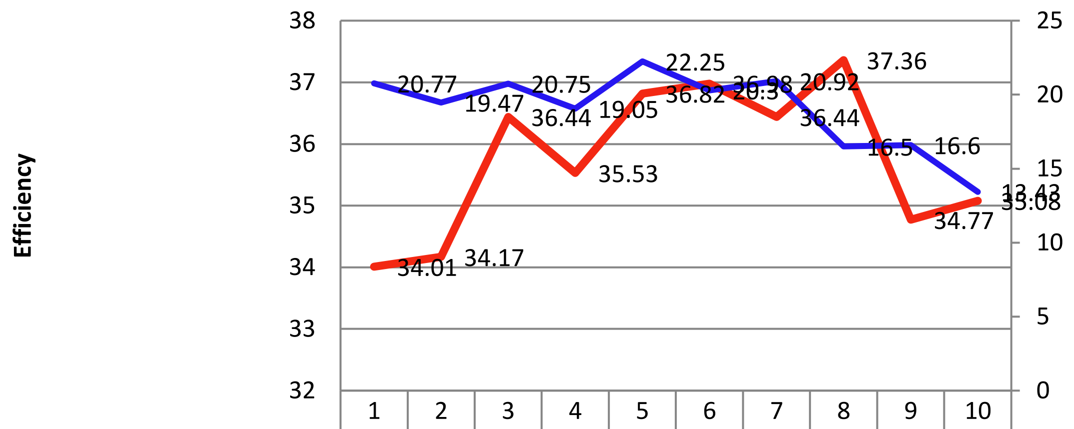


Figure 3. Exergy loss with Respect to Drying Time

4.3 Exergy Efficiency with Respect to Drying Time

Exergy efficiency is a critical performance metric that indicates how effectively the input exergy (available energy) is converted into useful work—in this case, the energy used for moisture removal from Amla. It is defined as the ratio of exergy output (useful exergy used to evaporate water from the product) to the exergy input (total exergy from biomass combustion), expressed as a percentage. At the beginning of the drying process, when the Amla fruits have high moisture content, heat and mass transfer are more effective, resulting in higher exergy efficiency, often ranging between 20–30%. During this initial period (typically the first 60–90 minutes), a large portion of the supplied exergy is used effectively for moisture evaporation [17]. As drying progresses and the moisture content reduces, the rate of water removal slows down, leading to a decrease in exergy efficiency. This happens because the thermal energy continues to be supplied, but the product absorbs less due to lower moisture availability, and a larger share of the energy is lost through exhaust gases, system walls, and unutilized heat. Toward the end of the drying cycle, exergy efficiency may drop to below 10–15%, especially if the dryer is not equipped with insulation or a control system to reduce fuel input during the falling-rate period.

Exergy efficiency varies non-linearly over time and is strongly influenced by biomass type, combustion quality, air velocity, and drying temperature. Monitoring exergy efficiency over the drying period can help identify optimal operating conditions to minimize fuel consumption, reduce exergy loss, and improve system sustainability.



	1	2	3	4	5	6	7	8	9	10
Gasifier Efficency(ηc)	34.01	34.17	36.44	35.53	36.82	36.98	36.44	37.36	34.77	35.08
Exergy efficiency(ηEX)	20.77	19.47	20.75	19.05	22.25	20.3	20.92	16.5	16.6	13.43

Figure 4. Exergy Efficiency with Respect to Drying Time

5. Mathematical Formulation

5.1 First Law Analysis

The drying process can be modeled as a steady flow process of heating, cooling and humidification. First law analysis states that the energy entering the thermal system, including fuel, electricity, and flow of matter is conserved and not destroyed.

The general equation of energy conservation of the accumulated air is made using a thermal energy balance [22-26]:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \qquad (1)$$

The general equation of mass conservation of the drying air is made using a thermal energy balance:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (2)$$

The air specific heat is calculated from Eq. (3). The constant 1.004 is the specific heat of dry air :

$$Cp = 1.004 + 1.88W \qquad (3)$$

Where W is the humidity ratio of the dry air.

The useful heat gain by a collector can be expressed as (Q_u)

$$Q_u = mC_p(T_o - T_i) \quad (4)$$

The first law efficiency of the solar collectors is defined as the ratio of the useful heat gain to the incident solar radiation on the collector surface

$$\eta_c = \frac{mC_p(T_o - T_i)}{I.A} \quad (5)$$

where I is the solar radiation incident on the tilted collector surface, A is the solar collector area

The drier efficiency is the product of the collector efficiency and drying chamber efficiency.

$$\eta d = \eta c * \eta dc \quad (6)$$

Where, ηd is solar drier efficiency. ηc is average collector efficiency and ηdc is drying chamber efficiency

5.2. Second Law Analysis

Second law analysis introduces the useful concept of exergy in the thermal systems. Second law analysis states that the part of the useful energy entering the thermal system including fuel, electricity and flow of matter is destroyed due to the irreversibilities. Exergy is the amount of maximum work obtained theoretically at the end of a reversible process in which equilibrium with the environment should be obtained. It is the measurement of the quality and grade of the energy. The energy and exergy balance of the system can be expressed as (neglecting the kinetic and potential energy change)

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \quad (7)$$

Or

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,in} - \dot{E}x_{mass,out} = \dot{E}x_{dest} \quad (8)$$

The exergy outflow of the drying chamber (Ex_{dco}) = $mc\,[(T_{dco} - T_a) - T_a \ln\frac{Tdco}{Ta}]$ (9)

The exergy Inflow of the drying chamber (Ex_{dci}) = $mc\,[(T_{dci} - T_a) - T_a \ln\frac{Tdci}{Ta}]$ (10)

The exergy loss (Ex_{loss})= $Ex_{dci} - Ex_{dco}$ (11)

Drying chamber Efficiency (η_{dc})=$\frac{T1-T2}{T1-Ta}$ (12)

The second law efficiency is estimated based on the following relations:

Exergy efficiency (η_{EX}) = $\frac{Exdco}{Exdci}$

CONCLUSION

This study evaluated the energy and exergy performance of a biomass-fired dryer for drying Amla (*Phyllanthus emblica*), with a focus on drying efficiency, specific energy consumption (SEC), exergy inflow, outflow, loss, and overall exergy efficiency with respect to drying time. The results demonstrated that biomass, particularly coconut shell and rice husk, can serve as a cost-effective and sustainable fuel source for thermal drying. Moisture content of Amla was successfully reduced from approximately 84% to 12% (wet basis), with specific energy consumption ranging from 4.2 to 6.5 MJ/kg of water removed, depending on fuel type and drying temperature. Exergy analysis revealed that exergy inflow peaked during the initial drying stage, while exergy efficiency was highest within the first 60–90 minutes due to rapid moisture evaporation. As drying progressed, exergy losses increased and efficiency declined, highlighting the need for optimized fuel control and heat recovery systems. The average thermal efficiency ranged from 15% to 25%, and exergy efficiency from 10% to 30%, depending on operating conditions. In conclusion, the biomass dryer proved to be an energy-efficient and environmentally friendly solution for post-harvest

Amla processing. Future work may focus on integrating solar pre-heating or automated fuel control to further enhance drying performance and reduce energy losses.

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