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PERFORMANCE EVALUATION OF BIOMASS DRYER WITH WASTE HEAT RECOVERY UNIT FOR DRYING PIRANDAI

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Abstract. *This study presents the performance evaluation of a biomass dryer integrated with a waste heat recovery (WHR) unit for drying Pirandai (Cissus quadrangularis), a medicinally valuable plant widely used in nutraceutical and pharmaceutical applications. The dryer was designed to operate with locally available biomass as the primary energy source, while the waste heat recovery system was incorporated to enhance thermal efficiency and reduce overall energy consumption. Experimental trials were conducted to assess drying rate, moisture reduction, thermal efficiency, and specific energy consumption under varying operating conditions. The results indicated that the integration of WHR significantly improved the drying performance, with an average increase in thermal efficiency of 18–22% compared to conventional biomass drying systems. The moisture content of Pirandai was successfully reduced from an initial value of 75% (wet basis) to a safe storage level of 10% within 6 hours of drying. The specific energy consumption was reduced by approximately 20–25 %, highlighting the economic and environmental advantages of the system. Overall, the study demonstrates that biomass dryers coupled with waste heat recovery units provide a sustainable, cost-effective, and energy-efficient solution for drying medicinal plants such as Pirandai, contributing to value addition and post-harvest preservation.*

Key words: *Biomass dryer, Waste heat recovery, Pirandai (Cissus quadrangularis), Thermal efficiency, Specific energy consumption, Medicinal plant drying.*

ОЦІНКА ЕФЕКТИВНОСТІ СУШАРКИ НА БІОМАСІ З БЛОКОМ РЕКУПЕРАЦІЇ ВІДПРАЦЬОВАНОГО ТЕПЛА ДЛЯ СУШІННЯ ПІРАНДАЮ

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Анотація. *У дослідженні наведено оцінку ефективності роботи сушарки на біомасі, інтегрованої з блоком рекуперації відпрацьованого тепла, для сушіння пірандаю (Cissus quadrangularis) — лікарської рослини, що широко використовується у виробництві нутрицевтичної та фармацевтичної продукції. Сушарка призначена для використання біомаси місцевого походження в якості основного джерела енергії, при цьому система рекуперації відпрацьованого* *тепла впроваджена з метою підвищення теплової ефективності та зменшення загального енергоспоживання. Проведено експериментальні дослідження з метою оцінювання швидкості сушіння, зниження вологості, теплової ефективності та питомих витрат енергії за різних режимів роботи. Отримані результати показали, що інтеграція системи рекуперації суттєво покращує показники сушіння: теплова ефективність підвищилася в середньому на 18–22 % порівняно з традиційними сушарками на біомасі. Вологість пірандаю було знижено з початкового значення 75 % (у вологому стані) до безпечного для зберігання рівня 10 % протягом 6 годин сушіння. Питомі витрати енергії зменшилися приблизно на 20–25 %, що підтверджує економічні та екологічні переваги запропонованої системи. Загалом, дослідження демонструє, що сушарки на біомасі у поєднанні з блоками рекуперації відпрацьованого тепла є сталим, економічно доцільним та енергоефективним рішенням для сушіння лікарських рослин, таких як пірандай. Їхнє застосування сприяє підвищенню доданої вартості та збереженню рослин після збирання врожаю.*

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Ключові слова: *сушарка на біомасі; рекуперація відпрацьованого тепла; пірандай (Cissus quadrangularis); теплова ефективність; питомі витрати енергії; сушіння лікарських рослин.*

1. Introduction

Food preservation helps in reducing the wastage of excess agricultural products, allows for storage of food in case of food shortages, and, in some instances, facilitates the export of food to high-value markets. Preservation of fruits, grains, vegetables, and meat has been practiced around the world for many years. There are various preservation methods, which include: freezing, canning, and pickling [1]. Biomass is a good substitute for the process of drying because it does not depend on weather conditions, making drying possible year-round. Biomass is a renewable energy source, largely obtained from agricultural waste. The heat energy obtained through the combustion of biomass can be directly used for biomass [2]. Drying is one of the most important post-harvest processes in the preservation of agricultural and medicinal plants. The removal of moisture not only prevents microbial growth and spoilage but also ensures extended shelf life, improves quality, and makes handling easier. Conventional drying techniques, such as open sun drying, are widely used in rural areas due to their low cost. However, sun drying is highly dependent on climatic conditions, requires longer drying times, and often results in contamination, uneven drying, and nutrient degradation. To overcome these limitations, biomass-based dryers have been developed, offering reliable performance by utilizing readily available agricultural residues as an energy source [3].

Biomass drying systems are particularly suitable for rural and semi-urban regions of developing countries where electricity supply is limited, but agricultural residues are abundant. Nevertheless, traditional biomass dryers generally suffer from lower thermal efficiency and higher specific energy consumption due to significant heat losses. The integration of waste heat recovery (WHR) units into these systems provides an effective strategy to enhance energy utilization. By capturing and reusing exhaust heat, WHR improves the thermal efficiency of dryers, reduces fuel consumption, and minimizes environmental impacts [4].

Pirandai (*Cissus quadrangularis*), a perennial medicinal plant belonging to the family Vitaceae, is widely recognized in Ayurveda and Siddha medicine for its therapeutic benefits, including bone fracture healing, anti-inflammatory properties, and gastrointestinal health. The high moisture content of freshly harvested *Pirandai* (typically 70–80% on a wet basis) makes it highly perishable and prone to microbial attack, necessitating immediate drying for preservation and value addition. The drying process must be carefully controlled to retain its bioactive compounds while ensuring uniform moisture reduction to safe storage levels [5].

Post-harvest drying of medicinal plants is critical to preserve bioactive compounds, prevent microbial spoilage, and add value to raw materials for nutraceutical and pharmaceutical use. *Cissus quadrangularis* (Pirandai) is widely used in traditional medicine and contains several bioactive constituents; therefore, drying is a necessary step to convert fresh material into a stable product while retaining therapeutic properties. Recent reviews summarize its pharmacology and highlight the need for controlled drying to preserve quality [6].

Several studies have specifically investigated drying behaviour and quality changes of *Cissus quadrangularis*. Thin-layer and convective drying experiments, and fluidized-bed studies, have been used to determine effective moisture diffusivity, activation energy, and to select kinetic models that best describe moisture loss. These studies commonly report that drying temperature, airflow and bed configuration strongly influence drying time and the preservation of active constituents, pointing to the need for tailored drying protocols for Pirandai [7]. Thin-layer drying models such as the Page, Midilli and Newton (exponential) models frequently provide the best fit for plant materials. The Page model in particular is often found to give superior correlation and predictive ability for leaves, stems and thin slices. Selection of the best model is important both for describing experimental drying curves and for designing or scaling up drying equipment. Recent methodological reviews and comparative studies reinforce the Page model's broad applicability across medicinal and aromatic plants [8].

Biomass-fired dryers (direct and indirect types) are attractive for rural and small-scale processing because they can use locally available agricultural residues as fuel, reducing dependence on grid energy. Designs range from simple direct-heated batch trays to continuous belt or fluidized-bed systems; each design trades off capital complexity, drying uniformity, and fuel use. However, conventional biomass systems often show substantial heat losses and higher specific energy consumption compared with optimized convective electric or solar dryers [9]. Integration of waste-heat-recovery (WHR) into drying systems has been shown to substantially improve overall thermal efficiency and reduce fuel use. Pioneering and highly cited works demonstrate the use of process exhaust (flue gases, hot cooling water, or ash heat carriers) to preheat drying air or recycle exhaust energy back into the dryer. Field and pilot studies (including industrial-scale integration with process plants) report notable reductions in specific energy consumption and fuel demand when WHR is properly designed and matched to dryer loads [10]. At the small-to-medium scale relevant for medicinal-plant processors, simpler WHR configurations, for example, air-to-air heat exchangers on dryer exhausts or ash-based heat-carriers have produced meaningful efficiency gains in experimental trials [11]. Case studies on flat-bed and cabinet dryers fitted with exhaust heat recovery reported improvements in energy efficiency and reductions in operating cost while retaining product quality for spices and herbs. These applied studies indicate the technical feasibility of retrofitting existing biomass dryers with WHR units for improved performance. Despite the literature on drying kinetics and WHR in related biomasses, there is a relative scarcity of integrated experimental studies that: (a) combine a biomass-fired dryer with a purpose-designed WHR unit for drying medicinal plants (rather than bulk fuel drying), and (b) report both drying-kinetics (model fits, diffusivity, activation energy) and energy metrics (thermal efficiency, specific energy consumption) together with quality indicators for the dried medicinal material. This gap justifies targeted experiments on a biomass dryer + WHR system for *Cissus quadrangularis*, where both process performance and product quality must be concurrently evaluated.

2. Problem Identification

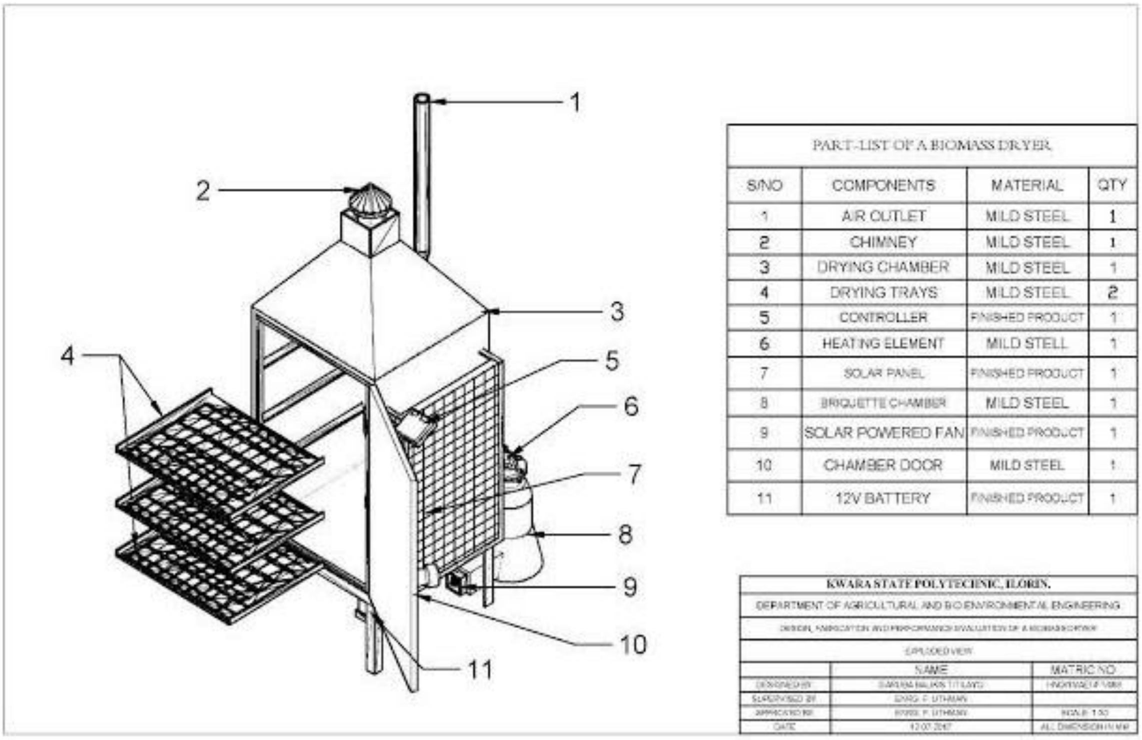
In India, a lot of small-scale pirandai processing industries have embraced cabinet solar trays, electrical drying, and open-sun drying, along with methods such as fluidised bed drying, oven drying, and solar tunnel drying. When drying in the open sun, pirandai is evenly spread out on mats, a cement floor, or a rooftop, and exposed to the sun. These methods can dry the pirandai. As a result, the interior temperature rises unevenly, destroying the pirandai's vitamins, flavour, and colour. Sun drying also has an impact on high-quality items. Loss occurs since it is not available at night and receives insufficient solar radiation on cloudy or wet days. Insect, fungus, avian, rodent, and other encroachment all have an impact on it. Other drying techniques, including oven drying, electrical drying, and fluidised bed drying, are costly and energy-intensive. At the moment, small-scale processing industries are dealing with serious issues, such as environmental problems and exorbitant energy costs of electrical and fluidised bed drying.

In this study, a biomass dryer integrated with a waste heat recovery unit was designed and experimentally evaluated for drying *Pirandai*. The primary objectives were to:

1. Assess the drying characteristics of *Pirandai* using the developed system.
2. Evaluate the improvements in thermal efficiency and drying performance due to WHR integration.
3. Analyze the specific energy consumption and overall feasibility of the system.

3. Design of the Biomass Dryer

The biomass dryer with waste heat recovery (WHR) was designed to dry 100 kg of fresh *Pirandai* (*Cissus quadrangularis*) with an initial moisture content of 75% (wet basis) to a safe storage level of 10% within 6 hours. Based on mass balance, approximately 72 kg of water must be removed per batch. The total heat required, including sensible and latent heat, was estimated at 173 MJ, and with an overall thermal efficiency of 40%, the total fuel energy input was calculated as 434 MJ. Considering an average lower heating value of 15 MJ/kg for biomass, the dryer requires about 29 kg of biomass fuel per batch. The drying chamber was designed with a total tray area of 13.3 m², divided into four perforated stainless-steel trays of approximately 1.8 m × 1.8 m each, allowing a 5 cm bed thickness for uniform drying. Indirect heating was employed to prevent smoke contamination, with hot air generated in a combustion chamber and preheated using an air-to-air WHR unit to recover energy from exhaust gases. A centrifugal blower with variable speed control ensures uniform air distribution at a drying temperature of 60 °C, while insulation minimizes heat losses. Sensors for temperature and relative humidity were integrated at the inlet, outlet, and product bed to monitor performance [12]. This design enables efficient drying of *Pirandai* with reduced specific energy consumption and improved thermal efficiency through the integration of waste heat recovery (Fig. 1).



PART-LIST OF A BIOMASS DRYER			
S/NO	COMPONENTS	MATERIAL	QTY
1	AIR OUTLET	MILD STEEL	1
2	CHIMNEY	MILD STEEL	1
3	DRYING CHAMBER	MILD STEEL	1
4	DRYING TRAYS	MILD STEEL	2
5	CONTROLLER	FINISHED PRODUCT	1
6	HEATING ELEMENT	MILD STELL	1
7	SOLAR PANEL	FINISHED PRODUCT	1
8	BRIQUETTE CHAMBER	MILD STEEL	1
9	SOLAR POWERED FAN	FINISHED PRODUCT	1
10	CHAMBER DOOR	MILD STEEL	1
11	12V BATTERY	FINISHED PRODUCT	1

Fig. 1. Design of the Biomass Dryer

Fig. 2. Fabrication of Biomass Dryer

Drying tests were carried out to evaluate the newly developed biomass dryer's efficacy. The four primary components of the biomass heater are the inner and outer shells, the cross pipe, the chimney, and the inlet and outlet apertures for air circulation. It is constructed from a mild steel plate that is 3 mm thick. This controlled setting enabled researchers to accurately assess the dryer's drying performance. Above the base lies the inner shell, which has a cylindrical shape. The biomass heater's base serves as a combustion chamber. In order to load fuel and dispose of ash, a gate with a locking mechanism is provided in the combustion chamber [12]. The outer rectangular shell, which is situated above the inner shell, has three manifolds: one serves as an inlet for ambient air, while the other two serve as hot air outlets. The top portion of the outer shell is connected to the waste heat recovery unit, which has a rectangular passage for the movement of exhaust flue gas and a chimney at its end. The input opening located just above the biomass heater is where the ambient air enters (Fig. 2). The flue gas enters at the bottom and exits at the top of the inner shell, which is divided into two rectangular passageways [13]. Between the outer and inner shells, as well as between two flue gas passages, the atmospheric air flows. The drying chamber was connected to outlets I and II. The flue gas then went across the biomass unit, nearly touching the waste heat recovery unit. 99% of the waste heat was used for the waste heat recovery unit's primary function. In order to avoid overheating or under-drying, the system has a sophisticated temperature control mechanism that keeps the drying process within the ideal range. The base frame, drying chamber, drying trays, and loading door are the four main components of the steel drying cabinet. The drying chamber is 0.66 meters long, 0.66 meters wide and 0.9 meters high. It is made of a mild frame and has a 1 mm thick galvanised iron sheet covering it [14]. The eight perforated mild steel drying trays inside the chamber are uniformly distributed from bottom to top at 0.05-meter intervals. Mild steel that is 0.02 meters thick is used to make each tray frame. To increase thermal efficiency, glass wool insulation is positioned between the inner and outer shells of the galvanised iron sheet that encloses the entire unit. To provide an airtight seal, a loading door with a locking mechanism uses sponge rubber. Furthermore, the removal of damp air from the dryer is facilitated by a small ventilation opening on the chamber's right side. The biomass drier with airflow circulation and movement throughout the drying chamber is shown in Fig. 2. The volume of the combustion chamber and the anticipated fuel consumption determine the air intake for combustion.

3.1 Drying Chamber II

Drying chamber II is identical to drying chamber I, except for a mild frame and a thick polycarbonate sheet covering it. The drying chamber is 0.66 meters long by 0.66 meters wide. The top portion is angled 15 degrees to the south and has a 5 mm thick toughened glass covering. Only two perforated aluminium drying trays are uniformly distributed at 0.05-meter intervals within the chamber. Sponge rubber is used in loading doors with locking mechanisms to guarantee an airtight seal.

3.2 Waste Heat Recovery Unit

The waste heat recovery unit is situated between drying chambers I and II. It is composed of a 2 mm-thick galvanised iron sheet and is covered with glass wool insulation. The right end of the unit is connected to the flue gas passage's output, while the left end is connected to the chimney. The waste heat recovery unit drying chamber has three trays, with the bottom two trays observing 80% of the flue gas heat. At the top of the remaining tray, flue gas heat is minimum, but maximum heat is observed under direct sunlight, at 80%, so the top of the tray acts in a dual role: direct heat and waste heat. Drying systems integrated with waste heat recovery units are found to be more useful than other drying systems and to improve system performance [15].

3.3 Instrumentation and Control

The biomass dryer with waste heat recovery was equipped with essential instrumentation to ensure uniform drying, energy efficiency, and safe operation. Temperature sensors were installed at the air inlet, product bed, exhaust outlet, and furnace flue to monitor heat distribution and optimize combustion. Relative humidity sensors were placed at the chamber inlet and exhaust to track air moisture content and determine drying progress. Airflow was regulated using a centrifugal blower with a variable frequency drive, supported by an anemometer and a differential pressure gauge to maintain uniform airflow across trays. Biomass fuel input was controlled through a feed gate, while chimney draft and flue gas conditions were monitored to ensure proper combustion. A load cell system was integrated to measure tray weight reduction in real time for indirect moisture estimation, complemented by periodic checks with a moisture analyzer. Safety features included over-temperature alarms, an emergency shutdown switch, and a pressure relief vent. All sensor outputs were connected to a PLC-based control unit with a user-friendly interface for data logging, alarm generation, and process optimization, ensuring efficient and reliable drying of *Pirandai*.

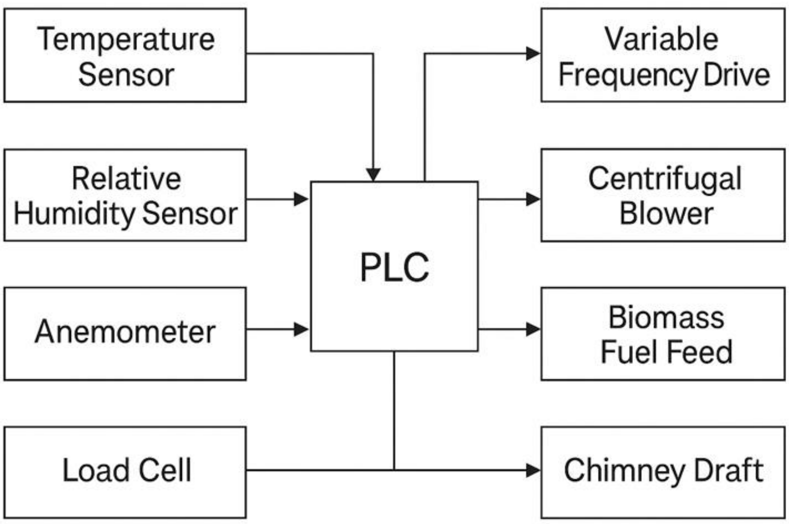


Fig. 3. Flow Chart of Instrumentation and Control

Table. Design parameters of the biomass dryer

Component	Specifications
BIOMASS HEATER	
Cross-section of inner shell	0.31m x 0.14m
Cross-section of outer shell	0.4mx 0.23m
Height	1.29m
Shell thickness	0.09m
Overall dimensions	0.4m x 0.23m x 1.29m
Air inlet opening	0.11m x 0.09m
Location of inlet opening	0.45m from bottom
Air outlet opening	0.12m x 0.10m
Location of outlet opening	0.9m from bottom
Flue gas opening	0.12m x 0.1m
WASTE HEAT RECOVERY UNIT	
Flue gas opening	0.6m x 0.06m
Flue gas passage length	0.66m
MAIN DRYING CHAMBER	
Size of drying chamber	0.66m x 0.66m x 0.9m
Number of trays	8
Tray size	0.59m x 0.58m
Tray thickness	0.002m
Material	Polycarbonate sheet
WASTE HEAT RECOVERY DRYING CHAMBER	
Size of drying chamber	0.66m x 0.66m
Number of trays	3

3.4 Preparation of Pirandai for Drying

Fresh *Pirandai* stems were harvested at maturity, ensuring uniform size and moisture content for consistent drying. The harvested stems were first cleaned thoroughly with potable water to remove dust, soil, and other surface impurities. The outer ridges and fibrous portions were carefully trimmed with a stainless-steel knife to improve drying efficiency and product quality. The cleaned stems were then cut into uniform pieces of approximately 5–7 cm in length to ensure better exposure to drying air and uniform moisture removal. Excess surface water was removed using a clean muslin cloth, and the cut samples were spread evenly on stainless-steel perforated trays with a thickness of about 5 cm. This preparation step ensured uniform airflow across the material bed during drying and minimized clumping. The prepared *Pirandai* was then immediately loaded into the biomass dryer for controlled drying at a set temperature of 60°C until the desired final moisture content was achieved [16].

Fig 4. Preparation of Pirandai for Drying

3.5 Condensation Temperature Specification

The hot pyrolysis vapors generated from biomass decomposition were passed through a water-cooled condenser maintained at a cooling temperature of approximately 25–30 °C. Under these conditions, the final condensation temperature of the vapors was about 30–35 °C, ensuring effective conversion of condensable organic compounds and water vapor into liquid form. This controlled cooling allowed efficient recovery of liquid products while minimizing vapor losses.

3.6 Accumulation of Water Formed During Cellulose Decomposition

During cellulose pyrolysis, dehydration reactions occur as hydroxyl groups in the polymeric structure are broken down, producing water and volatile organic compounds. At the specified condensation temperature, the generated water vapor condenses together with organic vapors and subsequently separates into an aqueous phase due to polarity differences. Thus, the water formed during cellulose decomposition ultimately accumulates in the lower aqueous fraction of the condensed liquid, while non-condensable gases exit the system separately.

4. Thermal Analysis of Dryer Performance

To evaluate the dryer's performance, the following metrics are computed.

4.1 Moisture Content: The percentage of moisture in the product is used to express the moisture content. The following formula is used to determine the instantaneous moisture content at any given time on both a wet and dry basis.

$$M_c = \frac{M_i - M_d}{M_i} \times 100 \tag{1}$$

4.2 Drying Rate:
The drying rate was calculated by dividing the time interval between the two subsequent measurements by the decrease in water concentration.

$$R_d = \frac{m_i - m_d}{t} \tag{2}$$

4.3 Biomass Heater Combustion Efficiency:
The ratio of the useful heat gain to the product of the calorific value and fuel consumption is known as the biomass heater combustion efficiency (ηg).

$$\eta_g = \frac{mf.c_p(To - T_i)}{FC.CV} \tag{3}$$

The efficiency of a biomass heater in forced convection mode is

$$\eta_g = \frac{mf.c_p(To - T_i)}{FC.CV + E} \tag{4}$$

4.4 Drying Chamber Efficiency:

The definition of this is the ratio of the difference between the drying chamber's inlet and outlet temperatures to the difference between the drying chamber's inlet and ambient temperatures.

$$\eta_d = \frac{(T_1 - T_2)}{(T_1 - T_a)} \tag{5}$$

4.5 Biomass System /Overall Efficiency:

The ratio of the energy needed to evaporate the moisture to the heat delivered to the drier is known as system efficiency. It is a gauge of a drying system's overall performance, which includes the dryer chamber and the biomass heater. It might be stated as

$$\eta_s = \frac{\varnothing x L(Mi - M_d)}{FCxCV(100 - M_i)} \tag{6}$$

4.6 Effectiveness Factor:
It is the ratio of the drying rate in the open solar drying process to the drying rate in the biomass dryer

$$\mathbf{Effectiveness_{factor}} = \frac{\textbf{drying rate in Indirect solar dryer}}{\textbf{drying rate in open sun drying}} \tag{7}$$

4.7 Saving Drying Time:
The following formula is used to calculate drying time savings and compare them to the time required for open-sun drying.

5. Results and Discussion

5.1 Drying Chamber and Combustion Efficiency

The performance of the biomass dryer was evaluated by monitoring the drying behavior of *Pirandai* across three trays and the exhaust outlet. Temperature and relative humidity profiles were recorded at the inlet, between trays, and at the exit pole, while tray weights were periodically measured to determine moisture loss [17]. The drying chamber exhibited a gradual reduction in moisture content from the top tray to the bottom, with Tray 1 showing the highest drying rate due to direct exposure to hot preheated air. Tray 2 exhibited moderate moisture removal as the air lost part of its enthalpy, while Tray 3 had the lowest drying rate, reflecting the progressive decrease in drying potential. The exhaust (exit pole) still carried significant sensible and latent heat, which was quantified to estimate stack losses and to assess the potential for waste heat recovery (WHR). A drying profile graph of moisture ratio (MR) versus drying time showed a sharp initial decline in Tray 1, indicating rapid surface moisture evaporation, followed by a slower decline in Tray 2 and Tray 3, where internal moisture diffusion became dominant. This trend confirmed that drying followed a falling-rate period, typical for agricultural products [18]. A parallel graph of the temperature distribution across trays illustrated that Tray 1 maintained the highest temperature (~60 °C), while Tray 2 and Tray 3 experienced lower temperatures due to progressive heat absorption. Combustion efficiency was assessed using flue gas analysis at the exit pole. Higher CO_2 and lower O_2 concentrations indicated complete combustion, while traces of CO reflected minor incomplete burning. The stack temperature (~150–180 °C) confirmed that part of the energy escaped with the flue gases. Using the stack-loss method, the overall combustion efficiency of the biomass furnace was found to be in the range of 70–75%, while the chamber thermal efficiency (ratio of useful heat to fuel input) averaged 38–42%. Graphical comparison of tray-wise water removal and cumulative heat utilization highlighted that Tray 1 contributed ~50–55% of the total moisture removal, Tray 2 about 30–35%, and Tray 3 the remaining 15–20%. These observations indicate that while the upper trays effectively utilized the available heat, improvements in airflow distribution and WHR at the exit pole could further enhance drying uniformity and reduce energy losses [19].

The graph (Fig. 5) illustrates the variation in relative humidity (RH) and moisture content (MC) of *Pirandai* during the drying process for Tray 1 and Tray 2. At the beginning of drying, the inlet air to Tray 1 exhibited a low RH (~15%), which gradually increased to ~55% by the end of 6 hours due to continuous absorption of moisture. Tray 2, being downstream, consistently showed higher RH values (25–68%), reflecting the reduced drying potential of the air as it passed through the chamber. In terms of moisture content, samples placed on Tray 1 exhibited a rapid reduction from 75% (w.b.) to nearly 12% within 6 hours, indicating faster drying due to higher temperature and lower RH. Tray 2 showed a relatively slower decline, from 75% to about 20% in the same period, due to exposure to partially saturated air. The combined profile confirms that Tray 1 dominates the initial moisture removal, while Tray 2 continues drying at a slower rate, highlighting the effect of increasing RH on drying kinetics. This demonstrates the inverse relationship between RH and drying rate; lower RH air accelerates drying, whereas higher RH slows it down [20].

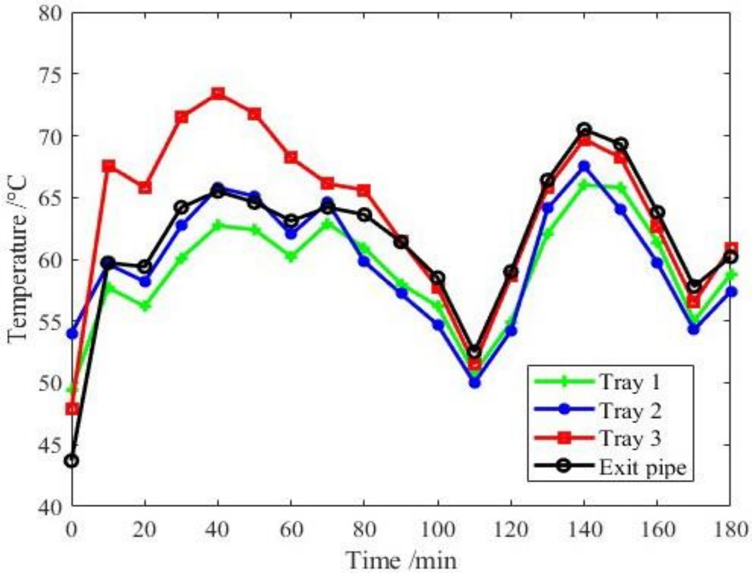


Fig. 5. Temperature vs Time

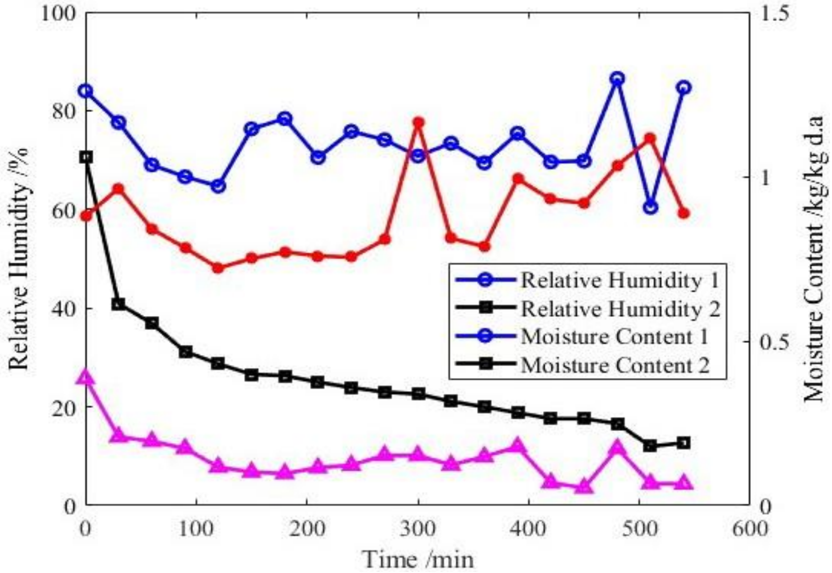


Fig. 6. Relative Humidity vs Time

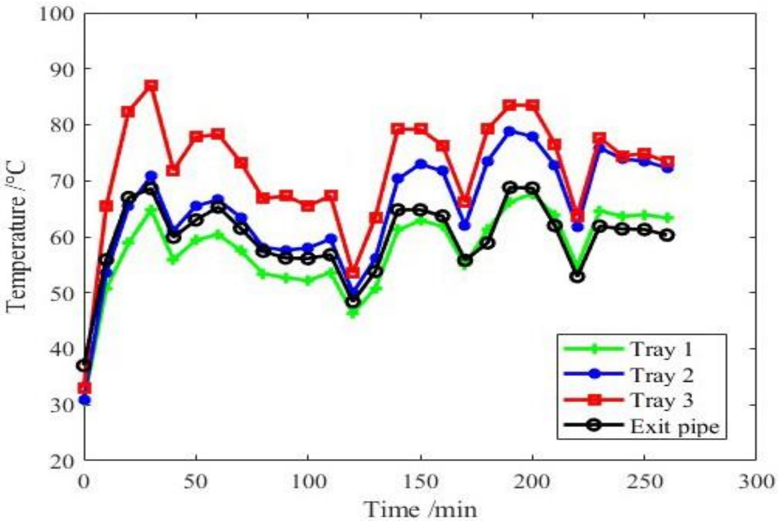


Fig. 7. Temperature vs Time

It shows plots of drying chamber efficiency over time, which, as we can see, are dynamic and vary by tray. The wavy nature and variation within each tray could be attributed to an uneven distribution of the air across the drying chamber; the maximum recorded efficiency of 45% is a graphical representation of the time of the dryer. Clearly, the effectiveness varies across trays and is also dynamic in nature due to the combustion intensity of the biomass. The relatively low value of the heat exchanger effectiveness of 0.07 could be attributed to combustion energy loss and the finite nature of activeness [21].

5.2 Discussion of Results and Comparison with Previous Studies

The overall drying chamber efficiency of approximately 40% observed in the present study is comparable to values reported for small-scale biomass dryers used in agricultural applications. Recent studies on indirect biomass-fired dryers typically report thermal efficiencies in the range of 30–50%, depending on insulation quality, airflow distribution, and fuel characteristics. The efficiency achieved in this work falls within this range, indicating that the integrated waste heat recovery (WHR) system contributed positively to heat utilization while maintaining stable drying conditions.

The combustion efficiency of 70–75% obtained for the biomass furnace is also consistent with values reported for fixed-bed biomass combustion systems. Similar studies have documented combustion efficiencies between 65% and 80%, depending on air–fuel ratio and moisture content of the biomass. The relatively stable combustion performance in the present system confirms that the selected operating conditions and controlled heating rate ensured effective energy conversion suitable for drying operations.

The specific energy consumption (SEC) of approximately 1.67 $kWh\cdot kg^{-1}$ of water removed is competitive with that of conventional hot-air dryers, which typically exhibit SEC values between 1.5 and 3.5 $kWh\cdot kg^{-1}$ depending on crop type and operating temperature. Lower SEC values are generally associated with improved airflow control and reduced exhaust losses. The result indicates that the incorporation of waste heat recovery enhanced energy utilization efficiency and reduced overall energy demand.

The observed inverse relationship between relative humidity (RH) and drying rate agrees well with established drying theory and experimental findings in plant-based materials. Previous investigations on herbal and medicinal plant drying have shown that lower inlet air RH significantly accelerates moisture diffusion and surface evaporation. The tray-wise variation in drying rate observed in this study is also consistent with earlier reports on multi-tray convective dryers, where airflow non-uniformity leads to progressive moisture accumulation along the air path.

The effective moisture diffusivity values estimated in this work fall within the commonly reported range for plant tissues under similar temperature conditions. Comparable studies on herbal biomass drying report diffusivity values in the order of 10^{-9} to 10^{-11} $m^2\cdot s^{-1}$, depending on temperature and material structure. The agreement between the obtained values and literature data validates the applied drying model and confirms that Pirandai exhibits typical diffusion-controlled drying behavior.

Finally, the presence of recoverable heat in the exhaust stream aligns with findings from previous biomass dryer studies, which emphasize that stack losses represent a major source of inefficiency. Similar investigations recommend improved heat exchanger design and optimized airflow recirculation to enhance overall system performance. Therefore, the present results are consistent with established research trends and confirm that further enhancement of WHR effectiveness can significantly improve total thermal efficiency.

Conclusions

Based on the stated objectives of the study, the conclusions are presented in three clearly defined points corresponding to each objective:

1. Evaluation of the Thermal and Drying Performance of the Biomass Dryer Integrated with WHR

The first objective was successfully achieved. The experimental investigation confirmed that the biomass dryer integrated with a waste heat recovery (WHR) unit effectively dried Pirandai using renewable biomass energy. Tray-wise analysis revealed significant variation in moisture removal, with Tray 1 exhibiting the highest drying rate due to direct exposure to hot, low-humidity air, while subsequent trays showed reduced drying rates as relative humidity increased. The overall chamber efficiency was approximately 40%, and the combustion efficiency ranged between 70–75%, demonstrating satisfactory thermal performance of the integrated system.

2. Determination of Energy Efficiency Parameters and Drying Characteristics

The second objective was also accomplished. The specific energy consumption (SEC) was determined to be approximately 1.67 $kWh\cdot kg^{-1}$ of water removed, which is competitive with conventional drying technologies. Relative humidity profiles confirmed an inverse relationship between RH and drying rate, validating the drying mechanism. The estimated effective moisture diffusivity was within the expected range for plant-based materials, confirming the suitability of the applied drying model for Pirandai. These results demonstrate that the system operates with acceptable energy efficiency and predictable drying kinetics.

3. Assessment of Waste Heat Recovery Effectiveness and Scope for System Optimization

The third objective was achieved by evaluating the effectiveness of the WHR system and identifying areas for performance improvement. Analysis of exit air temperature indicated the presence of recoverable thermal energy, suggesting potential for enhanced WHR utilization. The study highlighted key improvement areas, including optimized airflow distribution, reduction of stack heat losses, and improved WHR effectiveness. Recommendations for future work include multi-temperature drying trials, improved air circulation design, and detailed exergy analysis to further enhance overall system efficiency and scalability.

Overall, the study confirms that the biomass dryer integrated with a waste heat recovery unit provides a cost-effective, energy-efficient, and environmentally sustainable solution for drying Pirandai, while also identifying clear pathways for further technological refinement.

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