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Research Article

Design and Performance Analysis of Portable Vertical Burner Biomass Pellet for Green Tea Drying Process

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Abstract: This study aimed to design a portable vertical biomass pellet burner as an alternative solution to reduce energy costs in tea production, specifically for drying green tea using a ball tea dryer machine. The design combines a burner chamber unit with a multilayer heat exchanger to improve performance, and development was based on the drying air requirements of the process. The study used a Randomized Block Design (RBD) with two variables—feeding rate (5, 7, and 9 kg/h) and drying airflow (895.23, 1028.55, and 1103.47 CFM)—each tested at three levels. The performance was measured by the rate of temperature rise, drying air heating efficiency, and energy cost efficiency. The results showed that the burner design could meet the required airflow rate of up to 1150 CFM and reach temperatures of up to 120°C. To achieve the desired drying conditions, the optimal biomass pellet feeding rate was 7 kg/h, which costs approximately $0.09 per kilogram of dried tea—cheaper than using Liquid Petroleum Gas (LPG), which costs approximately $0.13/kg.The findings also revealed that both the airflow rate and feeding rate significantly affect the temperature increase rate and heating efficiency. Overall, this portable vertical biomass pellet burner can reduce green tea drying costs at ball tea drying stations by 30.28% compared with LPG usage.

Keywords: Biomass pellet; Design improvement; Green tea drying; Performance analysis; Vertical burner

1. Introduction

Tea production, particularly drying, is highly energy-intensive and essential for halting enzymatic reactions, enhancing product stability, and extending shelf life (K. R. Kumar et al., 2023; Jolvis-Pou et al., 2019). At the Tea and Quinine Research Center (PPTK) in Gambung, West Java, both Liquid Petroleum Gas (LPG) and biomass pellets are used as energy sources for green tea drying. The use of burners to convert biomass pellet into an air heating system energy source is necessary for both the tea leaf wilting and drying processes. For example, at PPTK Gambung, the ball mill tea drying machine requires biomass pellet up to 162.3 kg/batch process or LPG up to 25 kg/batch process to dries approximately 500 kg of tea leaf. PPTK Gambung green tea factory produced an average annual production of dried tea of 816,000 kg/year, with the overall energy requirement for combustion being 2,966,160 MJ/year. Biomass pellets are primarily employed during the withering stage, requiring 1.935 MJ/kg of dried tea, while LPG is used in two drying stages, consuming 0.933 MJ/kg and 0.767 MJ/kg of dried tea, respectively (Sugandi et al., 2022; Bardant et al., 2019). In 2022, energy expenses at PPTK Gambung accounted for 59.55% of total green tea production costs, with LPG's rising price being a major

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contributing factor. The current used of the horizontal burner provided an inefficient energy combustion, which also led to more emissions released into the environment. According to the daily measurement of emissions next to the burner, the CO measurement result reached 150–200 ppm at the smokestack. This highlights the need for alternative energy sources, such as biomass pellets, which are more cost-effective, renewable, and environmentally friendly (Klepacka and Florkowski, 2022; Nunes et al., 2016; Di-Giacomo and Taglieri, 2009) and alternative burner designs. While LPG offers advantages such as ease of use, high combustion efficiency, and lower emissions (Islam et al., 2021), biomass energy provides long-term environmental, social, and economic benefits (Choi and Manousiouthakis, 2020).

The development of biomass-based energy sources for industrial purposes, such as sugarcane bagasse (Racero-Galaraga et al., 2024), coconut husks (Alianto et al., 2025), cassava starch (Cifriadi et al., 2025), and microalgae (Mirzayanti et al., 2024), has been widely researched with the aim of providing environmentally friendly energy alternatives, sustainable energy, and reducing energy costs. Using plantation biomass waste for pellet production also supports green circular economy initiatives (Dale et al., 2017). Biomass pellets, typically produced by compressing finely ground dried biomass into solid forms of 6–10 mm diameter and 1–3 cm length, with a density of approximately 1.5 m^3/ton, are particularly promising when made from woody biomass (Kayo et al., 2014; Wang et al., 2013; Yokohama, 2008). Compared with firewood, biomass pellets offer more consistent heat and lower emissions (Johansson et al., 2004), and ongoing innovations in burner design have further improved combustion efficiency and reduced emissions (Toscano et al., 2014;Ahn and Jang, 2018). The burner's air supply system—particularly when using a cyclone or rotating airflow method—significantly impacts combustion efficiency (Pełka et al., 2023; Al-attab and Zainal, 2011).

Biomass waste to energy is an interesting issue in terms of the development of green circular economic concepts, especially in the production of tea. The large potential of biomass waste in tea plantations can be used as an environmentally friendly and sustainable energy source. To increase the effectiveness and efficiency of using biomass waste as an energy source, it can be converted into biomass pellets. After that, the efficiency of its combustion can be increased by developing an efficient biomass burner design. Biomass combustion is a multi-phase, multi-scale process that converts solid fuel into heat, gases, and particulate matter. Biomass combustion occurs in distinct stages: drying, devolatilization, volatile combustion, and char combustion (Zhou et al., 2019). Unlike fossil fuels, biomass contains higher volatiles, requiring careful control of primary and secondary air to optimize staged reactions. Deng et al., 2020 described a multi-zone model that considers air staging (primary, secondary, and tertiary) to enhance combustion efficiency and reduce emissions (CO and NOx), where a swirl and cyclonic airflows are used to delay or optimize volatile ignition location. The interaction between turbulent airflow and combustion chemistry in biomass burners is complex due to large particle size, inhomogeneous fuel properties, and slower reaction kinetics. Farokhi and Birouk, 2019 developed a model for biomass combustion of grate-firing furnace that incorporates chemical kinetics in turbulent reacting flows, making it suitable for modeling gas-phase combustion. Attanayake et al., 2023 described the pyrolysis process using a CFD-DEM model to better understand the process in a reactor.

In general, there are two types of burner design: vertical and horizontal burners. A vertical burner directs its flame and heat upward from the furnace floor, optimizing heat transfer by placing the flame symmetrically in the furnace cavity and reducing the risk of flame impingement on chamber walls. In contrast, a horizontal burner is typically mounted flush through the side of a furnace, projecting the flame horizontally, which can affect heat distribution and may require more complex management to ensure heating. Horizontal burners are widely used in heating and drying combustion systems due to their simple geometry and adaptability. However, several limitations have been identified (Lee et al., 2011) such as the flame traveling laterally in horizontal orientation, increasing the chances of incomplete combustion, especially under low airflow or uneven fuel feeding (Mihaescu et al., 2021). Horizontal systems typically struggle to achieve ideal stoichiometric air–fuel ratios due to the gravitational settling of solid fuels, leading to cold spots and soot formation (Pełka et al., 2023). Key factors influencing combustion include air velocity, air–fuel contact angle, and air inlet number and size (Deng et al., 2020). Vertical burner designs generally outperform horizontal configurations due to more effective air–fuel interactions. Proper air regulation improves combustion quality by raising temperature and burn duration while reducing CO emissions (Roy et al., 2013). However, higher air velocities may also result in greater heat loss through exhaust (Şener and Gül, 2021). Despite the dominance of horizontal burners, vertical burners remain underutilized and often lack integration with heat exchangers, resulting in capacity mismatches and reduced efficiency. Separately engineered burners and heat exchangers also limit the flexibility of airflow and temperature control. Although integrated biomass pellet burners with heat exchangers are typically used for space heating at lower temperatures (18°C–24°C), if adapted appropriately, they offer potential for tea drying (Büchner et al., 2015; Carlon et al., 2015).

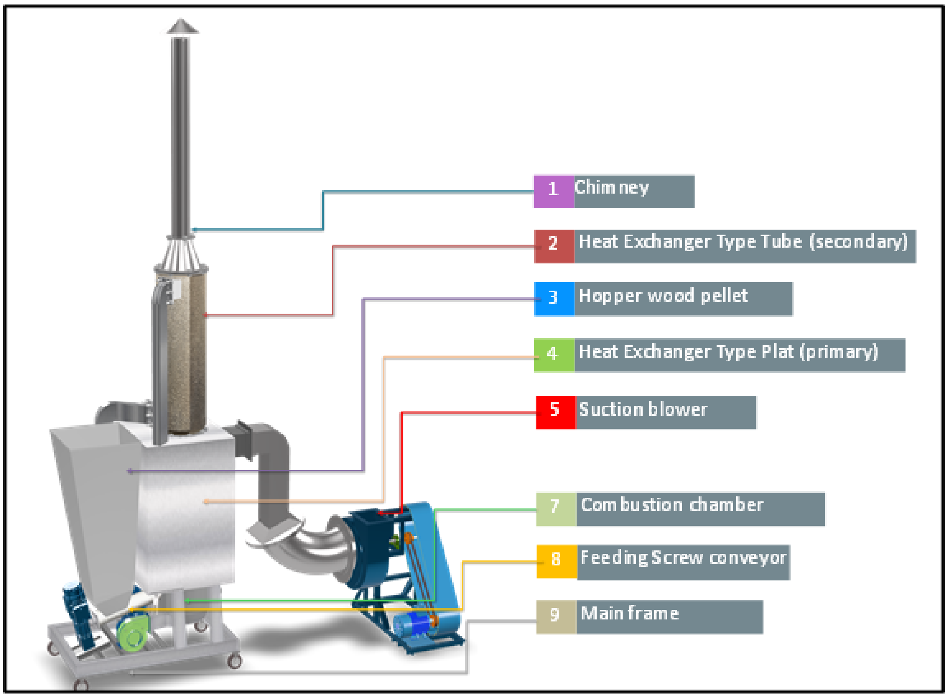
This study proposes a novel design for a compact, portable vertical biomass pellet burner integrated with a multilayer heat exchanger to provide hot air at high flow rates and temperatures ranging from 80°C to 120°C, meeting the operational needs of tea processing at PPTK Gambung. This study contributes to the advancement of biomass pellet burner technology by demonstrating its effective application in drying processes, specifically for ball tea leaves. The integration of a portable vertical burner with a heat exchanger presents a sustainable and cost-effective alternative to conventional LPG drying methods. The novelty lies in (1) the integrated vertical burner and multilayer heat exchanger system for flexible airflow and temperature control and (2) the evaluation of how biomass feeding rates and air discharge settings influence temperature rise and heating efficiency. The multilayer heat exchanger combines plate- and tube-type components to maximize heat transfer through increased surface area and contact time. The exterior plate-type exchanger delivers steady, high temperatures (Lee et al., 2011; Teixeira et al., 2009), while the interior tube-type exchanger captures direct flame heat, improving energy transfer (Burmawi et al., 2021). The biomass burner efficiency ranges from 66.8% to 85.5%, and when electrical energy for fan operation is included, the overall efficiency ranges from 54.8% to 77.4% (Carlon et al., 2015). The proposed portable burner design is compact and flexible, reducing investment costs and enabling the use of various drying systems requiring different airflow rates and temperatures. This integrated system is expected to offer an efficient, eco-friendly, and cost-effective drying solution for tea and other agricultural products.

2. Design of Portable Vertical biomass Pellet Burner

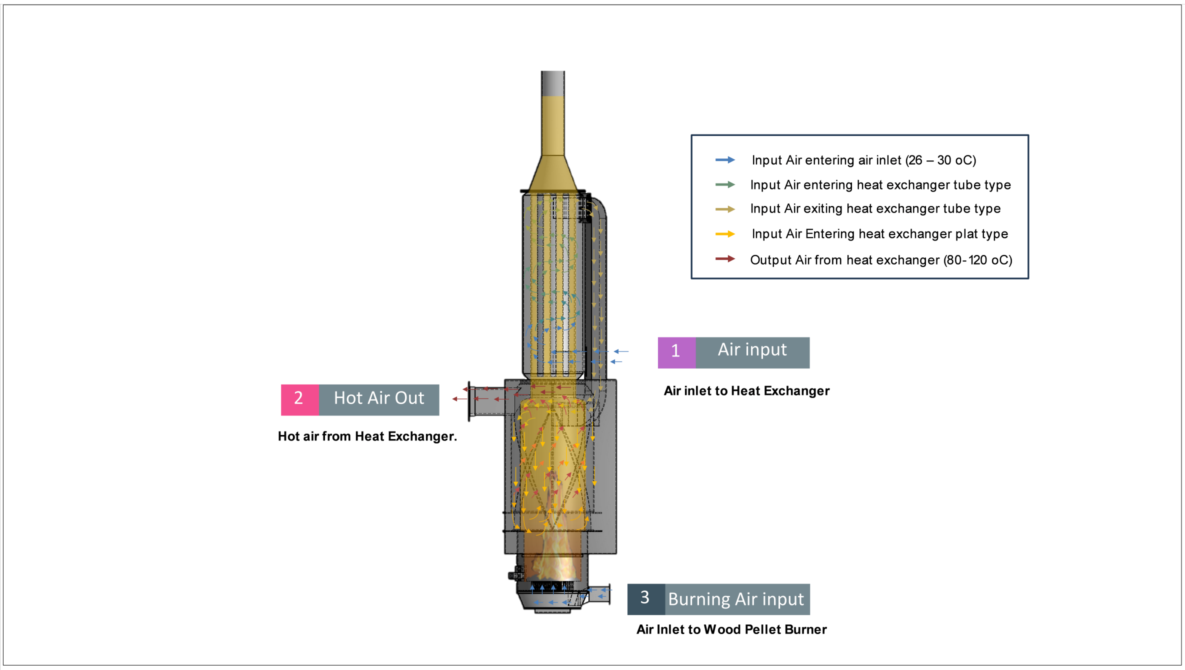
The analysis reveals that both the drying airflow rate and the biomass pellet feeding rate significantly impact the drying air temperature elevation and the air heating process efficiency. The current air heating system uses an LPG burner in conjunction with a separate heat exchanger connected to the burner unit. This configuration is employed during the second phase of the green tea drying process using a tea-type ball drying machine. The ball tea machine requires a hot air supply with an airflow range of 710.49–833.35 CFM and a temperature range of 80–120 ºC. The design requirement of the biomass burner to provide air drying for the ball tea dryer machine and monthly LPG consumption during this process is summarized in Tables 1 and 2 (Supplementary Information File).

A portable vertical burner biomass pellet machine has been developed to deliver heated air during the green tea drying process using the ball tea machine to offer a more sustainable alternative. This system provides a stable airflow of at least 800 CFM at a maintained temperature of 100 ºC. The design features a vertical combustion chamber that increases the contact angle between the combustion air and fuel, thereby enhancing the combustion efficiency. Additionally, the vertical burner (Figure 1a) incorporates a dual-layer heat exchanger system (Figure 1b)—comprising a primary plate-type exchanger encasing the combustion chamber and a secondary tube-type exchanger positioned above the chamber to capture rising combustion flames. The detailed dimensions of the proposed machine are provided in Figure 1 (Supplementary

Information File).



(a)



(b)

Figure 1 The Portable vertical burner biomass pellet (a) and the air heating systems using dual-layer heat exchanger unit (b)

The system includes a centrifugal push blower powered by a 186.43-watt motor with a 3-inch diameter pin, delivering combustion air to the chamber at a rate of 360.75 CFM. Furthermore, a 1,491-watt electromotor-powered suction blower equipped with an 8-inch diameter pin is used to generate the heated airflow for drying, operating at rates between 895.23 and 1150 CFM. The blower draws clean air through the primary and secondary heat exchangers. The heated air exiting the secondary exchanger is recirculated through the primary exchanger, thoroughly mixed, and then discharged via the hot air outlet. The proposed design emphasizes portability, user-friendly operation, and high combustion efficiency. The machine's dimensions are 1,200 mm in length, 1,200 mm in width, and 2,350 mm in height. The primary heat exchanger is constructed from 5-mm-thick SS 316 stainless steel, whereas the secondary heat exchanger uses 1-inch-diameter SS 314 stainless steel tubes. The main structural frame is made from UNP 7 iron, and the outer protective casing is fabricated from SS-201 stainless steel.

The system is equipped with a screw motor and a controller that regulates the fuel supply by modulating the biomass pellet feed rate from the hopper to the combustion chamber. This adjustable feeding mechanism helps maintain the target air temperature at the desired airflow rate. Controlling the feed rate also prevents excessive fuel accumulation, which could otherwise cause incomplete combustion and visible smoke emissions from the smokestack.

The system operates by feeding biomass pellets into the combustion chamber via a screw conveyor from the hopper. The heat generated from burning pellets first passes through the primary heat exchanger and then into the secondary heat exchanger. Fresh ambient air enters from the bottom of the secondary exchanger, creating turbulence due to the cylindrical shape and angled airflow entry. The heated air subsequently recirculates into the primary exchanger, where it mixes and rises along the direction of the exchanger fins before being drawn through the hot air outlet for use (Figure 1b).

3. Results

3.1 Materials and Equipment

The primary raw material used in this study was biomass pellets sourced from the Biomass Pellet Industry in Central Java Province. The biomass pellets used in this experiment have 25-30-mm length and 10 mm in diameter. The specific characteristics of these pellets are detailed in Table 3 (Supplementary Information File). Figure 1 shows the prototype of a vertically oriented biomass pellet burner integrated directly with a heat exchanger system.

Several instruments were used to assess the performance of the system. A TASI TA-612Cl thermometer data logger and thermocouple type K were used to record the temperature rise from the initiation of combustion in the chamber until the outlet air temperature stabilized, typically over an operational period of 1.5 to 2 hours. The ambient air temperature and relative humidity (RH) were monitored using an ELITECH RC-4HC thermohygrometer data logger. An NTC GM816 anemometer was used to measure the airflow rate at the suction blower outlet. Multiple weighing devices were employed to evaluate the physical properties of the biomass pellets. A digital scale (ACIS AW-X-7.5 model) was used to measure the bulk density of the fuel, while a KENKO KK-BL digital scale was used to determine the moisture content of the fuel. The unit density of individual pellets was measured using a Superior Mini Digital Scale (model I-2000), and a 1000 mL measuring cup was used to determine the bulk volume for density calculations. The calibration results of the tools used in this experiment are provided in Table 4 (Supplementary Information File).

3.2 Experimental Design

3.2.1 Biomass Pellets Feeding Rate

The primary fuel used in the machine performance analysis is biomass pellets. The biomass pellet feeding rate test aims to determine the optimal speed ratio of the screw conveyor motor, which is controlled via an on/off timer integrated into the control panel to achieve the desired input feeding rate. The bulk density of the biomass pellets, which is measured both before and after passing through the screw conveyor over a specified running time, is a key factor influencing the fuel supply. Detailed information on the fuel feeding rate calibration is presented in Tables 5 and 6 (Supplementary Information File).

3.2.2 Drying Airflow Rate Output

The air system of an engine includes two main types: combustion air and drying air (heated air). The combustion air provides the oxygen necessary to support the fuel burning process in the combustion chamber. Drying air is clean environmental air that passes through the heat exchanger system to reach the target temperature and airflow required for drying. This drying air is divided into two flows: pushed air, which moves from the secondary heat exchanger and is known as secondary supply air, and suctioned air, which is drawn in by the suction blower. The suctioned air carries the heated mixture from the secondary to the primary heat exchanger, ensuring uniform temperature distribution before exiting through the hot air outlet. The airflow rate is controlled by adjusting the suction blower motor speed (RPM) using a frequency setting, allowing the operator to match the drying airflow to specific process requirements. Calibration tests of the hot air output, measured through a 0.01 m^2 cross-sectional area of the suction blower outlet, are provided in Table 7 (Supplementary Information File). These settings are essential for maintaining efficient heat transfer and stable drying performance. The temperature of the heated air output was measured at 4 different positions in the cross-sectional area of the suction blower outlet using a type K thermocouple to obtain the average temperature of the heated air output during combustion.

3.2.3 Air heating rate testing

The airflow rate setting plays a critical role in determining the overall thermal efficiency of the air heating system. The system's performance is highly dependent on airflow optimization, as it directly affects heat transfer and combustion stability. Therefore, the efficiency of the portable vertical burner biomass pellet machine is closely linked to the control of both the airflow rate and biomass feeding rate. To evaluate this relationship, a two-factor experimental design was implemented, varying biomass feed rate (kg/hour) and airflow output (CFM) at three levels each, as detailed in Table 8 (Supplementary Information File). Each combination was tested in triplicate, totaling 27 experimental runs. This systematic approach facilitates the precise identification of optimal operating conditions that maximize drying air temperature, ensure stable combustion, and improve fuel efficiency.

3.2.4 The Efficiency of Air Heating System

The efficiency of the air heating system reflects the performance of the combustion engine and the effectiveness of heat transfer within the heat exchanger relative to the volume of fuel consumed (Mahmoud et al., 2021; Balakheli et al., 2020). According to Carlon et al., 2015, the heating efficiency of the drying furnace is calculated using Equations 1–4. This efficiency metric compares the useful energy output delivered by the heating unit to the total energy input from fuel combustion, which may involve the use of wood pellets or LPG as fuel sources.

Air Heating Energy (Q_{air})

$$Q_{\text{air}} = M_{\text{air}} \times C_{p_{\text{air}}} \times (T_2 - T_1) \tag{1}$$

$$M_{\text{air}} = \rho_{\text{air}} \times A_{\text{blower outlet}} \times V_{\text{air}} \tag{2}$$

Fuel Energy (Q_{bb})

$$Q_{\text{bb}} = M_{\text{bb}} \times HV_{\text{bb}} \tag{3}$$

Machine Heating Efficiency (η)

$$\eta_{\text{heating}} = \frac{Q_{\text{air}}}{Q_{\text{bb}}} \times 100\% \tag{4}$$

In which:

η_{heating} = Heating system efficiency (%)
Q_{air} = Air heating thermal (kJ)
Q_{bb} = Thermal combustion (kJ)
$C_{p_{\text{air}}}$ = Air density (kJ/kg.K)
M_{air} = Air mass per unit time (kg/hour)
T_1 = Ambient Air Temperature (K)
T_2 = Heating Air Temperature (K)
ρ = Air density (kg/m^3)
V = Air velocity (m/s)
A = Cross-sectional area of the blower air outlet (m^2)
M_{bb} = Fuel consumption rate (kg/hour)
HV_{bb} = Fuel calorific value (kJ/kg)

3.2.5 Drying Thermal Efficiency

According to Yi et al., 2020, drying heat efficiency is a key parameter for evaluating the dehydration process's effectiveness. It is calculated by comparing the energy required for drying to the actual available energy for the drying operation, as expressed in Equation (5):

$$\eta_{\text{Dryer}} = \frac{Q_{\text{in}}}{Q_{\text{out}}} \times 100\% \tag{5}$$

In which:

η_{Dryer} = Heating system efficiency (%)
Q_{out} = Energy provided for drying (kJ)
Q_{in} = Energy required for drying (kJ)

3.2.6 Energy Required for Drying

The total energy required during the drying process can be estimated using the following equation (Equation 6-7):

$$Q_{\text{in}} = Q_1 + Q_2 \tag{6}$$

In which:

Q_{in} = The amount of thermal used to heat and vaporize air (kJ)
Q_1 = The amount of thermal used to evaporate water (kJ)
Q_2 = The amount of thermal used to heat a material (kJ)

$$Q_1 = E + H_{lb} \tag{7}$$

In which:

Q_1 = Energy to evaporate water (kJ)
E = Water vapor loads (kg H_2O)
H_{lb} = Latent heat (kJ/kg)

The amount of water evaporated from the product is estimated by assuming that the moisture present in the material is pure water. The energy required to evaporate this water at a specific temperature can be estimated using the following equation (Equation 8):

$$H_{lb} = 2501 - (2.361 \times 10^{-3})T \tag{8}$$

3.2.7 Energy provided for drying

The energy required for drying can be calculated using Eq. (9):

$$Q_2 = m \times C_p \times \Delta T \quad (9)$$

In which:
Q_2 = The energy required for air heating (kJ)
C_p = The specific heat capacity of drying air (kJ/kg°C)
m = The mass air supplied (kg)
ΔT = Increase in air temperature (°C)

3.3 Analysis Method

The experiment was conducted using a Randomized Block Design (RBD) approach. Data were collected in three replicates within a single day and grouped into morning, afternoon, and evening sessions. Statistical analysis was conducted using two-way repeated measures analysis of variance and pairwise comparisons in SPSS to assess the significance of each factor on the heating system's efficiency. Furthermore, multiple linear regression analysis was performed in Microsoft Excel to develop a quantitative model for predicting the final temperature and air heating system efficiency across different input feeding and drying airflow rates.

4. Results and Discussion

4.1 Air Heating Rate

The temperature difference between the inlet (ambient air) and outlet (heated air) reflects the effectiveness of the engine in transferring heat. The temperature difference was chosen to depict the heating performance of the machine to avoid bias regarding the ambient temperature and the environmental conditions. Temperature readings were recorded at one-minute intervals over a continuous two-hour operation period, starting from the ignition point of combustion. This monitoring captured the dynamic changes in thermal performance and the system's stabilization trend. Figure 2 shows the results, which illustrate the heat-up phase and steady-state behavior of the air heating process.

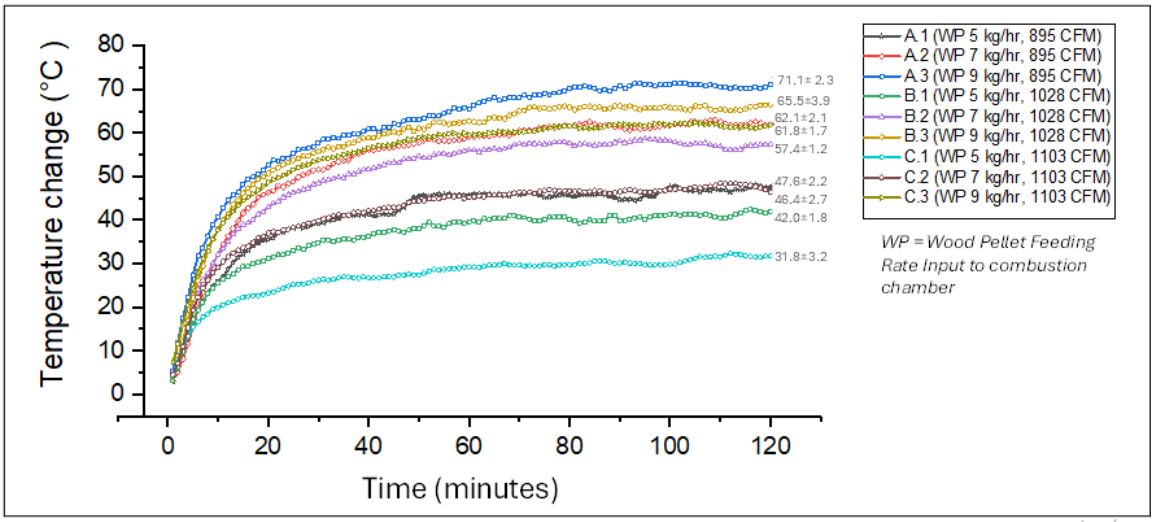


Figure 2 The increased rate of air temperature over time for each experimental variation

As shown in Figure 2, Treatment A3 demonstrates the highest difference in output–input air temperature. This is attributed to the high fuel input of 9 kg and the lowest blower airflow rate of 895 CFM. In contrast, Treatment C1 yielded the smallest temperature increase, corresponding to the lowest fuel input of 5 kg and the highest blower airflow rate of 1103 CFM. A higher fuel input rate correlates with greater heat generation, resulting in a more substantial temperature rise (Sharma and Sheth, 2016). Conversely, a higher airflow rate reduces the residence time of air in contact with the heat exchanger surface, limiting effective heat transfer. This leads to greater energy loss through unabsorbed heat escaping with the exhaust airflow (Thabari et al., 2023; Enagi et al., 2022; Jandačka and Holubčík, 2020).

A stable operating temperature in a portable vertical burner biomass pellet machine is critical for ensuring effective heat delivery. During combustion, the ignition heat gradually increases the heat exchanger's surface temperature. Once thermal equilibrium is reached, the rate of increase in the temperature of the outlet air stabilizes. Temperature stability is achieved when both the fuel feed and airflow rates are consistently maintained.

The two-hour observation period is divided into four distinct operational stages, as outlined in Table 9 (Supplementary Information File). These stages were defined based on the data trends illustrated in Figure 2. The most rapid temperature rise occurs during the initial hour, followed by a transition into the stabilization phase. Figure 3 presents the trend of the heated air temperature during each of these intervals, highlighting the thermal performance across the operating cycle.

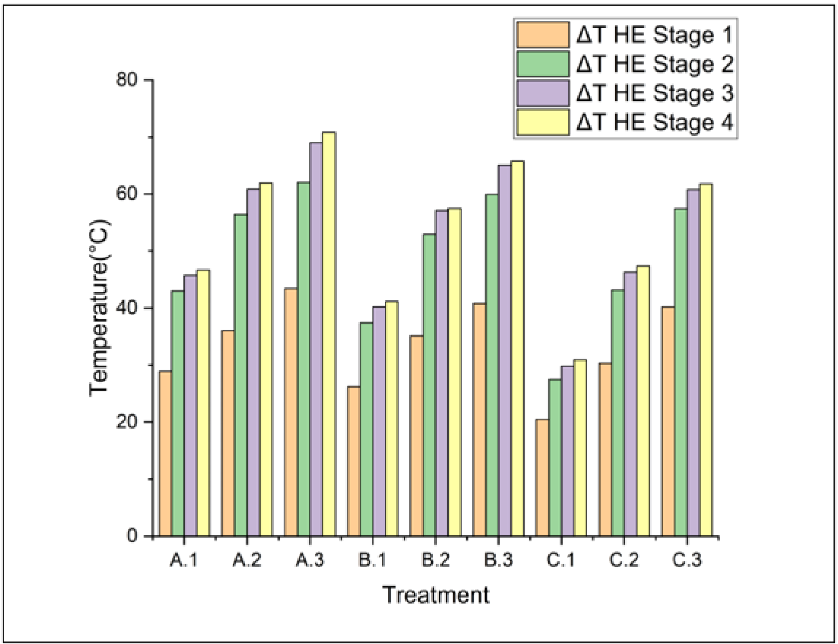


Figure 3 Changes in the heated air temperature at each heating interval

Figure 3 illustrates the variation in the temperature of the heated air across different heating intervals for each experimental run. The graph shows that thermal stability was first observed at approximately the 60th minute (Stage 3) and continued to increase gradually until the end of the 120-minute duration (Stage 4). To further investigate the temperature consistency across heating stages for all test variations, a repeated measures analysis was conducted in SPSS using a simple linear model.

Table 10 summarizes the results of this analysis (Supplementary Information File). The findings indicate that Stage 1 shows significant mean differences compared with the subsequent stages, highlighting the substantial temperature changes during the initial combustion phase. By Stage 2, the system begins to approach thermal stability, as the temperature difference with Stage 3 is statistically insignificant. Additionally, the comparison between Stage 3 and Stage 4 revealed an insignificant mean difference of 0.989, confirming that the system reached a stable temperature condition during the later phase of operation.

4.2 Air Heating Process Optimization

A simulation was conducted to analyze the response of the heated air temperature to changes in the biomass pellet feeding rate and blower motor speed. This analysis used the Multiple Linear Regression (MLR) method to predict air temperature at different heating stages, as shown in Table 11 (Supplementary Information File) and Figure 4. In the model, X_1 represents the blower airflow rate (CFM), and X_2 represents the biomass pellet feeding rate (kg/h). Table 1 presents the predictive equation that estimates the temperature of heated air based on these two inputs. The model's performance is assessed using the R^2 (coefficient of determination), which indicates how well the independent variables (X_1 and X_2) explain the changes in the dependent variable (air temperature). An R^2 value closer to 1 indicates that the model fits the data well and provides more accurate predictions (Siburian et al., 2023; Chakraborty and Goswami, 2017).

The R^2 values in Table 1 show that the combination of airspeed and biomass pellet input can explain over 80% of the variation in heated air temperature. The strongest relationship is seen in Stage 4, where the R^2 reaches 88.2%, suggesting high prediction accuracy in the stable heating phase. In addition to R^2, the Root Mean Square Error (RMSE) was used to measure the prediction error of the model. A smaller RMSE indicates better accuracy, ideally close to zero (Ağbulut et al., 2021; A. Kumar et al., 2021). Table 1 shows that Stage 1, representing the initial heating phase, has the lowest RMSE value, indicating high prediction precision during the early combustion stage.

Table 1 Comparative analysis of multi-risk assessment frameworks

Temp (Y)	Intercept	X1 Variable	X2 Variable	MSE	RMSE	R2
ΔT HE at stage 1	31.536	- 0.026	4.073	11.522	3.394	0.820
ΔT HE at stage 2	57.963	- 0.050	5.956	20.110	4.484	0.840
ΔT HE at stage 3	65.842	- 0.059	6.585	23.658	4.484	0.846
ΔT HE at stage 4	67.847	- 0.060	6.633	20.097	4.483	0.882

Description: Y= Heated Air Temperature; X1= Blower Velocity; X2= Biomass Pellet

The selected model for estimating temperature was chosen based on the highest R^2 value, even though it exhibited a relatively higher RMSE, particularly within the 90°C–120°C range observed during Stage 4. This stage corresponds to the longest heating duration and reflects the most stable thermal behavior during the initial drying phase. The resulting regression model is as follows (Equation 10):

$$Y = 67.85 - 0.060X_1 + 6.63X_2 \tag{10}$$

Where: Y represents the temperature difference between the heated air and ambient air (°C), X_1 is the blower airspeed (CFM), and X_2 is the biomass pellet feeding rate (kg/h). This equation highlights the inverse relationship between blower speed and temperature rise, while indicating a direct correlation between increased fuel input and elevated output temperature. In terms of enhancing the temperature difference, it is required to enlarge the biomass pellet feeding rate (X_2) and setting the blower speed (X_1) should be set at the lowest speed. Figure 4 depicts the correlation between the observation data (X) and the prediction data obtained using the proposed prediction model (Equation 10) with R^2 ranging from 82% to 88%.

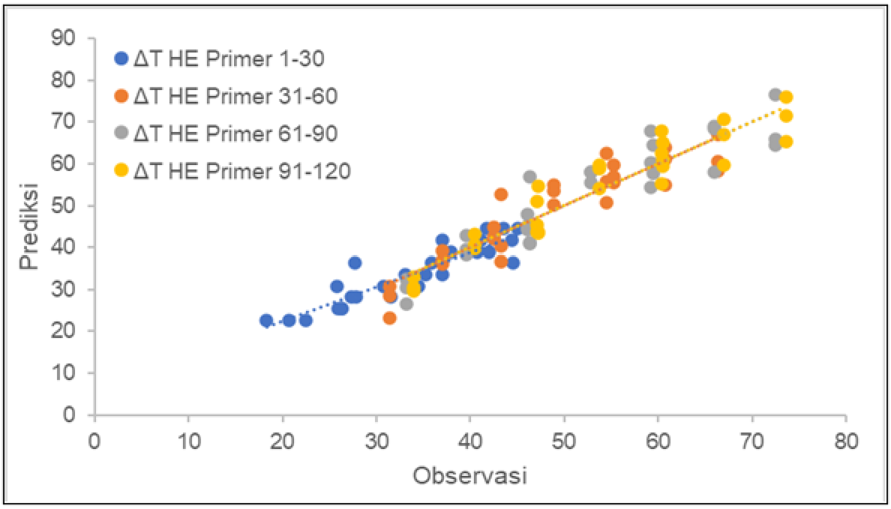


Figure 4 Forecasted and actual temperature changes during each combustion stage (in mm^3)

4.3 Air Heating System Efficiency

The combustion efficiency serves as a key indicator for evaluating both the energy losses from the fuel supplied and the actual useful energy (Ozsoysal, 2010). In this context, the energy produced by the biomass pellets is used as the denominator when calculating the energy required to increase the air temperature. Temperature changes were categorized into four distinct ranges to analyze the system's performance, allowing for a clearer observation of both heat variation and stability over specific intervals. Figure 5 shows the average heat transfer efficiency of the machine across these intervals.

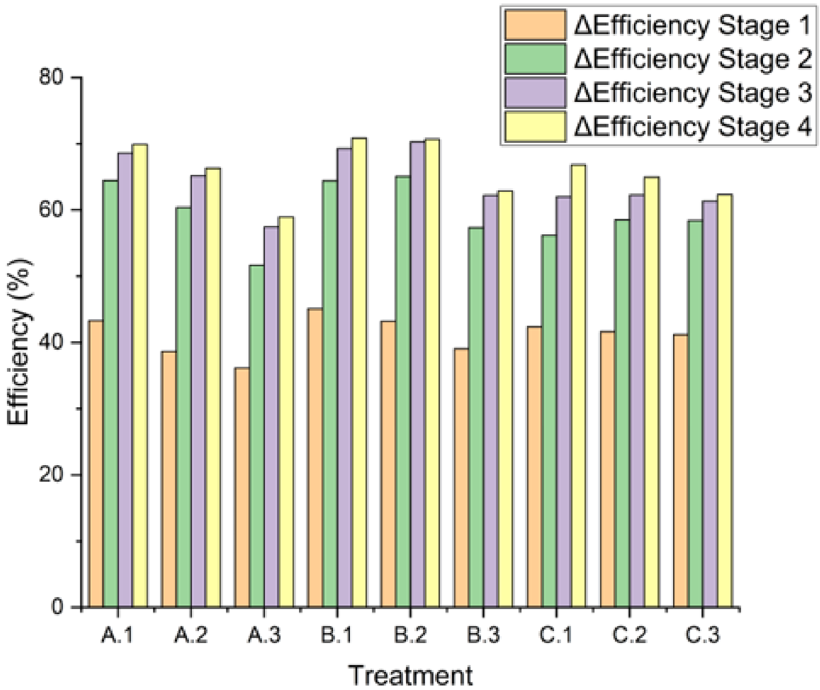


Figure 5 Efficiency of combustion in heat exchanger for each treatment and period

The highest heat exchanger efficiency during biomass pellet combustion was observed in treatment B1, reaching 70.83% with an airflow rate of 1028 CFM and a biomass pellet supply of 5 kg. The lowest efficiency, 58.96%, occurred in treatment A3, associated with an airflow rate of 895 CFM and a biomass pellet supply of 9 kg. In treatments A and C, the efficiency decreased as the biomass pellet supply increased. For treatment B, B2 slightly outperformed B1 by 0.15%.

The peak efficiency of treatment B1 was recorded during the first 1–20 min (Stage 1).

However, treatment C demonstrated greater consistency in efficiency stability over time. The efficiency stability was analyzed using repeated measures with a simple linear model in SPSS, with the pairwise comparisons presented in Table 11 (Supplementary Information File). The analysis shows that the efficiency varies significantly over time, especially during the first 1–30 min. Beyond this period, the differences in efficiency diminish. Although the efficiency values at Stages 3 and 4 differ significantly, the mean difference of 1.677 indicates that the system is approaching a stable state. This initial variability occurs in the first hour because heat is primarily used to raise the heat exchanger to its optimal operating temperature, rather than fully heating the airflow. Consequently, the efficiency of the heat exchanger improves and stabilizes when operated for longer durations.

4.4 The effect of air velocity and biomass pellet supply on the temperature changes and air heating efficiency

Table 2 shows the significant effect of the independent variables, namely, biomass pellet supply and airflow mass, on heating efficiency and temperature difference. The corrected model section reveals that the effects of biomass pellet supply, air mass flow, and their interaction on both temperature difference and efficiency are statistically significant, with p-values (Sig.) less than 0.05 (α), confirming the data's reliability. The intercept values indicate that the efficiency and temperature difference can vary independently of biomass pellet supply, air mass, or their interaction.

A significance value (Sig.) below 0.05 denotes a meaningful effect (Alita et al., 2021). The air mass flow rate has a significant impact on both heat exchanger efficiency and temperature change, whereas the biomass pellet supply primarily influences temperature change but has no significant direct effect on efficiency within individual treatments. Moreover, the combined effect of biomass pellet supply and blower airflow velocity on combustion efficiency is consistent across all treatments, although their impact on temperature difference is less pronounced.

The analysis confirms that increasing the air mass flow supplied to the heat exchanger chamber reduces the temperature difference between the heated air output and the ambient environment while simultaneously improving the heat exchanger efficiency (Chabane et al., 2013). This is because a higher air mass flow enhances the convective heat transfer, leading to more effective energy use. Table 1 details these relationships, showing that the temperature gradient decreases as the air flow rate increases, but the overall thermal efficiency improves significantly.

To validate the environmental effect of using the proposed machine, we measured the CO produced by the machine, as illustrated in Figure 2 (Supplementary Information File). The emission data measured on the proposed mobile vertical burner biomass pellet are provided in Table 12 (Supplementary Information File). It showed that the proposed burner design enables the reduction of CO emissions from the combustion process of the biomass pellet. This confirmed that the biomass pellet combustion process is more efficient than that using the existing horizontal burner.

4.5 Estimation of drying cost efficiency using a portable vertical biomass pellet burner machine

The analysis is prioritized in the final drying stage of the tea processing process using a ball-type tea drying machine. The performance system of the ball tea machine is a system of rolling and shrinking the water content by providing hot steam and conducting vertical rotation by the machine, allowing the dried shoots to dry evenly (Prayoga et al., 2021). The standard-type ball tea type drying machine used as a reference has a height specification of 200 cm, tool length of 270 cm, width of 110 cm, ball tea machine length of 160 cm, ball tea machine diameter of 150 cm, blower 38 cm, 2 HP 1425 motor rpm, and 2 HP drive motor 1445 rpm.

Table 2 Effect of independent variables on efficiency and temperature difference

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	Efficiency	892.343a	8	111.543	4.934	0.002
	Temperature difference	4108.067b	8	513.508	31.358	0.000
Intercept	Temperature difference	84604.813	1	84604.813	5166.531	0.000
	Efficiency	89667.093	1	89667.093	3966.399	0.000
Air Mass	Temperature difference	896.887	2	448.443	27.385	0.000
	Efficiency	213.751	2	106.875	4.728	0.022
Biomass Pellet Supply	Temperature difference	3152.660	2	1576.330	96.261	0.000
	Efficiency	33.717	2	16.858	0.746	0.488
Air Mass & Biomass Pellet Supply	Temperature difference	58.520	4	14.630	0.893	0.488
	Efficiency	644.875	4	161.219	7.131	0.001
Error	Temperature difference	294.760	18	16.376		
	Efficiency	406.920	18	22.607		
Total	Temperature difference	89007.640	27			
	Efficiency	90966.356	27			
Corrected Total	Temperature difference	4402.827	26			
	Efficiency	1299.263	26			

a. R Squared = 0.687 (adjusted R Squared = 0.548)
b. R Squared = 0.933 (adjusted R Squared = 0.903)

The processing capacity of the machine is 250 kg of dry tea or the equivalent of 1,000-1,200 kg of fresh shoots per unit (1-1.2 tonnes) of wet shoots. The highest water content for ball tea processing is 51.09%, and it is dried to a water content of 5.25% with a drying time of 11–13 h (Lestari et al., 2022). The energy usage comparison between LPG and biomass pellets shows the required ratio of LPG, namely 0.1 kg LPG gas/kg dry tea, based on the standard reference for processing green tea at PPTK Gambung (Table 3). For biomass pellet requirements, the previously obtained equation $Y = 67.85\ 0.060X_1 + 6.63X_2$ is used according to the reference process conditions in Table 13 (Supplementary Information). Thus, the biomass pellet requirement is 12.49 kg/hour. A calculation analysis is then conducted from these process conditions. The average temperature of the processing room is around $27°C$ which is used as a benchmark ambient temperature. From the results of data processing, the efficiency of the drying process using LPG was found to be much higher than that using biomass pellets. This is because LPG can be used directly in the drying machine, whereas a heat exchanger is required for biomass pellet fuel.

In this heat exchanger application, additional electrical energy is also required to drive the push air blower and burner air blower, each of which is 0.186 kW, as well as the screw conveyor drive motor of 0.373 kW. The addition of a driving motor implement increases electricity consumption by 20% compared with that of LPG. Based on the cost of heat energy consumption with the purchase price of LPG gas and biomass pellets, costs will be reduced by 35.43%. Thus, with the increase in the cost of using electricity in the biomass pellet heat exchanger, the total efficiency of drying energy costs will decrease by 30.28% compared to LPG.

Table 3 Comparison of the energy use of LPG and biomass pellets in ball tea drying machines

Ball Tea Performance Conditions		Value	Unit
Initial mass		484.31	kg/Batch
Final mass		250.00	kg/Batch
Initial water content		51.09	%
Final water content		5.25	%
Mass of solids		236.88	kg
Water evaporated		247.43	kg
Initial water mass		13.13	kg
Water evaporation mass loss		243.3	kg
Ambient air temperature		27.00	°C
Hot air temperature		120.00	°C
Water hlb		2,182.27	KJ
CP tea		4.20	kJ/kg°C
Q sensible		219,682.07	kJ
Q latent		511,321.96	kJ
Q out		731,004.03	kJ/Batch
Fuel Usage	**LPG**	**Biomass Pellet**	**Unit**
Fuel amount	25.00	162.31	kg/Batch
Fuel heat	11,254.61	4,331.96	kJ/kg
	47,089.29	18,124.92	kJ/kg
Q in	1,177,232.21	2,941,765.24	kJ/Batch
Drying Efficiency	62.10	24.85	%
Electrical Energy	**LPG**	**Biomass Pellet**	**Unit**
Cylinder ball tea	-	19.39	kW
Blower fan	-	19.39	kW
Push air blower	-	2.42	kW
Ignition blower	-	2.42	kW
Screw conveyors	-	4.85	kW
Electrical energy needs	38.78	48.47	kW
Assumption of Drying Cost Requirements			
Fuel prices	1.21	0.12	$/kg
Electricity prices	0.07	-	$/kWh
Fuel (LPG)	0.01	0.08	$/kg dried tea
Electricity	0.01	0.01	$/kg dried tea
Cost of Ball Tea Drying Energy	0.13	0.09	$/kg dried tea

5. Conclusions

The temperature within the heat exchanger is primarily influenced by two factors: the velocity of the heated air (airflow rate) and the quantity of biomass pellet fuel supplied. Increasing the airflow rate enhances the convective heat transfer, which significantly improves the efficiency of the overall heat exchanger. As the airflow rate increases, the temperature difference between the heated air outflow and the surrounding environment decreases due to more effective heat distribution and reduced thermal losses. The design and performance analysis of the portable vertical biomass pellet burner integrated with a heat exchanger demonstrates its ability to meet the specific heat and airflow requirements of the ball tea drying process. This system offers a cost-effective alternative to LPG-based drying methods by using renewable biomass pellets, thereby reducing operational expenses and environmental impact. Moreover, the compact and adaptable design concept ensures versatility, making it suitable for various drying applications across different agricultural products. This flexibility supports broader agricultural processing adoption, enhancing energy efficiency, and promoting sustainable practices in the drying industry.

6. Contribution and Recommendation

This study contributes to advancing biomass pellet burner technology by demonstrating its effective application in drying processes, specifically for ball tea leaves. The integration of a portable vertical burner with a heat exchanger presents a sustainable and cost-efficient alternative to conventional LPG drying methods. The recommendations for future applications are outlined in the following statements: (a) The design and performance principles established here can be adapted and optimized for drying other agricultural products, such as cassava and tapioca starch, (b) Given the unique moisture content and drying characteristics of these crops, further research is recommended to customize airflow rates, temperature settings, and biomass fuel supply for optimal drying efficiency and product quality, (c) Implementing this biomass burner system in cassava and tapioca starch processing could significantly reduce energy costs and environmental impact, supporting more sustainable agricultural industries, (d) It is also advised to explore scale-up opportunities and automation controls for continuous and large-scale drying operations, enhancing process consistency and operational efficiency, and (e) Finally, future studies should evaluate the long-term durability and maintenance requirements of the burner system when used with diverse biomass fuels and agricultural products.

Author Contributions

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