The Effect of Preheater on Heat and Mass Transfer Efficiency Using Rotating Drum Roaster

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ABSTRACT

Indonesia is the third-largest coffee producer globally, facing challenges including rising raw material costs, increased energy consumption, and unpredictable weather conditions. One potential solution is optimizing energy efficiency during roasting. This study investigates the effect of preheating on time and energy efficiency in heat and mass transfer by utilizing waste heat to preheat green Robusta coffee beans. The experiment was conducted on a laboratory scale using a rotating drum roaster with a double-layer drum made of stainless steel and clay, at 200 °C under atmospheric pressure. Two treatments were applied: roasting with a preheater and without, each repeated three times for data reliability. Results showed that the preheater reduced total energy consumption by 62.33%, from 39.081 kJ to 15.364 kJ, and total power usage by 50.83%, from 43.424 kJ/s to 21.339 kJ/s. LPG consumption decreased significantly by 60.65%, from 0.829 kg to 0.326 kg. The preheater also shortened roasting time from 900 s to 720 s. Coffee beans roasted with a preheater exhibited greater mass reduction (0.580 kg) compared to those roasted without (0.642 kg), indicating more efficient moisture and volatile compound removal. Beans with a preheater achieved a medium to dark roast level (Agtron #45 to #55) within 12 minutes, while those without preheating required 15 minutes to reach a similar range. These results demonstrate that preheating significantly improves both energy and time efficiency without compromising roast quality, offering a promising approach to enhancing the sustainability and performance of coffee roasting processes.

Keywords: *Coffee, heat transfer, mass transfer, preheater, roasting.*

I. Introduction

Indonesia is the third-largest coffee producer in the world, with production steadily increasing over the last five years, reaching approximately 794.8 thousand tons in 2022 [1]. Coffee production in Indonesia was estimated to reach 794.8 thousand tons in 2022, an increase of approximately 1.1% compared to the previous year (YoY/Year-on-Year). Indonesia recorded its highest coffee production in 2021. The lowest coffee production occurred in 2017, at 716.1 thousand tons, while in 2018, it reached 756 thousand tons. Subsequently, production increased to 752.5 thousand tons and 762.4 thousand tons in 2019 and 2020, respectively. In 2021, it rose again to 786.2 thousand tons [2]. This upward trend highlights Indonesia's potential to strengthen its position in the global coffee market, especially through enhancing added value via downstream processing [3]. Downstream processing refers to activities beyond primary production, involving transformation steps from raw coffee cherries into green beans (primary processing), and then further into roasted and ground coffee (secondary processing) [4]. Among these, roasting represents a crucial phase that directly affects the final product's aroma, flavor profile, color, and physical

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properties [5],[6]. Roasting begins with an initial heating stage where moisture evaporates rapidly, followed by complex chemical reactions as the process progresses. These reactions include the Maillard reaction and caramelization, which are key contributors to the development of characteristic coffee aromas and flavors [7],[8]. Throughout the roasting process, the moisture content of the coffee beans decreases significantly, generally from an initial level of 11–12% to as low as 1–3% at the end of roasting [6],[9].

In a rotating drum roaster system, heat transfer occurs through a combination of three primary mechanisms: radiation (heat transferred from the burner to the outer drum surface), conduction (heat passed directly from the drum wall to the coffee beans), and convection (heat carried by hot air circulating within the drum and between the beans) [9]. Ensuring a stable and homogeneous thermal environment is essential to achieving uniform roasting results and avoiding defects such as scorched or underdeveloped flavors [8]. Support for coffee downstream processing can be achieved by optimizing products and utilizing other resources [10]. These efforts are crucial for achieving a sustainable coffee agroindustry by implementing a closed and cyclical production model in the production process [11].

Despite technological advancements, one of the main challenges in coffee roasting is energy efficiency. The roasting process is energy-intensive, with substantial heat losses typically occurring through exhaust gases. In industrial-scale systems, exhaust gases can reach temperatures of 320–860 °C and represent a potential source of reusable thermal energy [12]. To address this, several industrial solutions have been introduced. For instance, the PROBAT RKV green coffee preheating system utilizes exhaust heat to preheat green coffee beans using 100 °C dry air, reportedly reducing energy consumption by 20% and shortening the roasting cycle time. In furnace combustion systems, incorporating air preheaters has been shown to improve combustion efficiency from 83% to as high as 95%, demonstrating the effectiveness of preheating strategies in thermal processes [13].

However, there is still a limited number of studies that systematically evaluate the application of preheating on a laboratory scale, particularly in coffee roasting using small-capacity drum roasters. Most existing studies focus on large-scale industrial systems or other food drying processes. Moreover, comprehensive data on how preheating influences heat and mass transfer dynamics, roasting time, energy consumption, and ultimately, coffee bean quality, remain scarce. From a sustainability perspective, optimizing energy use in roasting is crucial. The increasing costs of raw materials and energy, coupled with the need to minimize environmental impact, demand innovative approaches to improve process efficiency [14],[15]. Preheating, by recovering and utilizing waste heat, offers a promising solution to reduce energy requirements and improve roasting consistency and quality.

Based on these considerations, this study aims to investigate the effect of preheating on heat and mass transfer efficiency, energy consumption, roasting time, and final coffee bean characteristics using a laboratory-scale rotating drum roaster with a double-layer drum (stainless steel and clay). The study was conducted at an initial roasting temperature of 200°C under atmospheric pressure for 15 minutes. It is hypothesized that the use of a preheater will enhance heat transfer efficiency, reduce energy consumption and roasting time, and improve the uniformity of moisture loss and mass reduction, ultimately leading to better roasted bean quality compared to roasting without preheating. By filling this research gap, the study aims to provide scientific evidence supporting the potential of preheating as a practical approach to enhancing the energy efficiency and quality of coffee roasting processes, particularly for small to medium-scale applications. The findings are expected to contribute valuable insights for both researchers and coffee industry practitioners seeking more sustainable and efficient roasting solutions.

II. Material and Methods

This study used Robusta green coffee beans as the main raw material. The experiment was conducted using an experimental method with parameters summarized in Table 1. These parameters were selected based on laboratory-scale optimal conditions to simulate an actual roasting process while ensuring controlled and repeatable results.

Table 1. Experimental Parameters

Parameters	Value
Drum surface area	0.094285 m^2
Average coffee bean surface area	0.000081 m^2
Roasting time	900 s
Initial roasting temperature	200 °C
Airflow velocity	3.1 m/s
Mass of green coffee beans	0.75 Kg
Thermal conductivity of clay	1.7218 W/mK
Drum diameter	0.2 m
Volumetric flow rate	0.031428

The roasting experiments were carried out using a rotating drum roaster designed with a double-layer drum: an outer layer made of stainless steel with a thickness of 3 mm, and an inner layer composed of clay with a thickness of 10 mm, as shown in Figure 1. This configuration aims to improve thermal stability and uniform heat distribution inside the drum.

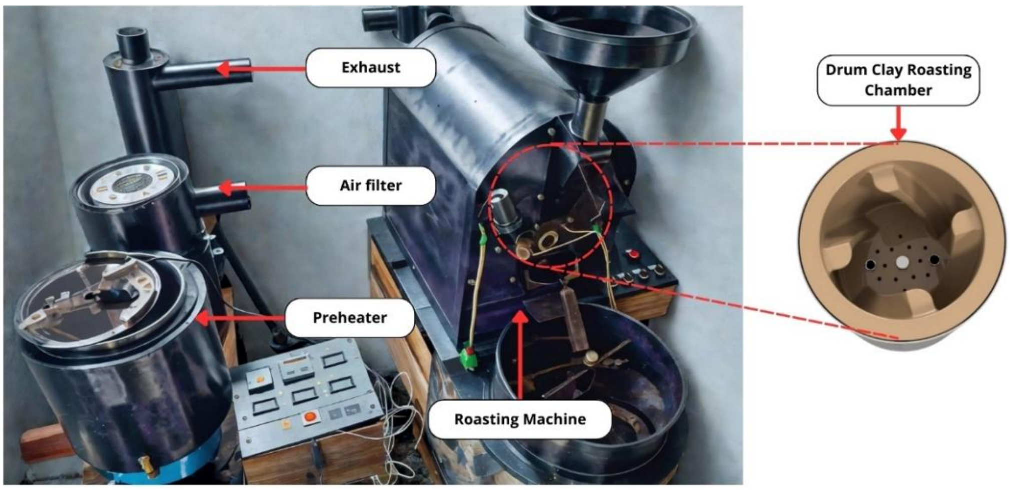


Fig. 1. Experimental research facility

Two different treatments were applied: one using a preheater to preheat the green beans and the other without preheating, serving as a control to validate the effect of the preheater. The preheating system utilized waste hot air to increase the initial temperature of the beans, thus potentially reducing energy consumption and roasting time. The schematic diagram illustrating the heat and mass transfer processes is presented in Figure 2.

The experimental procedure started by calibrating all thermal sensors to ensure accurate measurements. Sensor calibration was performed using standard reference points at the melting point of ice (0 °C) and the boiling point of water (100 °C), and further validated with a certified digital thermometer to guarantee precision. A total of 0.75 kg of Robusta green beans was prepared for each trial. The roasting machine was preheated until the combustion chamber reached 200 °C. For the control treatment (without preheating), beans with an initial moisture content of 11.4% were directly roasted for 15 minutes. Meanwhile, for preheating treatment, beans initially had a moisture content of 13.6%; these were first subjected to preheating to reduce their moisture content to 11.4% and raise their temperature to approximately 80 °C before roasting under the same conditions. This standardization of initial moisture content aimed to eliminate potential bias and ensure that differences in results were solely attributed to the preheating effect.

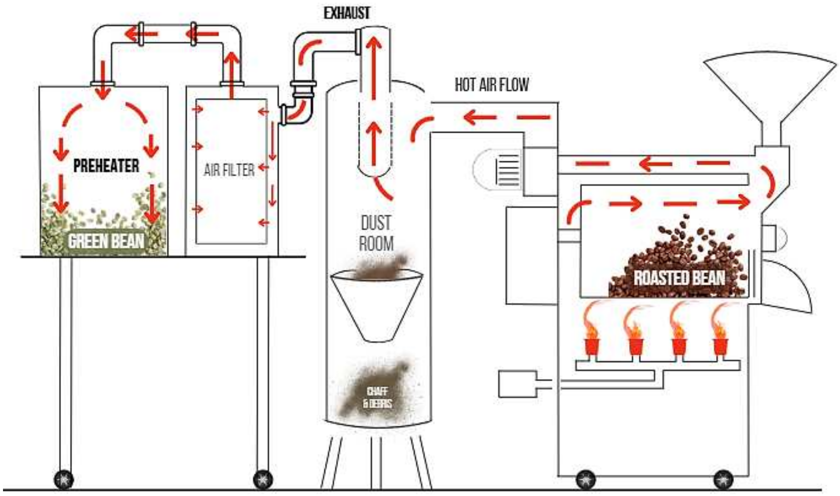


Fig. 2. Heat and mass transfer scheme

The experiments were conducted with three replications for each treatment to ensure reliability and consistency. Controlled variables included the mass of coffee beans (0.75 kg), initial roasting temperature (200 °C), roasting duration (15 minutes), and airflow velocity (3.1 m/s). Energy efficiency was analyzed by comparing input and output energy using the heat energy equation, where m represents the mass of the beans, c is the specific heat capacity, and ΔT is the change in temperature. Heat transfer is analyzed in the roasting process from each cycle, calculated with several equations below:

a. Heat transfer from the hot gas to the coffee bean surface

In the initial phase of the roasting process, heat is transferred from the surrounding hot air or combustion gas to the surface of the coffee beans. This external heat transfer plays a critical role in raising the surface temperature of the beans. The amount of heat transferred is calculated using Eq. (1). This subsection focuses on external convection heat transfer from the hot air to the beans' surface, which serves as the foundation for subsequent internal heating and chemical transformations in the beans.

$$\dot{Q}_{gb} = G_g \times C_{pg}(T_{g,i} - T_{g,o}) \quad (1)$$

b. Heat generated from exothermic reactions during roasting

During roasting, several exothermic chemical reactions occur within the coffee beans, including pyrolysis, Maillard reactions, and degradation of organic compounds. These reactions release heat internally. The total heat generated is calculated using Eq. (2). This subsection explains that the beans themselves act as internal heat sources due to chemical activity, which accelerates the roasting process and influences the development of flavor, color, and aroma.

$$\dot{Q}_r = Q_r \times m_{b(d.b)} \quad (2)$$

c. Heat loss due to moisture evaporation in coffee beans

As coffee beans are heated, the moisture contained within the beans evaporates. This evaporation consumes a significant amount of heat energy known as the latent heat of vaporization. The heat required for this process is calculated using Eq. (3). This subsection discusses the endothermic nature of moisture loss, which decreases the available heat for internal reactions and may affect the overall energy efficiency of the roasting process.

$$\dot{Q}_{ev} = \Delta H_v \left(-\frac{dx}{dt}\right) m_{b(d.b)} \quad (3)$$

To evaluate the final product quality, an Agtron spectrometer was used to measure roast color level, while mass loss was recorded to assess moisture reduction efficiency. Additionally, gas fuel (LPG) was used as the main heat source, and its consumption was monitored to support the energy analysis. Limitations of this study include its laboratory-scale setup, which may differ from large-scale industrial roasting systems in terms of thermal dynamics and operational complexities. Furthermore, the results are specific to Robusta beans with physical and chemical characteristics and might vary when applied to different coffee varieties or processing conditions.

III. Results and Discussions

The temperature variation measurements of coffee beans and the roasting chamber over a roasting duration of 15 minutes (900 seconds) at an initial heating temperature of 200 °C were analyzed to compare the effects of using a preheater versus no preheater. The preheater significantly influenced the temperature change pattern of the beans and the roasting chamber during the roasting process. Figure 3 presents the roasting profile of coffee beans over time, with roast levels determined using an Agtron spectrometer [16]. Beans roasted with a preheater achieved a dark to very dark roast (Agtron #35 to #25) within 15 minutes, while those without preheating only reached a medium to moderately dark roast (Agtron #55 to #45). Furthermore, the preheater reduced roasting time by approximately 2–3 minutes to achieve a medium roast, indicating that preheating significantly accelerates the roasting process and improves time efficiency without compromising roast quality.

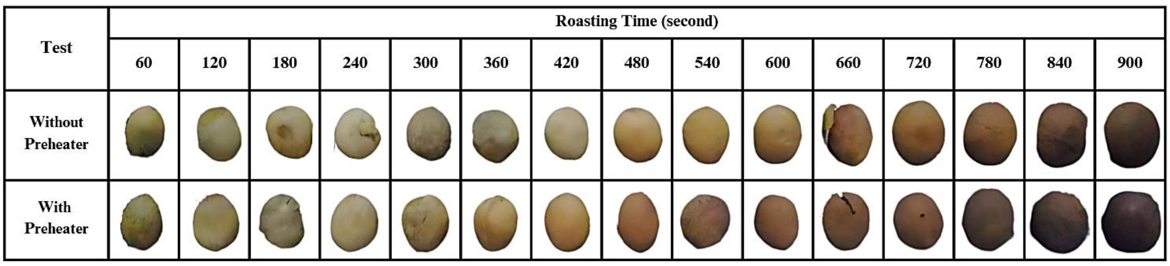


Fig. 3. Coffee bean roasting profile preheater and without preheater

Table 2 provides detailed experimental data comparing the temperature evolution of coffee beans relative to the roasting chamber temperature. The preheated beans consistently maintained higher temperatures, reaching 178 °C at 900 seconds, while beans without preheating only reached 172 °C. During the initial phase (0–150 seconds), both methods showed a temperature drop due to heat absorption by the beans. In the stabilization phase (150–450 seconds), preheated beans maintained slightly higher temperatures. In the final heating phase (450–900 seconds), the preheater condition exhibited a clear advantage in temperature stability and heat absorption, demonstrating enhanced heating efficiency and more uniform roasting.

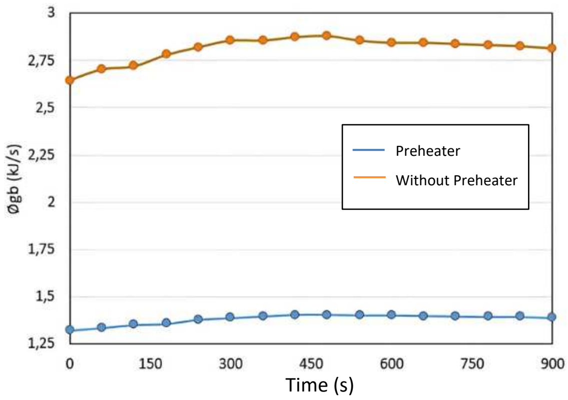
Table 2. Experimental data on coffee bean temperature and roasting chamber temperature

Time	Bean temperature (°C)		Roasting chamber temperature (°C)	
(s)	Preheater	Without preheater	Preheater	Without preheater
0	80	33	200	200
60	115	66	195	189
120	150	113	189	186
180	155	122	187	175
240	162	131	179	168
300	163	134	176	162
360	165	142	173	162
420	165	153	170	159
480	165	159	170	158
540	166	164	171	162
600	166	167	171	164
660	167	168	172	164
720	170	170	173	165
780	172	171	174	166
840	175	172	175	167
900	178	172	178	169

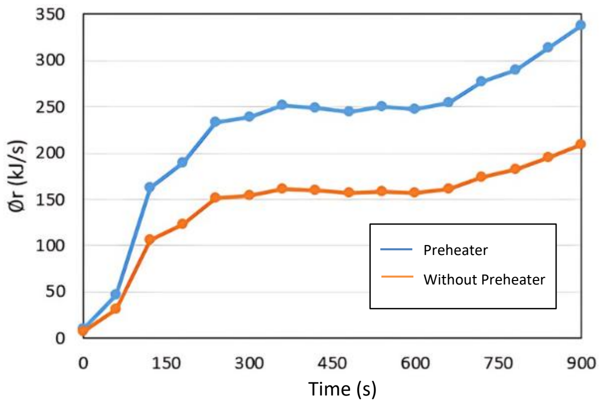
The experimental findings clearly indicate that the application of a preheater significantly improves the thermal efficiency of the coffee bean roasting process (Figure 4). Specifically, without a preheater, the average thermal energy required to roast coffee beans was 2.81 kJ (Figure 4a), amounting to a total of 40.002 kJ/s over 900 seconds. In contrast, the treatment with a preheater required only an average of 1.38 kJ, totaling 17.93 kJ/s within 720 seconds. The data suggests a considerable reduction in both average and total heat energy, which corresponds to faster and more uniform heat transfer. This outcome aligns with the theory of convective and radiative heat transfer, where preheating enhances the temperature gradient between the air and the bean surface, thereby accelerating the heat penetration process. Such improvements support the theory of convective heat transfer efficiency, as discussed by [17], who highlighted that preheating air in food drying systems can greatly increase overall heat transfer coefficients and system effectiveness. Preheated systems exploit higher initial air temperatures, increasing the temperature gradient between the air and the food surface, thus speeding up internal heat absorption and reducing required external energy.

The exothermic heat released from the beans (Figure 4b) was greater in the preheated treatment (average 204.17 J; total 2.65 kJ/s in 720 seconds) compared to the non-preheated condition (average 143.12 J; total 2.289 kJ/s in 900 seconds). This suggests that the preheating treatment enhanced the internal chemical reactions, such as Maillard reactions and caramelization, critical for achieving the medium to dark roast profile (Agrton #45–55). Preheated processes improve exergy efficiency and boost energy self-reliance within the material by promoting internal heat generation. Preheating or preheated fluid use in thermal systems can increase energy efficiency by 8.66% and exergy efficiency by 7.66%, supporting the results of your coffee roasting system [18].

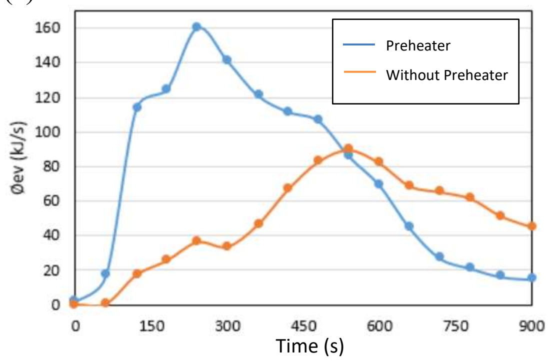
The moisture evaporation energy (Figure 4C) was higher with preheating (average 86.4 J; total 1.12 kJ/s in 720 seconds), compared to 48.3 J and 7.72 J/s in 900 seconds without a preheater. This shows faster and more effective dehydration, contributing to reduced roasting time and enhanced product uniformity. Similar conclusions were drawn by [19], who analyzed energy and exergy performance of hybrid solar dryers and emphasized that preheating can significantly improve thermal efficiency and reduce total energy consumption in food processing. Preheated green bean enhances the vapor pressure differential, increasing moisture migration and accelerating drying or roasting processes, which aligns directly with your results. Furthermore, the overall energy savings (62.33%), LPG consumption reduction (60.65%), and power savings (50.83%) in your study illustrate strong economic and environmental benefits, reinforcing preheating as a crucial advancement in sustainable food processing technologies.



(a)



(b)



(c)

Fig. 4. Heat transfer: (a) Hot gas to coffee bean, (b) Exothermic, (c) Moisture evaporation

Preheating the green bean intake slightly enhances mechanical and thermal efficiency due to convective heat transfer [20]. The roasting process uses heat energy generated by gases from combustion within the coffee roasting machine, which reaches high temperatures. Before these gases are released into the environment, their heat is recovered to preheat the feed gas entering the preheater. This process of using heat in the exhaust gas reduces the energy required to heat the feed gas separately, thereby increasing energy efficiency. This experiment gives a result: coffee roasting equipped with a preheater can significantly reduce energy consumption 170.8 kJ by up to 38% through efficient heat transfer. Chantasiriwan [21] Investigate the air preheater is a key factor in enhancing the net efficiency of a power plant beyond its current limit.

This study repurposes waste energy by incorporating it into a preheater to reduce the moisture content of coffee beans by increasing their temperature, thus shortening the roasting process or reducing the turning point duration. This clearly indicates that operating a solar dryer system in mixed mode with forced convection and the assistance of a preheater or backup heater can significantly enhance the efficiency of drying processes and extend food preservation [22]. These studies demonstrate that preheating can enhance heat transfer efficiency across various applications, although the optimal conditions vary.

The measurement results of coffee bean mass changes during a 15-minute roasting process with an initial heating temperature of 200°C is shown in Table 3.

Table 3. Coffee bean mass measurement before and after roasting

Test	Coffee bean mass (Kg)	
	Before roasting	After roasting
Preheater	0.75	0.580
Without preheater	0.75	0.642

Table 3 shows changes in coffee bean mass before and after roasting. Beans roasted with the preheater showed greater mass loss (final mass of 0.580 kg) than those roasted without preheating (0.642 kg), reflecting more effective moisture reduction. Table 4 and Figure 5 further detail moisture content dynamics during roasting. At 300 seconds, beans with the preheater had a moisture content of 6%, while without preheating, it remained around 7%. By 900 seconds, preheated beans reached 1.6%, compared to 3.1% without preheating. These findings demonstrate that preheating enhances moisture evaporation by improving heat transfer rates, thus supporting higher drying efficiency.

Figure 5 illustrates the reduction trend of coffee bean moisture content throughout the roasting process for both treatments. At the beginning (0 seconds), both treatments started with the same initial moisture content of 11.4%. Over time, a continuous decrease in moisture content was observed; however, the beans treated with a preheater exhibited a significantly faster rate of moisture reduction. At approximately 300 seconds, the moisture content in the preheater-treated beans had already decreased to around 6.9%, while beans without preheating remained higher at about 7.4%. By the end of the roasting process (900 seconds), the moisture content of beans with preheating dropped to 1.6%, whereas the beans without preheating still had a moisture content of approximately 3.1%.

These findings clearly demonstrate that the use of a preheater effectively accelerates moisture evaporation in coffee beans, thus enhancing the drying efficiency during roasting. The faster reduction in moisture content can be attributed to the improved heat transfer efficiency provided by the preheater system. From the perspective of mass and heat transfer theory, the presence of a higher initial bean temperature and a steeper thermal gradient increases the evaporation rate of internal water [23], [24].

Table 4. Coffee bean moisture content during roasting

Time (s)	Coffee bean moisture content (%)	
	Preheater	Without preheater
0	11.4	11.4
60	9.5	10.7
120	8.6	10.2
180	7.9	9.3
240	7.5	8.4
300	6.9	7.4
360	6.1	6.9
420	5.9	6.1
480	5.8	5.8
540	5.1	5.3
600	4.6	4.7
660	3.6	4.2
720	2.6	3.9
780	2.2	3.7
840	1.8	3.3
900	1.6	3.1

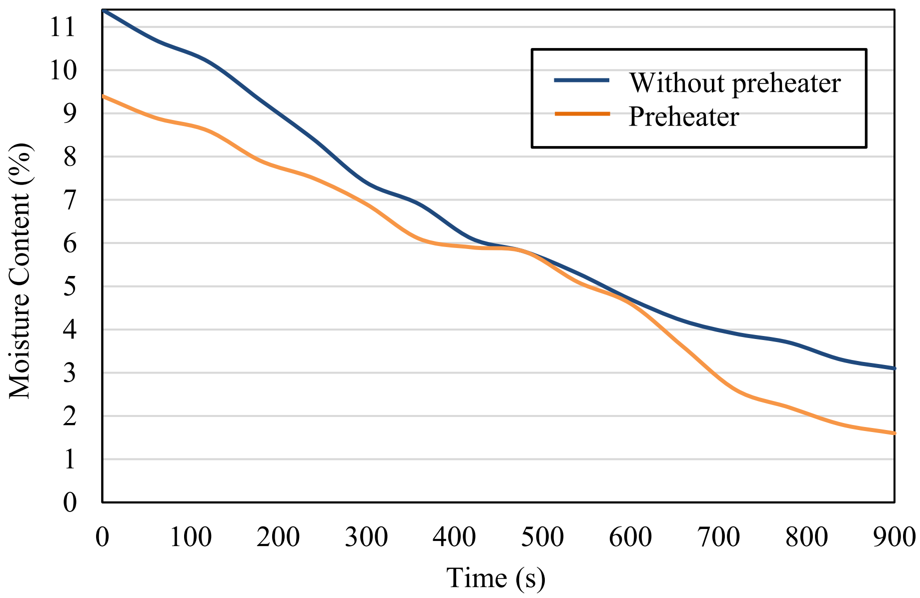


Fig. 5. Comparison of moisture content during the roasting process with and without a preheater

Moreover, the significant decrease in moisture content using a preheater indicates a more energy-efficient roasting process, as less energy is wasted in overcoming latent heat losses. This aligns with previous studies indicating that preheating can optimize drying and roasting processes across various materials by improving thermal penetration and reducing total energy consumption. Ultimately, the application of preheating not only accelerates the roasting process but also supports more sustainable and cost-effective production practices.

IV. Conclusions

The application of a preheater in the coffee roasting process significantly enhanced the efficiency of heat transfer, resulting in marked reductions in energy consumption and fuel use. In this study, coffee beans roasted with a preheater required an average heat energy of only 1.38 kJ, with a total of 17.93 kJ/s over 720 seconds, compared to 2.81 kJ and a total of 40.002 kJ/s over 900 seconds without a preheater. The total power required was also significantly reduced: from 43.424 kJ/s without a preheater (requiring 15 minutes) to 21.339 kJ/s with a preheater (requiring 12 minutes), leading to a total power saving of 50.83%. Furthermore, total energy consumption decreased by 62.33%, translating to substantial LPG fuel savings of 60.65% (reducing from 0.829 kg to 0.326 kg). These quantitative improvements demonstrate that preheating not only shortens roasting time but also lowers operational costs and environmental impact. The increased exothermic heat released by the coffee beans with a preheater (average 204.17 J and total 2.65 kJ/s) compared to the process without a preheater (average 143.12 J and total 2.289 kJ/s) further supports the effectiveness of preheating in promoting internal chemical reactions, such as Maillard reactions and caramelization, which are crucial for developing complex flavors and achieving medium-to-dark roast profiles (Agrton #45–55). The higher evaporation energy with preheating (average 86.4 J and total 1.12 kJ/s) also confirms better moisture removal, contributing to a more uniform and stable final product quality. These results indicate that the use of a preheater optimizes the entire heat transfer mechanism, covering radiation, conduction, and convection, leading to improved thermal effectiveness and final bean consistency.

However, it is important to acknowledge the limitations of this study. The experiments were conducted at a laboratory scale using a specific batch of Robusta beans, which may not completely represent larger-scale industrial conditions. Additionally, this research did not incorporate sensory analysis to evaluate aroma, flavor, and consumer-related organoleptic properties, which are crucial for final product acceptance. Thus, future studies should validate these findings at industrial scales and include comprehensive sensory evaluations. Such research will help ensure that preheater technology can be effectively implemented in large-scale coffee production, supporting more energy-efficient, cost-effective, and high-quality roasting processes in practice.

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