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# Experimental Analysis and Numerical Simulation of Coffee Bean Drying in Packed Beds with Different Coffee Bean Stack Height

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**ABSTRACT**

This research aims to optimize the coffee bean drying process through numerical simulation using numerical computational tools. Drying coffee beans plays a crucial role in enhancing their quality and shelf life and contributing to food sustainability. The aim of this study was to develop an accurate and efficient simulation model to analyze the coffee bean drying process using the packed-bed drying method and variations in the stack height of coffee beans. The objectives of this research include achieving the lowest Specific Energy Consumption (SEC) to improve energy utilization efficiency and determining the value of the Ratio of Specific Energy Consumption (RSEC) by comparing drying processes with and without refrigeration systems. This research also considers the limitations of the drying air temperature and humidity used. The results demonstrate a strong correlation between the simulation model and experimental data regarding moisture content, providing insights into energy usage optimization for coffee bean drying. Refrigeration systems for coffee bean drying yield an RSEC value below 1, indicating good energy utilization efficiency. Thus, this research significantly contributes to the development of efficient and effective coffee bean drying methods.

***Keywords:***
Numerical simulation; coffee bean drying; packed bed drying; specific energy consumption

## 1. Introduction

Post the COVID-19 pandemic, food security has become increasingly vital [1]. The Food and Agriculture Organization (FAO) defines food security as access to safe and nutritious food. The pandemic has significantly impacted the agricultural sector and food supply in Indonesia. Due to social restrictions, decreased production due to reliance on human labor and reduced consumer demand negatively affect farmers' harvest yields [2]. This situation is particularly concerning given that the subsector of plantations remains a key driver of the national economy, contributing a high

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percentage of the agricultural sector's exports. In the plantation sub-sector, coffee is a prominent commodity, with Indonesia being the world’s fourth-largest coffee producer [3].

As one of the most widely consumed beverages in the world and very easily recognized for its distinctive aroma and psychoactive effects, coffee is a drink made from roasted coffee beans [4]. Arabica and Robusta coffee are the two main genera cultivated for commercial products worldwide and have a wide variety of variations. Traditionally, coffee is produced under the canopy of tall forest trees or intercrops such as bananas, oranges, or leguminous trees, which produce food, firewood, and other fodder crops. However, since the 1970s, coffee plantations have changed drastically regarding cropping patterns and practices, especially in meeting the high demand for coffee and overcoming the presence of leaf fungus [5].

However, ensuring the production of high-quality and durable coffee beans remains challenging. The drying process is crucial for eliminating excess moisture from beans and preventing the growth of fungi and warehouse pests that can compromise the quality of coffee [6]. Given Indonesia’s tropical climate and high humidity levels, effective coffee bean drying is critical for post-harvest handling. Considering the significance of food security and the positive impact on Sustainable Development Goals (SDGs) No. 12 and 2, improving drying technologies has become a top priority [7].

Due to the high humidity level (13.97%), Lilia *et al.,* [8] discovered that coffee beans sun-dried in South Ogan Komering Ulu District, South Sumatra, Indonesia contained OTA contamination. OTA is a mycotoxin created by fungi in the genera Aspergillus and Penicillium that reduce the quality of coffee beans. The quality of production affects market price and safety because storage mold can release toxic chemicals that threaten health [9]. The increase in OTA was primarily due to the inefficient postharvest treatment of the coffee beans, particularly the inefficient drying processes. Traditional sun drying takes a long time, depending on the weather, and it can tain coffee beans due to dust and moisture absorption in high relative humidity situations. To overcome the postharvest problem of coffee beans, ideal drying conditions must be established to reduce energy consumption while maintaining the quality of the coffee beans [10].

The drying process uses heat to evaporate moisture from the grain, removing moisture that has separated from the food tissue. As a result, this process involves the simultaneous transfer of heat and mass, thus necessitating energy supply. Air is a common medium for transferring heat to tissues for drying and removing moisture. To ensure successful drying, air with a sufficiently high temperature and low relative humidity must flow smoothly [11]**.** Current drying technologies are usually used under controlled conditions, resulting in a higher-quality output. However, these systems frequently have high costs and energy consumption levels. Considering environmental concerns and the constraints of fossil fuels, it is critical to continue reducing energy consumption in the food sector. This project attempts to protect food prices from volatile fluctuations in fossil fuel prices, thereby increasing the overall sustainability of the food system [12].

Without the requirement for actual tests, a computational model for the numerical simulation of an actual situation allows us to make improvements, optimize, and test alternatives to determine the best conditions [13]. This study investigates Indonesia’s coffee bean drying process using a numerical simulation approach. By constructing meticulous mathematical models, this study identified the optimal drying time with the highest efficiency for achieving the desired drying level. Additionally, this study aimed to obtain the lowest Specific Energy Consumption (SEC) and assess the Ratio of Specific Energy Consumption (RSEC) value with refrigeration systems compared to non-refrigerated drying [14]. Various researchers have published specific energy consumption data for various drying systems to designate the energy consumption of different dryers. The ratio of energy consumption to the mass of the sample on a dry basis or the ratio of energy consumption to the mass of water removed from the sample during the drying process is used to calculate the SEC [15].

The findings of this research are expected to significantly contribute to our understanding of and development of more efficient and effective drying methods for coffee beans. The implications include advancements in the design of drying equipment, the creation of long-lasting and durable food products to ensure food security and sustainable agriculture, and the reduction of logistical costs in food production through efficient drying techniques. To attain the research objectives and address the challenges of coffee bean drying, the authors believe that numerical computing is a suitable and relevant method for implementation. Therefore, this study makes a valuable scientific contribution to enhancing food security and promoting agricultural development in Indonesia.

## 2. Methodology

### *2.1 Mass Transfer and Specific Energy Consumption of the Coffee Bean Drying Process*

The mass transfer refers to the mass movement due to different concentrations in the mixture. Some of the driving forces for mass transfer include differences in concentration (in the case of liquids), pressure differences (in the case of gases), and differences in moles or mass fractions (in the gas or liquid phase). In the case of drying coffee beans, the mass of the coffee beans consists of the water mass and the dry mass, as defined in Eq. (1). Eq. (2) represents the moisture ratio (MR) [16,17].

$$m_{tot} = m_{wet} + m_{dry} \tag{1}$$

$$MR = \frac{X_t - X_e}{X_0 - X_e} \tag{2}$$

As a result, $X_t$ indicates the moisture content on a dry basis at a specific time, $X_0$ represents the initial moisture content on a dry basis, and $X_e$ represents the equilibrium moisture content on a dry basis. $X_e$ is smaller than $X_t$ and $X_0$, so it is considered 0 [18-20].

In addition, the specific energy consumption (SEC) of the drying process of the coffee beans is discussed. Energy management is vital for improving energy efficiency, and the SEC is a useful indicator for identifying possible energy efficiency gains [21,22]. The SEC is defined as the energy ratio used to make a product. The SEC during the drying process is represented by Eq. (3) [23,24].

$$SEC = \frac{P \cdot t}{m_{ev}} \tag{3}$$

As a result, SEC denotes the Specific Energy Consumption (kJ/kg of water), $P$ the total energy (kW), $t$ the drying time (s), and $m_{ev}$ the amount of water evaporated (kg). The drying process can be performed without refrigeration by comparing the lowest SEC value obtained with and without a refrigerated system [25]. As a result, the ratio of the specific energy consumption is given by Eq. (4) [26,27].

$$RSEC = \frac{SEC_{Ref}}{SEC_{Noref}} \tag{4}$$

### *2.2 Drying Simulation*

In this research, numerical simulations of coffee drying were performed using characterization data at drying air temperatures of 60 °C, 70 °C, and 80 °C, as well as varying specific humidity at 7 and 14 g $H_2O$/kg dry air. During the experiment, the air temperature and specific humidity were maintained constant using a heat pump drying system previously used by Dzaky *et al.,* [20]. Furthermore, by employing an air mass flux of 0.757 kg/m$^2$s in the drying system, this study examined the effect of variations in layer heights of 7, 15, 35, 55, and 75 mm [28].

In this step, input values for an air mass flow of 700 L/min in a 6-inch diameter and specific humidity are supplied to calculate the requisite Activation Energy ($E_a$) and pre-exponential factor ($A$) values for the simulation [29,30]. The air-drying temperature was 60 °C, 70 °C, and 80 °C, and the initial coffee bean mass depended on the coffee stack thickness, which was about 86.4, 185.1, 432, 678.9, and 925.7 g, with the bulk density value before drying being 676.98 kg/m$^3$, initial moisture content of the coffee beans was 49% wet bases (wb), and desired final moisture content of 12% wb are inputs [31]. The drying rate constant and drying time of the coffee beans were estimated.

Figure 1 shows a schematic of the coffee drying process using the packed-bed method. The conditioned drying air, characterized by flow rate ($\dot{V}$), specific humidity ($\omega$) and temperature ($T$), flows upward through a perforated 304 stainless steel plate at the bottom and then passes through the coffee-packed bed. As the air moves through the packed bed, it undergoes changes: a reduction in the flow rate due to resistance from the material, an increase in specific humidity as it absorbs moisture from the material, and a decrease in temperature as its heat energy is absorbed by the material to evaporate water. Here, $h_d$ represents the thickness of the coffee-packed bed, and $\Delta y$ denotes the number of coffee layers, which correlates with the bed thickness. $D_d$ is the diameter of the drying chamber used in the drying process.

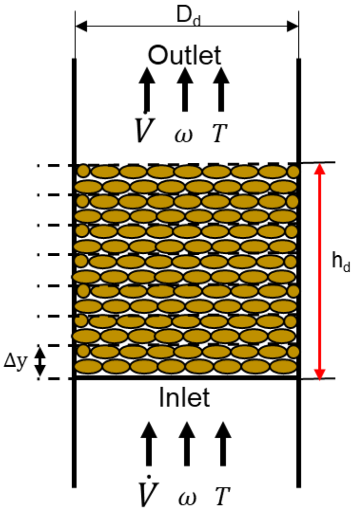

**Fig. 1.** Schematic of packed bed dryer

### *2.3 Energy and Mass Balance Model*

In the simulations, the fundamental equations of energy and mass balance were employed as an effective approach to predict the drying process of coffee beans. Modeling the mass and heat transfer processes in a drying system requires using the equations of mass balance and energy balance. The energy balance equation, which can be examined for both air and the material being dried, plays a crucial role in understanding the intricate dynamics of energy distribution throughout the drying process [32]. Furthermore, the energy balance equations for both air and material are given by Eq. (5) and Eq. (6) [33].

$$\dot{m}_{da}(Cp_{da} + \omega_i Cp_v)T_{a,i} - \dot{m}_{da}(Cp_{da} + \omega_o Cp_v)T_{a,o} - \dot{Q}_{gen} = [m_{da}(Cp_{da} + \omega_o Cp_v)]\frac{dT}{dt} \quad (5)$$

$$\dot{m}_{ev}Cp_v(T_a - T_m) - \dot{m}_{ev}L + \dot{Q}_{gen} = m_{dm}Cp_{dm}\frac{dT_m}{dt} \quad (6)$$

where $\dot{Q}_{gen}$ is obtained from Eq. (7) [33,34].

$$\dot{Q}_{gen} = hA_{ht}\Delta T \quad (7)$$

$$\Delta T = T_a - T_s\,; T_a = \frac{T_{a,i} - T_{a,o}}{2} \quad (8)$$

$$A = \frac{6}{D_i}A_d\Delta Y(1 - \varepsilon) \quad (9)$$

Furthermore, the heat transfer coefficient given by Eq. (10) can be determined by considering various parameters, including $C_{p,da}$ as the specific heat capacity of dry air, $\dot{m}_{da}$ as the air mass flow, $\rho_a$ as the air density, heat transfer dimensionless Eq. (11), and Prandtl number ($Pr$) Eq. (13) [35].

$$h = C_{p,da}u_a\rho_a Jh Pr^{-\frac{2}{3}} \quad (10)$$

$$Jh = 1.77Re_p^{-0.44}, Re_p \geq 30 \quad (11)$$

$$Re_p = \frac{\rho_a \dot{m}_{da} D_i}{\mu_a}, \mu_a = 0.0000185 \quad (12)$$

$$Pr = \frac{C_{p,da}\mu_a}{K}, K = 0.03023 \quad (13)$$

$$u_a = \frac{\dot{m}_{da}A_d}{\rho_a} \quad (14)$$

The mass transfer of water vapor in air Eq. (15) and in material Eq. (16) and Eq. (17) [33,29].

$$\dot{m}_{da}\omega_i - \dot{m}_{da}\omega_o + \dot{m}_{ev} = m_{da}\frac{d\omega}{dt} \quad (15)$$

$$\frac{dX}{dt} = -kX \quad (16)$$

$$\frac{d\left(\frac{m_w}{m_{dm}}\right)}{dt} = -k\frac{m_w}{m_{dm}} \quad (17)$$

In this case, the change in $m_w$ with time refers to the evaporation of water from the material, which can be expressed as Eq. (18) [29].

$$\frac{dm_w}{dt} = \dot{m}_{ev} \tag{18}$$

Using these equations, a better understanding of the effects of mass and heat transfer on the coffee bean drying process can be acquired. Furthermore, these equations can be implicitly expressed to obtain the energy balance between air and material to determine the values of the variables $T^+_{a,i}$ and $T^+_m$ in each balance. The implicit equation used to determine the energy balance of the air and material sides can be expressed as Eq. (19) and Eq. (20).

$$\dot{m}_{da}(Cp_{da} + \omega^+_{i-1}Cp_v)T^+_{a,i-1} - \dot{m}_{da}(Cp_{da} + \omega^+_i Cp_v)T^+_{a,i} - hA_{ht}\left(\frac{T^+_{a,i-1}+T^+_{a,i}}{2} - T^+_m\right) = \left[m_{da}\left(Cp_{da} + \left(\frac{\omega_{i-1}+\omega_i}{2}\right)Cp_v\right)\right]\frac{(T^+_{a,i-1}+T^+_{a,i}-T_{a,i-1}-T_{a,i})}{2\Delta T} \tag{19}$$

$$\dot{m}_{ev}\left[Cp_v\left(\frac{T^+_{a,i-1}+T^+_{a,i}}{2} - T_m\right)\right] + (-2437T^+_m + 2502000) + hA_{ht}\left(\frac{T^+_{a,i-1}+T^+_{a,i}}{2} - T^+_m\right) = m_{dm}Cp_{dm}\left(\frac{T^+_m - T_m}{\Delta t}\right) \tag{20}$$

In addition, the mass transfer of water vapor in air can be calculated directly using Eq. (21).

$$\dot{m}_{da}(\omega^+{}_{i-1} - \omega^+_i) - \dot{m}_{ev} = m_{da}\left(\frac{\omega^+_{i-1}+\omega^+_i-\omega_{i-1}-\omega_i}{2\Delta t}\right) \tag{21}$$

Furthermore, the above equations employ the notation "j" for time and "i" for node in the simulation. The notation "+" signifies future time, while the absence of the "+" sign implies this time. Figure 2 presents an explanation of this notation.

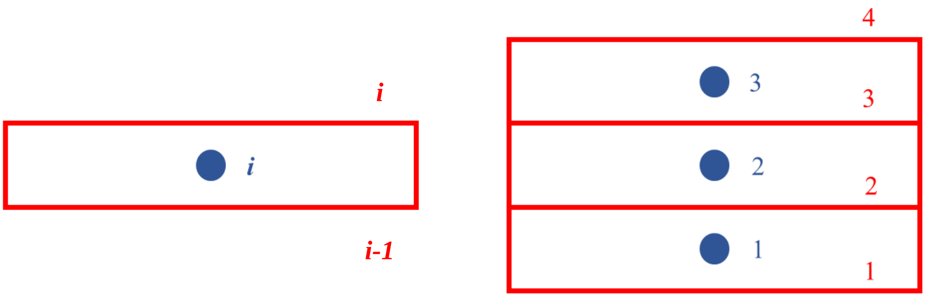

**Fig. 2.** Illustration of nodes and time on packed bed drying

For example, at drying air temperature, the simulation and mathematical models can be obtained as follows at Table 1.

**Table 1**
Description of nodes and time in the simulation and mathematical models

| Simulation Model | Mathematical Model |
|---|---|
| $T_{a(i,j+1)}$ | $T^+_{a,i}$ |
| $T_{a(i-1,j+1)}$ | $T^+_{a,i-1}$ |
| $T_{a(i,j)}$ | $T_{a,i}$ |
| $T_{a(i-1,j)}$ | $T_{a,i-1}$ |

Furthermore, the simulation of the changes in $m_w$ over time related to water evaporation from the material. Then, this can be expressed using Eq. (22) [29].

$$m_w = \rho_{dm} A_d \Delta y (1-\varepsilon) X_{db} \tag{22}$$

$$\dot{m}_{ev} = -k m_w \tag{23}$$

$$x_{db}^{+} = x_{db} e^{-k\Delta t} \tag{24}$$

### 2.4 Development of the Simulation Model

The next critical step is to apply the created mathematical model to numerical computing tools to construct the simulation model. The simulation algorithm is illustrated in Figure 3, and it outlines the steps from initiating the simulation process to obtaining the final results.

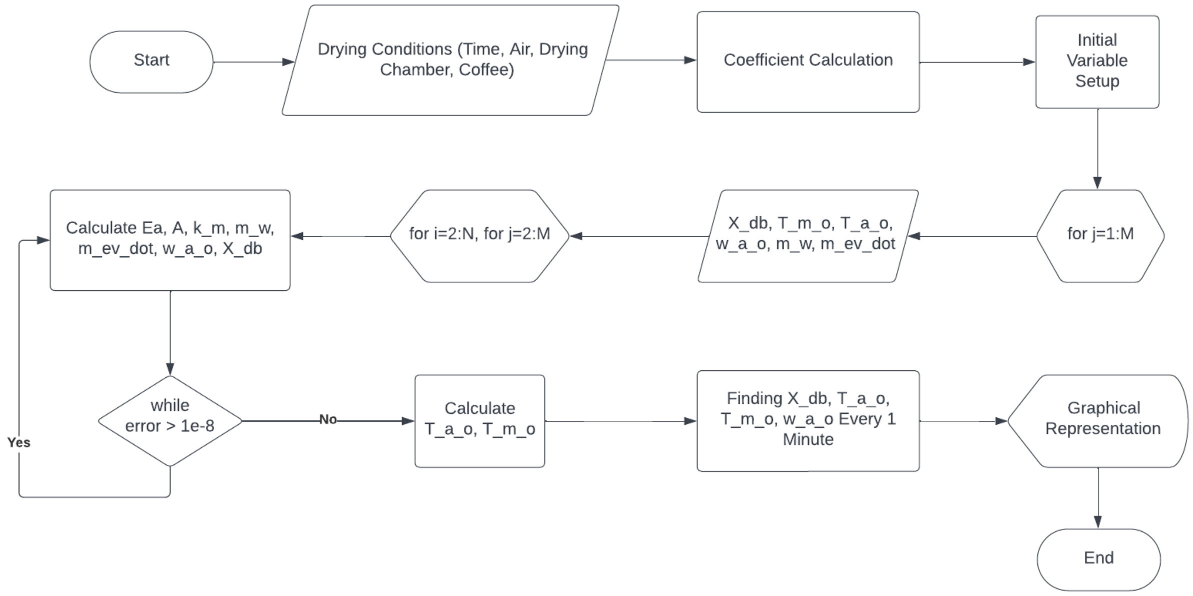

**Fig. 3.** Coffee drying simulation program algorithm

Variations in the drying conditions were used as input to calculate coefficients based on numerical calculations. The calculations determine the outlet air temperature, material temperature, moisture content, and specific humidity as functions of time until the drying process is complete. The numerical computation results were then interpreted as curves and tables in Microsoft Excel.

### 2.5 Mesh Independence Test

When the size of the mesh elements changes, the numerical solution of a computational simulation changes significantly or converges [36-38]. The number of nodes in the mesh was adjusted in this test to investigate how the simulation results respond to the number of up to 120 nodes at a time step of 1 s. The temperature testing was conducted in the room temperature range of 28 °C on 30 °C. The simulation results were consistent with the experimental data because the material temperature initially corresponded to room temperature before the drying process began.

The results presented in Table 2 of this experiment reveal that the finer the mesh, the smaller the material temperature difference. This indicates that mesh or node modifications significantly affected the simulation. By performing this test, it is possible to confirm that the simulation results are relatively robust and reliable when using nodes with minimal temperature differences. Node 100 was selected because it produced only a small difference in material temperature.

**Table 2**
Mesh independence test

| Node | Material Temperature | Difference in Material Temperature at Each Node |
|---|---|---|
| 20 | 30.30 | 1.12 |
| 40 | 29.18 | 0.39 |
| 60 | 28.79 | 0.20 |
| 80 | 28.60 | 0.12 |
| 100 | 28.48 | 0.08 |
| 120 | 28.40 | - |

## 3. Results

### *3.1 Simulation Validation*

Based on the results of the drying experiment for 7-mm-thick coffee beans, a drying simulation can be constructed using the experimental conditions applied. Figure 4 illustrates the validation of the drying temperature profile of coffee beans by comparing the air temperature between the experiment and simulation for a layer of coffee beans with a thickness of 7 mm, a drying air temperature of 80 °C, a specific humidity of 7 g $H_2O$/kg dry air, and an air mass flux of 0.757 kg/m$^2$s.

In the 1-h experiment, the initial air temperature in the drying chamber was 28 °C. The outlet air temperature of the drying chamber increased sharply during the first 300 s. However, from 300 to 3600 s, the temperature gradually increased to 66 °C. Both experimental and simulation air temperatures tended to increase over time. The simulated air temperature during the 1-h drying process reached 75 °C, which is 9 °C higher. This discrepancy was attributed to heat loss from the drying chamber to the environment during the experiment.

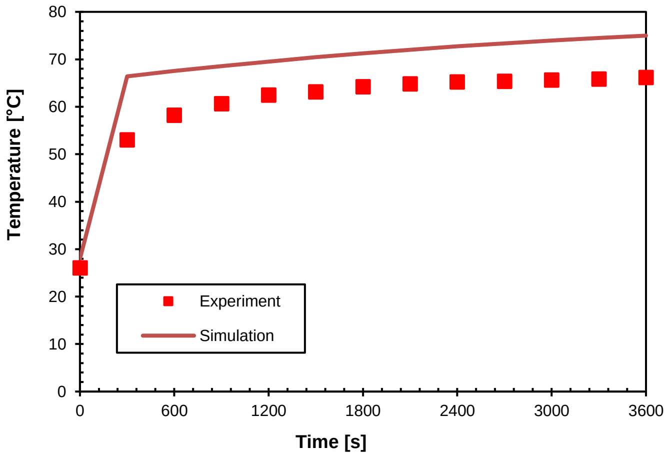

**Fig. 4.** Validation of the outlet air temperature in the drying chamber over time

Based on Figure 5, the reduction in the dry basis moisture content of coffee beans at a layer thickness of 7 mm, drying air temperature of 80 °C, specific humidity of 7 g $H_2O$/kg dry air, and air mass flux of 0.757 kg/m$^2$s, is compared between the experimental and simulation results. Initially, both the experiment and simulation showed that the coffee beans had a dry basis moisture content of 0.96 kg water/kg dry mass. The moisture content decreased consistently over time in both cases. The comparison of the experimental and simulation results yielded a coefficient of determination. ($R^2$) of 0.9995, indicating a linear relationship between the simulation model and the experimental data. The $R^2$ value, which is near 1, verifies the simulation model's accuracy in predicting the moisture content of coffee beans and gives credibility to the simulation results in this study [39,40].

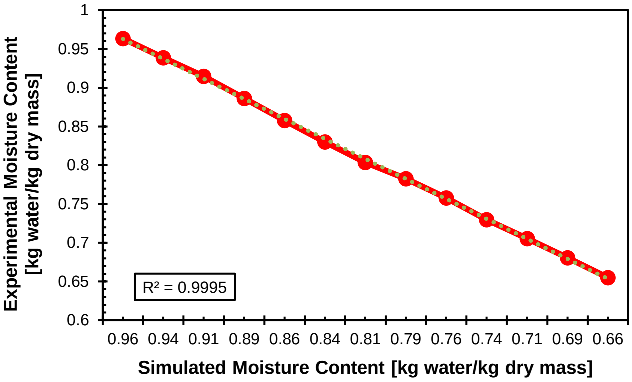

**Fig. 5.** Comparison of experimental and simulation results for moisture content

The small differences between the experimental and simulation data were attributed to the identical trend patterns observed in both datasets. This minor discrepancy is reflected in Figure 4 and Figure 5. In Figure 4, the trend of temperature increase between the experimental and simulation results is identical. Meanwhile, Figure 5 shows that the $R^2$ value is close to 1, indicating that the simulation data effectively explain the occurrences in the experimental process.

### *3.2 Specific Humidity vs Drying Time*

This study investigated the relationship between specific humidity levels and variations in the stack height of coffee beans during the drying process. The results revealed that the height of the coffee bean pile significantly influenced the specific humidity absorbed by the coffee beans. The line in Figure 6 indicates that the specific humidity in the drying chamber increased at the beginning of the drying process and was directly proportional to pile height. At a height of 75 mm, the specific humidity of the coffee bean pile rose to 7.93 g/kg dry air within 1 s, whereas at the minimum height of 7 mm, the humidity level was 7.3 g/kg dry air.

The taller the coffee bean pile, the longer the time required for the specific humidity to rise, and the maximum specific humidity value also increased proportionally. This is because higher coffee bean piles contain more water that must be evaporated, resulting in longer drying times. The water diffusion process becomes more challenging as the pile height increases, and the amount of water vapor that must be removed from the coffee beans also increases.

Figure 6 shows a graph of the specific humidity of the outlet drying chamber air versus drying time. The drying air was entered the drying chamber at a specific humidity of 7 [g/kg dry air]. As the air passes through the coffee bean pile, evaporation occurs at the surface of the coffee beans, causing a certain amount of water vapor to be carried out with the drying air, leading to an increase in the specific humidity of the air at the beginning of the drying process. As the drying process continued, the moisture content of the coffee beans decreased, and the rate of moisture transfer from the surface of the beans to the drying air also decreased, gradually reducing over time. At the end of the 14-hour drying period, the specific humidity was the same as that of the drying air at the beginning of the process. This condition indicates that the evaporation of water from the surface of the coffee beans to the drying air has ceased, as the moisture content of the beans has reached 0% on a wet basis.

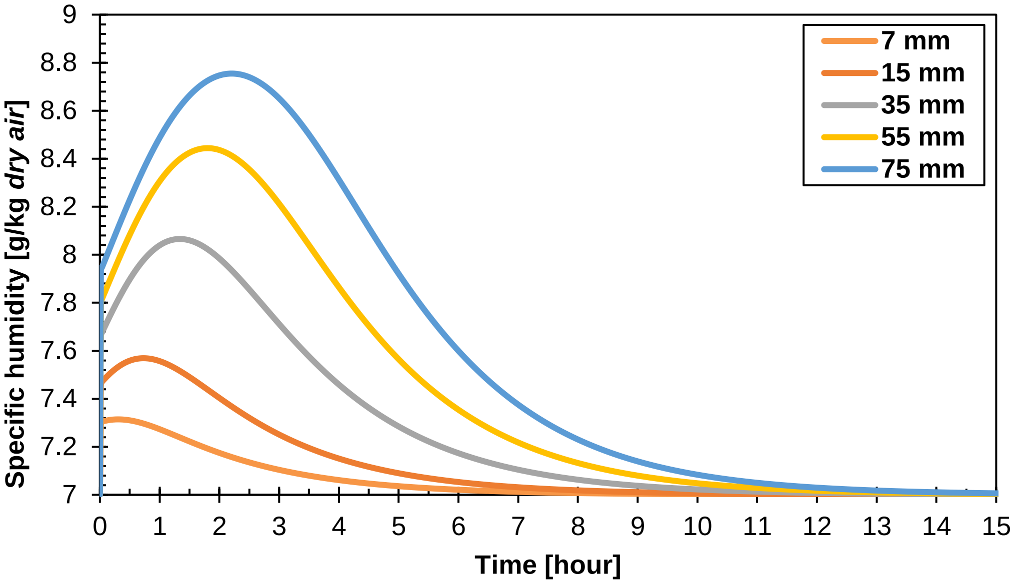

**Fig. 6.** Relationship between specific humidity and stack height variation in coffee beans during drying

### *3.3 Moisture Content vs Drying Time*

This analysis highlights the relationship between moisture content and variation in coffee bean stack height during the drying process. Figure 7 shows the graph of dry basis moisture content of the coffee beans versus drying time, which demonstrates the ability to dry the coffee beans to a moisture content of 12% wet basis (wb) or 0.136 dry basis (db) within 3 hours 50 minutes to 5 hours 50 minutes. At this point, the decrease in moisture content starts to slow down when the moisture content drops below 12% wet basis. This is because the water content inside the coffee beans is very low, and the decreasing concentration gradient between the inner and outer parts of the beans results in reduced evaporation of water from the surface. This condition is reflected in the specific humidity graph (Figure 6), which shows the point at which the moisture content reaches 12% wet basis. The most rapid decrease in moisture content to 0.136 dry basis occurred at a stack height of 7 mm, while the slowest decrease was observed at a stack height of 75 mm. Overall, the moisture content approaches zero after approximately 14 hours of drying, indicating that there is no remaining water in the coffee beans, leaving only the dry matter.

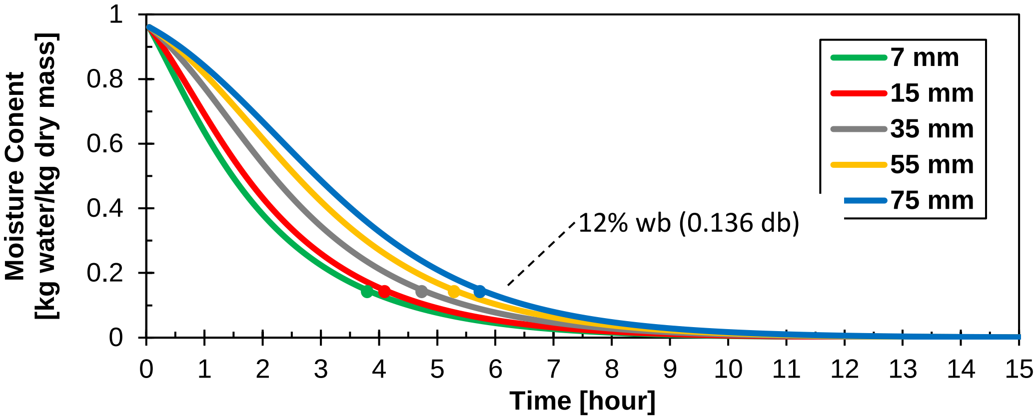

**Fig. 7.** Relationship between moisture content and variation in coffee bean stack height during drying

### *3.4 Air and Material Temperature vs Drying Time*

Figure 8 shows that the outlet air temperature of the drying chamber and the average coffee bean temperature increase over time. From 0 to 2 h, both the outlet air temperature and the coffee bean temperature significantly increase. This is due to the fact that when the moisture content of the coffee beans is still high (with a large temperature difference between the drying air and the beans), some of the energy carried by the drying air is absorbed by the coffee beans, which have a lower temperature than the drying air, resulting in a significant temperature difference. From 2 to 5 h, the temperature rise begins to level off. At this point, the moisture content of the coffee beans is lower and approaches 12% wet basis. As the moisture content continues to decrease, the temperature difference between the drying air and the material also decreases, leading to reduced heat transfer from the air to the coffee beans. As a result, from 5 to 15 hours, the temperature rise of both the air and the coffee beans slowed down significantly, and by the 15-hour mark, the temperature difference between the outlet air of the drying chamber and the coffee beans was only about ±0.5 °C.

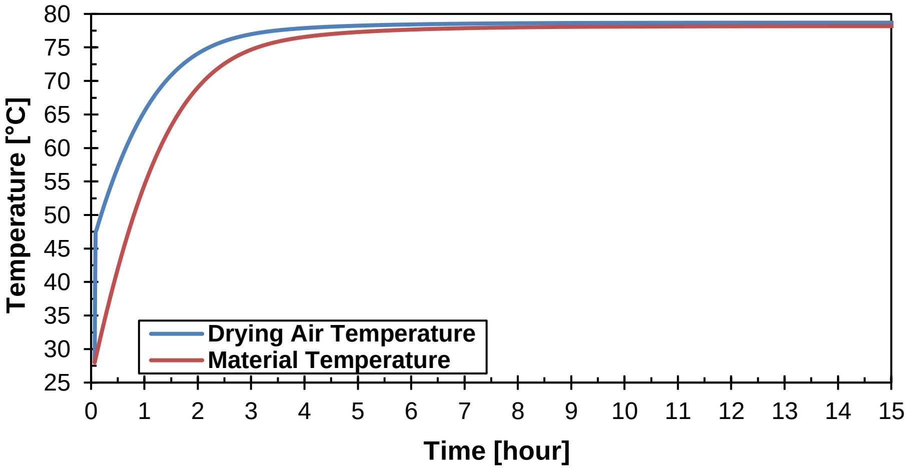

**Fig. 8.** Comparison of drying air and material temperatures in a 35-mm stack of coffee beans

### *3.5 Specific Energy Consumption (SEC)*

The simulation results analyzed the Specific Energy Consumption (SEC) at various drying air temperatures during the coffee bean drying process. SEC is estimated in this analysis based on the energy required to dry the coffee beans. The SEC is a crucial indicator of drying efficiency. The power used as an input parameter in the data processing, which was generated from the experimental results of the one-hour drying process, is shown in Table 3. Based on Table 3, the comparison between power with and without refrigeration at the same temperature shows a clear difference. At 80 °C without refrigeration, the power is lower. At 60 °C with refrigeration, the power is the same as that at 80 °C without refrigeration.

**Table 3**
Power input generated by the experiment over a one-hour operation

| | With Refrigeration | | | Without Refrigeration | | |
|---|---|---|---|---|---|---|
| Temperature [°C] | 60 | 70 | 80 | 60 | 70 | 80 |
| Power [kJ/s] | 0.78 | 0.83 | 0.89 | 0.65 | 0.71 | 0.78 |

Figure 9 and Figure 10 illustrate the SEC calculations based on differences in coffee bean stacks, demonstrating an intriguing trend: the more significant the coffee bean stack, the lower the SEC needed for drying. The SEC for each change in the coffee bean stack was lower at a drying air temperature of 80 °C than at 60 °C and 70 °C. In other words, the higher the drying air temperature and the amount of coffee beans, the lower the required SEC. Without a refrigeration system, the air humidity in the drying chamber was determined from the ambient air humidity (14 g/kg dry air). The simulation results show many comparisons between the drying air temperature and the coffee bean stack height to the Specific Energy Consumption (SEC). Surprisingly, the pattern observed from the simulation results was comparable to that observed from the simulated results using a refrigeration system. The SEC for each variation of the coffee bean pile tended to be lower at a drying air temperature of 80 °C, indicating that the higher the drying air temperature and the higher the coffee bean pile, the lower the necessary SEC. These data suggest that considering factors such as the temperature and pile height of coffee beans throughout the drying process can enhance energy efficiency. Therefore, optimizing the coffee bean drying process is vital for ensuring an appropriate pile height.

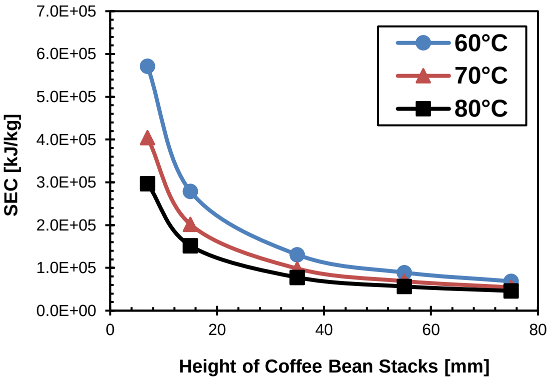

**Fig. 9.** Height of coffee bean stacks for specific energy consumption with refrigeration system

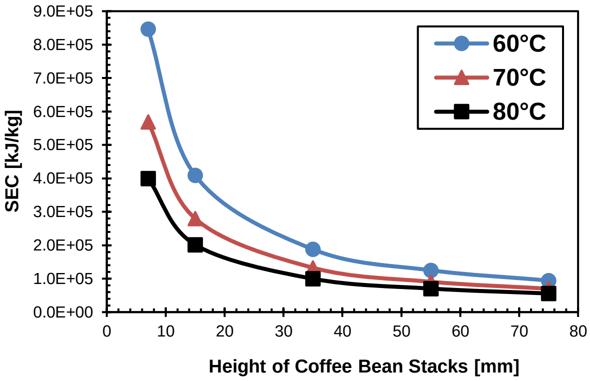

**Fig. 10.** Height of coffee bean stacks for specific energy consumption without refrigeration system

Figure 11 depicts the relationship between drying air temperature and Specific Energy Consumption (SEC) during the drying of coffee beans with and without a refrigeration system. According to the graph, the system without refrigeration had a higher SEC value than the system with refrigeration. This finding is intriguing because it demonstrates that the use of refrigeration during the coffee bean drying process can significantly reduce energy consumption. A refrigeration system can optimize energy utilization during operation and increase operational efficiency. This could be a significant step toward a more efficient and sustainable coffee bean drying process.

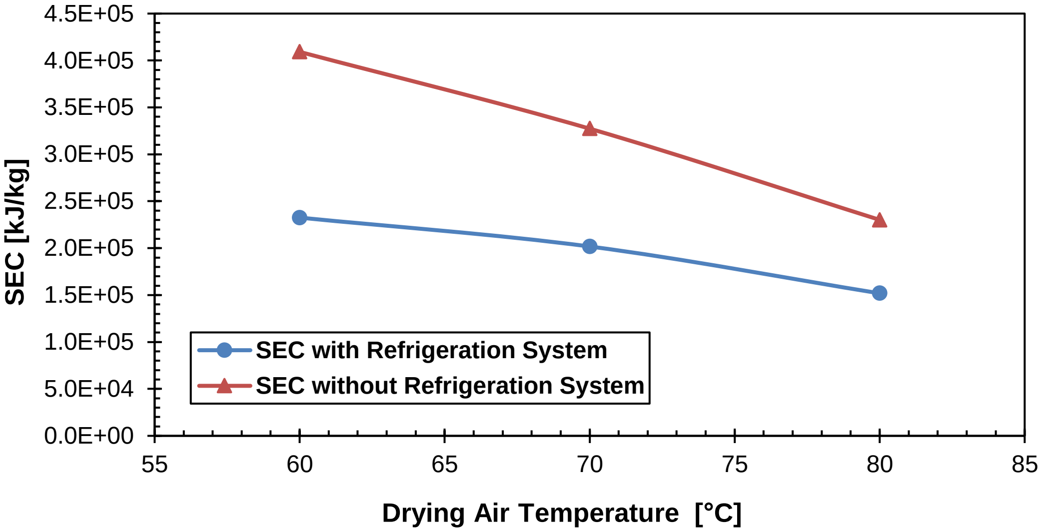

**Fig. 11.** Drying air temperature and specific energy consumption of coffee beans with and without refrigeration

### *3.6 Ratio of Specific Energy Consumption (RSEC)*

The Specific Energy Consumption Ratio (RSEC) compares the SEC under drying with a refrigeration system to SEC without a refrigeration system. The lower the RSEC value, the more efficient is the system. The system is considered unprofitable when the RSEC exceeds 1. The relationship between the variation in the coffee bean heap and the RSEC value is shown in Figure 12. Notably, all variations in the graph had RSEC values less than one, indicating that drying with a refrigeration system is more lucrative than drying without one because of decreased energy use. The lowest variation was a pile thickness of 7 mm, and the drying air temperature was 60 °C. However, it should be noted that the longer the drying time, the lower the drying air temperature and the smaller the pile of coffee beans.

We can discover suitable parameters for more efficient energy utilization in the coffee bean drying process using SEC and RSEC analyses. This allows coffee producers to take essential steps to eliminate unnecessary energy consumption during coffee bean drying. Their total operational efficiency can also be improved. As a result, not only does this research yield interesting insights and has substantial practical implications for the coffee bean processing business. These findings could assist the coffee industry in developing more sustainable and environmentally friendly drying methods and decreasing the negative environmental impact by effectively reducing energy use.

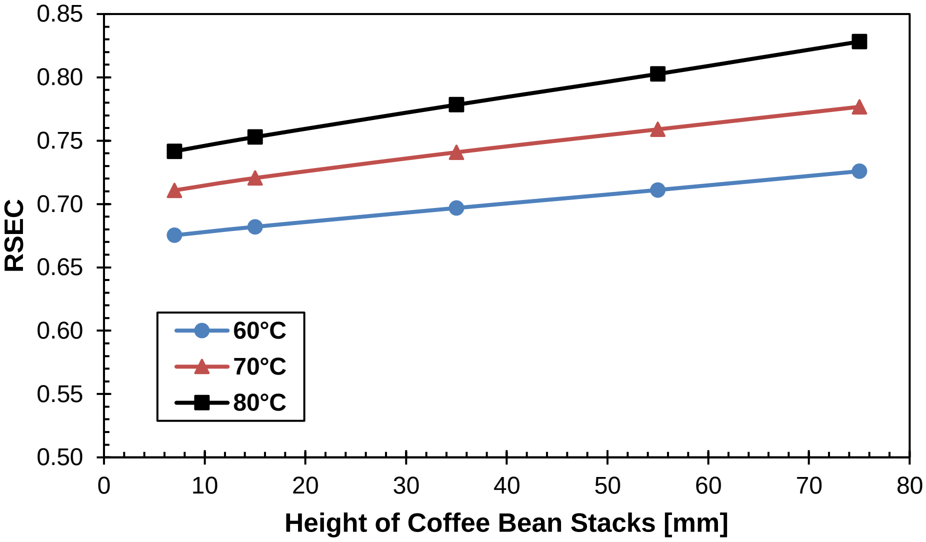

**Fig. 12.** Relationship between coffee bean stack variation and RSEC value

## 4. Conclusions

According to the research findings, the height of the coffee bean stack considerably affects the specific humidity and moisture content throughout the drying process. The amount of specific humidity absorbed by the beans was controlled by the stack height; lower stack heights resulted in faster drying rates. Furthermore, moisture content was impacted by stack height, with lower stacks losing moisture more quickly. Using a refrigeration system for drying coffee beans also showed a modest energy efficiency gain over non-refrigerated alternatives, which can be seen from the comparison of SEC values for the same drying air temperature. The smallest SEC value was 151.863 kJ/kg at 80 °C with a refrigeration system, whereas the highest SEC value was 409.195 kJ/kg at 60 °C without a refrigeration system. In general, an RSEC value of less than 1 indicates that drying with a cooling system is more advantageous than drying without a cooling system because of the lower energy consumption. The smallest RSEC value was 0.68 at a temperature of 60 °C with a stack height of 7 mm, and the highest RSEC value was 0.83 at a temperature of 80 °C with a stack height of 75 mm.

## 5. Future Research

The limitations of this study lie in the range of variations used, which is limited to temperatures of 60 °C, 70 °C, and 80 °C. For Robusta coffee (*Coffea canephora*), this temperature range is appropriate; however, for varieties like Arabica, the temperatures are too high. Therefore, in future studies, it would be beneficial to include a temperature range below 55 °C so that the simulation results can be applied to different types of coffee, including Liberica and Excelsa, even though they are still less common. Future research could also focus on optimizing airflow variations to determine the flow rate that provides higher efficiency, along with a lower specific humidity, while also considering energy consumption.

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