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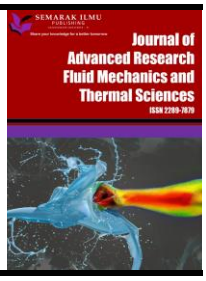

Investigation of Thin-Layer Drying of Coffee Beans Using a Double-Condenser Compression Refrigeration System: Effects of Air Mass Flux, Specific Humidity and Drying Temperature

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ABSTRACT

The drying process is the key to the quality of the coffee produced. The allowable moisture content of coffee beans is 12%. The air mass flux, specific humidity, and the drying temperature are varied using a bed dryer drying system combined with a double condenser refrigeration system. Robusta coffee beans are used in this research to obtain the characterization of coffee beans. The highest drying rate constant is obtained by 2.44 × 10^{-4} s^{-1} directly proportional to the increased air mass flux and drying air temperature, with a value of 1.701 kg/s m^2 and 80 °C, but inversely proportional to the specific humidity, with a value of 7.01 g/kg d.a. The lowest activation energy value was 31.88 kJ/mol when the air mass flux was 1.701 kg/s m^2, the drying air temperature was 80 °C, and the average specific humidity was 7.01 g/kg d.a. In this work, the developed correlation is proposed to practically predict the activation energy (EA) and the pre-exponential factor (A) with equation $Ea = 24.767\,\phi_{am}{}^{-0.244}\,\omega^{0.225}$ and $A = 0.380\,\phi_{am}{}^{-2.796}\,\omega^{2.766}$ respectively. Based on Ea and A correlation equation, it can be used for designing a bed dryer type coffee drying system for a larger scale.

1. Introduction

Food is a basic need for every human being that requires constant fulfilment. Food diversification is an effort toward food security by reducing dependence on only one type of food [1]. Not only are sago, corn, and cassava potential food resources in Indonesia, but coffee also offers a significant opportunity [2]. This commodity is expected to support the agro-industry development, especially in Indonesia [3]. In addition, the coffee processing industry is included in the food industry, which has considerable potential in the Indonesian economy, allowing Indonesia to occupy the top 10 largest economies in the world in 2022.

Indonesia's national food security and sovereignty program is trying to develop local resources, including the substitution of non-rice and non-wheat food imports using the coffee plant. For instance, it is the number one area for potential in this respect globally [4]. Where coffee is grown

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using the local wisdom of each region in Indonesia, the role of technology in food diversification programs is crucial to increasing productivity, producing quality food products, and ensuring production efficiency. So, the local food products can be made that are healthy, tasty, practical, and affordable, rendering them acceptable to the community and giving them a high export value [5].

Coffee is a fashionable brewed drink consumed worldwide, an essential component of daily life. Global coffee consumption has increased at an average annual rate of 1.9% over the last 50 years [6]. Coffee has a pleasant taste sensation, consisting of a balanced combination of bitter and sour. However, due to embedded enzymes, fresh coffee beans are vulnerable to post-harvest infections and deterioration, including browning, softening, and spoiling [7-9]. Coffee drying is essential in producing coffee because it removes moisture from the beans, preventing spoilage and improving their flavour and aroma. Different methods are used to dry coffee beans, including natural sun drying, mechanical drying, and hybrid drying methods, so the beans reach 12% moisture content (wet basis) [10]. Sun drying is the traditional method of drying coffee beans and is still used in Indonesia. In this method, the beans are spread out in a thin-layer on a surface exposed to the sun and air until they reach the desired moisture content. This method is simple and low-cost, but it can be affected by weather conditions, and it can take several weeks for the beans to dry completely. In addition, unpredictable weather conditions, dust, and insect contamination can affect the quality of the coffee produced [11]. Mechanical drying methods use hot air to remove moisture from the beans. These methods are faster and more efficient than sun drying. The maximum drying temperature for Robusta coffee is 80 °C. If processing is not done correctly, it will seriously affect the composition of the coffee beans and reduce their commercial value. Low-temperature drying is one of the most effective and efficient methods for solving this problem [12]. The drying system takes a long time to evaporate the remaining water. However, over-drying can cause excessive energy consumption [13].

Many pathologies, including cancer, breast and colon cancer, psychoactive reactions (alertness, mood swings), metabolic problems (type 2 diabetes), and liver dysfunction, may be helped by some of the chemicals included in coffee drinks, according to certain studies (cirrhosis) [14-15].

Sutida Phitakwinai *et al.,* conducted thin-layer coffee parchment (Coffea arabica) tests at controlled temperatures (50 °C, 60 °C, and 70 °C) and relative humidities (10%–30%) [16]. The research was carried out on various models of thin-layer drying obtained from previous experiments. The Midilli-modified model was chosen to design the optimal dryer. Coradi *et al.,* described the drying kinetics of coffee (*Coffea arabica L.*) that evaluated the best mathematical model to fit the experimental drying data. This drying was carried out with different air humidities (40%, 50%, and 60%), temperatures (23 °C, 40 °C, and 60 °C), and coffee quality. To describe the coffee drying curve, the Midilli model best fits Coradi *et al.,* research. The effective diffusion coefficient is directly proportional to the drying air temperature and the decrease in RH, which is explained by the Arrhenius equation [17].

Drying systems have an important role in food manufacturing and food processing worldwide [12,18]. However, drying can affect key quality parameters associated with dry food products, such as colour, taste, microbial load, texture, taste, aroma, and nutritional properties. Several previous studies have examined the effect of drying procedures using solar drying [16], hot air drying, freeze-drying (FD) [19-20], geothermal energy [10,21], and fluidized drying on the quality of coffee beans [22].

Research conducted by Raiza Manrique found that a solar-biomass hybrid system for drying coffee beans, combining burning coffee husk pellets with a photovoltaic-thermal system, could reduce the moisture content of coffee beans by up to 12% (wet basis) with 80% lower operating costs [23]. Atalay compared solar and heat pump dryers, which recovered 50% of the waste heat [24]. Research conducted by Wenjiang Dong on drying Robusta coffee beans with several drying methods concluded that heat pump drying offers the greatest market potential for prospective applications when considering its drying effectiveness, high-quality retention, and production cost [25].

Based on the development of coffee bean drying research, the author attempted to analyze the characteristics of coffee beans more profoundly using a dehumidified air refrigeration system. The novelty of this research lies in coffee bean drying using a refrigeration system for dehumidifying and heat recovery. This system is a new approach; before setting up a drying system on a large scale, it is necessary to characterize the drying of the material to be dried. So that for each material to be dried, there are different optimum conditions. This research focuses on drying air humidity, temperature, and air mass flux on the drying rate constant, activation energy, and A value of water desorption in coffee beans using a modified bed dryer combined with a refrigeration system [26]. This work will also obtain a correlation between the air mass flux and specific humidity to predict the values of activation energy (EA) and pre-exponential factor (A). With the correlation equation EA and A value, it can be used further in the process of designing coffee drying systems on a larger scale. The heat source of the coffee bean drying system is an electric heater and condenser refrigeration system (heat recovery). The electric heater acts as the primary air heater, while the heat source from the condenser is integrated with the cooling system. This refrigeration system helps to dry humid air at low temperatures in the evaporator refrigeration system [27,28]. Furthermore, the high-temperature condenser (output from the compressor) can be used for heat recovery. In this way, electric energy consumption can be minimized using the refrigeration system.

2. Methodology

2.1 Sample Preparation

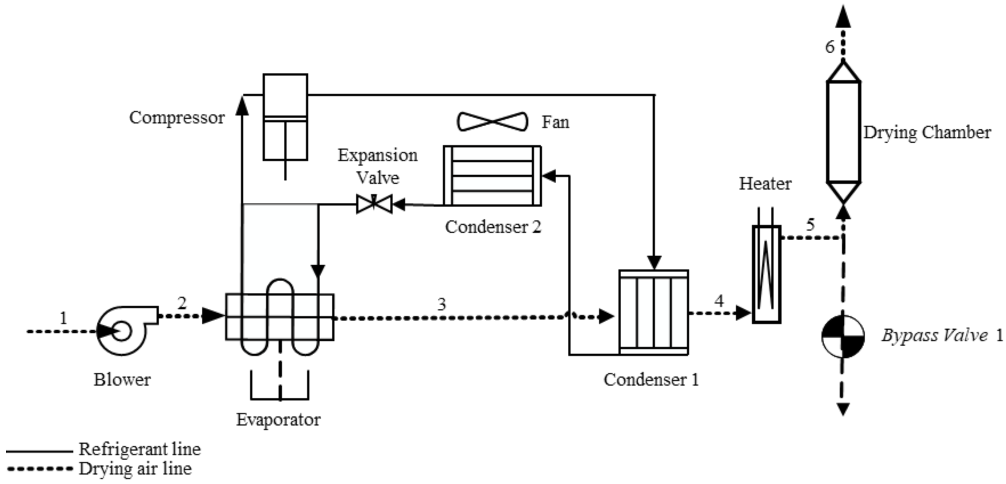
The method used in this study is experimental. The coffee bean (also known as parchment coffee) samples are Robusta coffee cherries harvested in Pangandaran, West Java Province, Indonesia. The harvested coffee cherries are sorted intact, peeled, and fermented in water for 36 hours until the mucilage layer on the surface of the coffee beans is removed; they are washed and drained. After the coffee beans are drained, they are stored in a plastic vacuum container and stored in a chiller with a temperature of 5 °C. The coffee beans stay at room temperature for 16 hours before the experiment begins in order to achieve equilibrium conditions [16,29]. The water content of coffee beans is dried using an oven at 105 °C for 16 hours to obtain the initial moisture content [30]. The initial moisture content of coffee beans is 49.09% on a wet basis. Figure 1(a) shows the condition of coffee beans ready for drying, and Figure 1(b) shows the condition of the coffee beans after the drying process has a darker colour than before the drying process.

(a) (b)

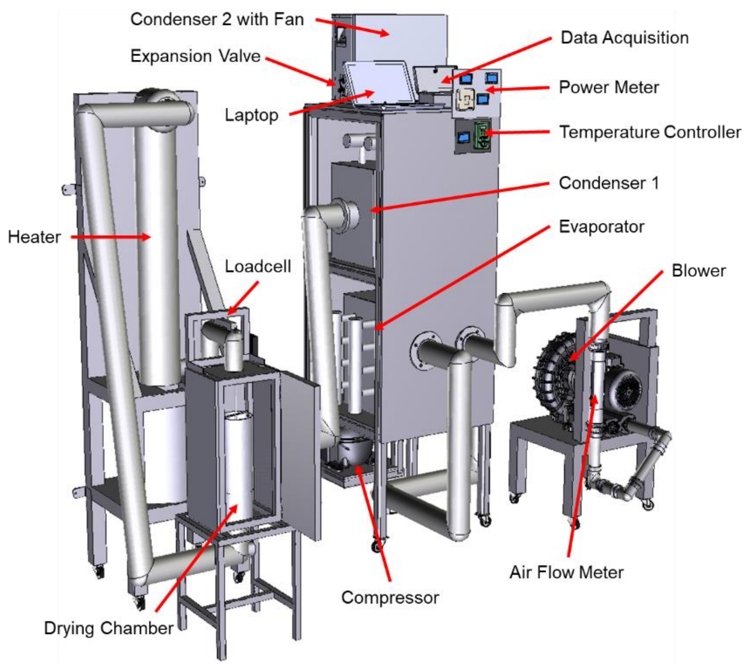
Fig. 1. (a) Wet parchment Robusta coffee before drying, (b) Coffee beans after drying process

2.2 Drying System and Measurement

Based on Figure 2(a) shows the schematic of the drying system for the refrigeration system line and drying airline. The coffee beans are dried by forced convection using a bed dryer combined with a refrigeration system for dehumidification and heat recovery in drying air. The refrigeration system consists of a compressor, condenser 1, condenser 2 equipped with a fan, an adjustable expansion valve, and an evaporator. The refrigerant used in the refrigeration system is R134a. While Figure 2(b) shows the component position of the drying system, which consists of a blower, heater, and drying chamber. The evaporator in the refrigeration system functions as an air dehumidifier by adjusting the expansion valve opening, which produces the evaporator outlet temperature. The temperature outlet of the evaporator is varied by 10 °C, 15 °C, and 20 °C [31]. The aim is to obtain variations in the specific humidity of the drying air (function of dry bulb temperature and relative humidity. Unfortunately, the specific humidity is different even when the evaporator outlet temperature is set the same for each variation of air mass flux.



(a)



(b)

Fig. 2. (a) 2D Experimental schematic, (b) 3D Experimental setup

Condenser 1 recovers heat for the initial stage of heating the drying air. The maximum drying temperature for Robusta coffee beans is 80 °C, so an electric heater is needed to meet the heat requirement in the drying chamber. The outlet temperature of the heater varies from 60 °C to 80 °C in increments of 5 °C. Because the drying chamber used is a cylinder with a diameter of 4 inches, the blower air flow rates varied from 300, 400, 550, and 700 lpm are equivalent to the air mass flux of 0.729, 0.972, 1.336, and 1.701 kg/s m^2, respectively. The air mass flux (ϕ_{am}) is the ratio of the airflow rate multiplied by the air density to the cross-sectional area of the drying chamber. Furthermore, this experiment was carried out using only a heater (without a refrigeration system).

The measurements for this experiment used a rotameter for drying air flow rate measurement, type k thermocouple for temperature measurement, HIH Honeywell 4031 RH meter for relative humidity measurement, and Zermic loadcell for mass measurement. The data were collected using National Instrument data acquisition. The initial mass of the dried coffee beans was 31.744×10^{-3} kg (single layer for 4 in cylindrical drying chamber shown in Figure 3) and will undergo a drying process for an hour. The mass of the material to be dried consists of the mass of water and the mass of dry material, which can be defined as

$$m_t = m_w + m_d \tag{1}$$

where m_t is the total mass (g), m_w is the mass of water in the material (g), and m_d is the mass of dry material (g). In determining the drying characterization of coffee beans, it is necessary to process the mass obtained into moisture content over time. Moisture content is divided into two: X_{wb} is moisture content on a wet basis Eq. (2), and X_{db} is moisture content on a dry basis Eq. (3) [32].

$$X_{wb} = \frac{m_w}{m_t} \tag{2}$$

$$X_{db} = \frac{m_w}{m_d} \tag{3}$$

Furthermore, it is necessary to define the moisture ratio of the material based on Eq. (1). Because the moisture equilibrium of the material is very small, the X_e value can be considered close to 0 [33-35]. Thus, the MR equation can be seen below Eq. (4).

$$MR = \frac{X_t - X_e}{X_o - X_e} \tag{4}$$

where X_t is the moisture content of the dry basis at time t, X_o is the initial moisture content of the dry basis, and X_e is the equilibrium moisture content of the dry basis. The drying rate constant of the coffee bean drying process can be obtained from the following Eq. (5).

$$MR = \exp\left(-k\ t\right) \tag{5}$$

where k is the drying rate constant (s^{-1}), and t is the drying time (s) which both sides of Eq. (5) in natural logarithm, the equation is as follows Eq. (6).

$$ln(MR) = -k\ t \tag{6}$$

In this case, activation energy is the minimum energy required for a reaction to transport water from within the material to the surface of the material until the water on the surface of the material evaporates into the environment (free stream). A reaction will occur if the particles' kinetic energy exceeds their activation energy. This reaction is an essential concept in thermodynamics and chemical kinetics and is often used to predict and understand the rate and extent of chemical reactions. Activation energy can be important in determining the rate at which moisture is removed from dried material. In a convective drying process, the activation energy may be related to the energy required to vaporize the water or other solvent in the material [36]. The relationship between activation energy and drying rate coefficient can be known through the help of the Arrhenius Eq. (7) [37].

$$k = A\, e^{-Ea/RT} \tag{7}$$

It can also be turned into a linear equation by looking at the relationship between $\ln(k)$ to $\frac{1}{T}$ as shown below Eq. (8).

$$\ln(k) = \left(-\frac{Ea}{R}\right)\frac{1}{T} + \ln(A) \tag{8}$$

where Ea is the activation energy (kJ/mol), R is the ideal gas constant (8.314 J/mol K), T is the temperature (K), and the quantity A is represents the pre-exponential factor (s^{-1}). This variable can be treated as a constant for a given reacting system over a reasonably wide temperature range.

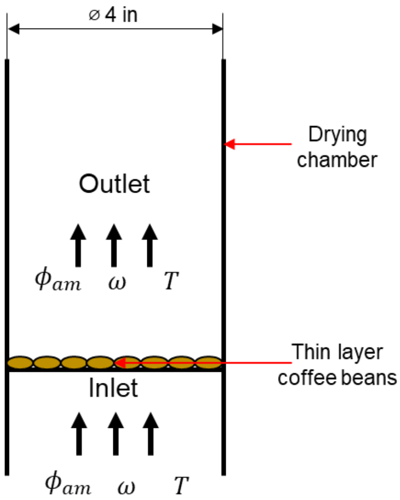


Fig. 3. Drying chamber schematic

3. Result and Discussion

3.1 Drying Air Temperature and Specific Humidity

The results of the research allow for the construction of a psychometric diagram of the average humidity conditions of the drying air used during the drying process (Figure 4).

At condition 1 is the state of the air in the environment before entering the blower, with an average specific humidity of 14.46 g/kg d.a and an average temperature of 25.58 °C. Meanwhile, in conditions 2, 3, and 4, the condition of air coming out of evaporator at points 2, 3, and 4 are the temperature of the evaporator outlet air, which is set at 20 °C, 15 °C, and 10 °C with average specific humidity values obtained at 12.28, 8.58, and 6.27 g/kg d.a, respectively. Lowering the evaporator temperature to 10 °C causes a decrease in the moisture content in the drying air of up to 56.64% when compared to not using a refrigeration system (point 1).

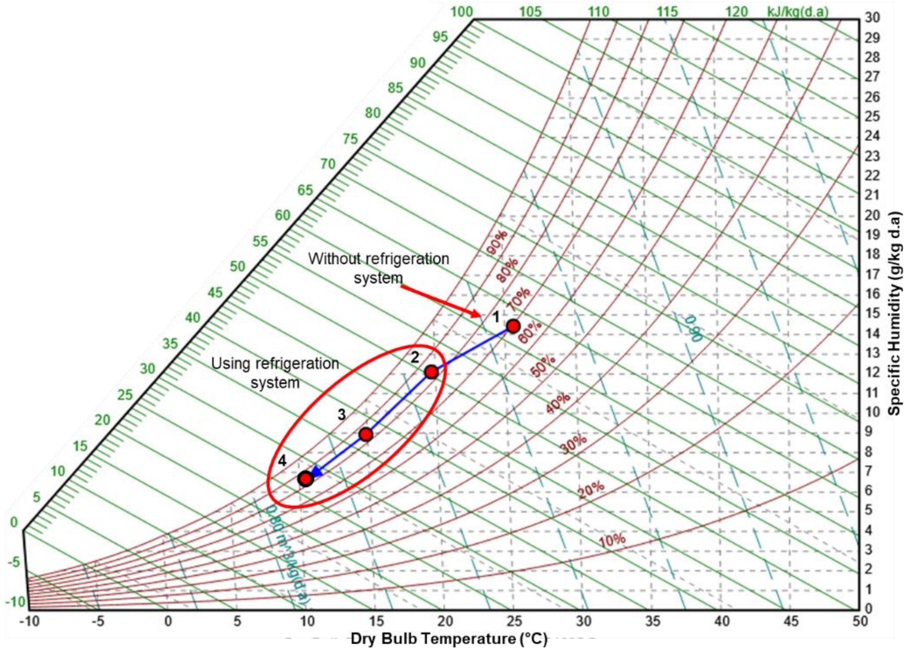


Fig. 4. Psychometric diagram

3.2 Coffee Beans Drying Kinetics

Figure 5 demonstrates the drying process carried out at an air mass flux of 0.729 kg/s m^2 for the drying air without using a refrigeration system to see the effect of the heater temperature on the moisture content of the coffee beans. The coffee beans moisture content is decreased when the heater temperature is higher, resulting in lower moisture content. The highest slope occurs at a temperature of 80 °C.

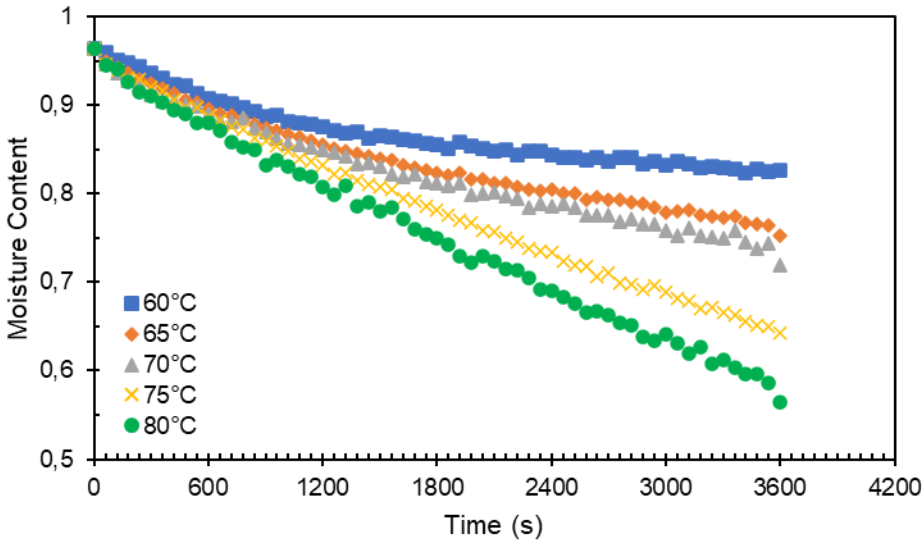


Fig. 5. Moisture content vs drying time at an air mass flux of 0.729 kg/s m^2 for the drying air without the refrigeration system

Based on Figure 5 illustrates the highest decrease in moisture content at 80 °C, while Figure 6 represents the moisture ratio to drying time at the heater temperature of 80 °C. Air humidity conditions are regulated by setting the evaporator outlet air temperature (6.53, 8.82, 12.23 g/kg d.a) and without using a refrigeration system (14.43 g/kg d.a). It can be seen that the decreasing moisture ratio trend occurs as drying time goes by. By lowering the humidity of the drying air using a refrigeration system, the highest reduction in moisture ratio was obtained at the evaporator outlet temperature setting of 10 °C (air mass flux of 1.336 kg/s m^2 indicated a specific humidity value of 6.53 g/kg d.a).

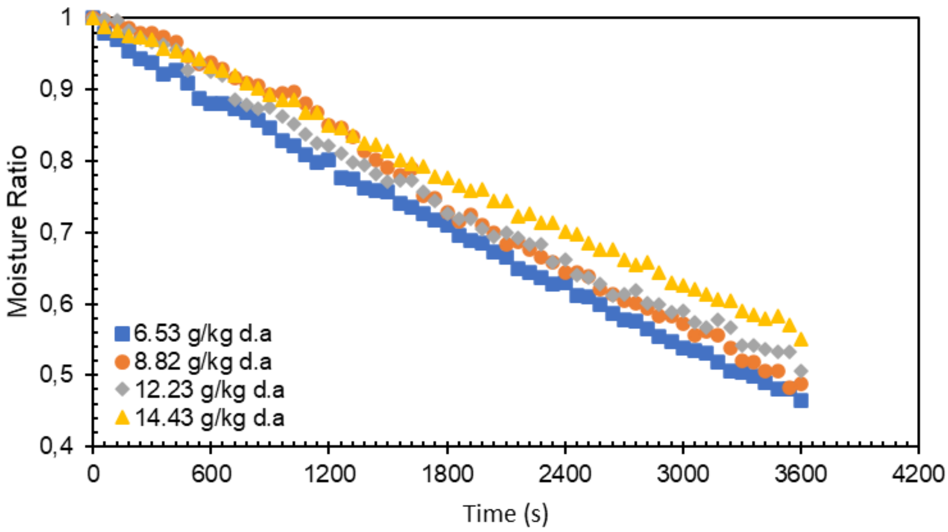


Fig. 6. Moisture ratio vs drying time at an air mass flux of 1.336 kg/s m^2 for the drying air, 80 °C heater temperature at various specific humidities

After the moisture ratio value is obtained for each drying condition, the coffee's drying rate constant value can be determined by plotting ln (MR) vs time. Figure 7 illustrates that the drying rate k on the slope ln (MR) vs time tends to increase when the air mass flux is higher. Other drying rate constant values can be seen in Figure 8.

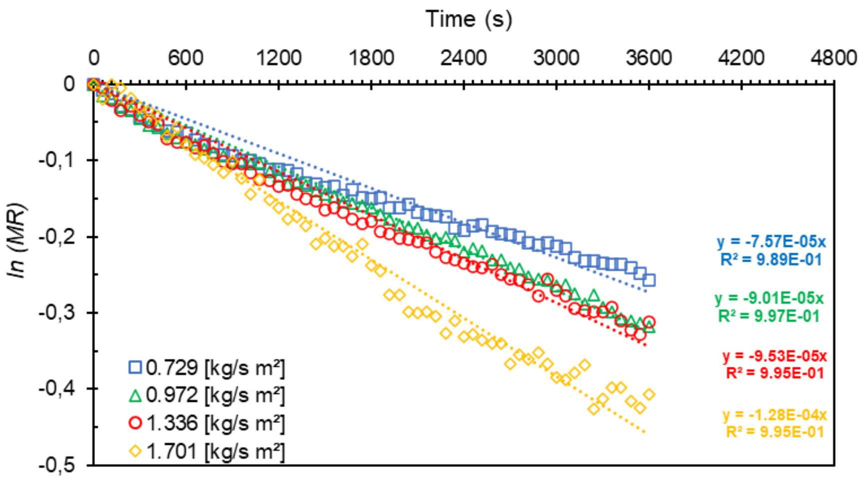


Fig. 7. Ln (MR) vs time at 60 °C heater temperature and average specific humidity of 6.27 g/kg d.a

The value of the water vapor evaporation rate at each point in the drying process is given by the drying rate constant. Figure 8 demonstrates that the drying air temperature and specific humidity have an impact on the drying rate constant for the same air mass flux. When employing a refrigeration system at a heater temperature of 80 °C and the lowest average specific humidity levels, the drying rate constant value will increase at the same air mass flux. The experiment's greatest drying rate constant value was 2.24 × 10^{-4} s^{-1} at an air mass flux of 1.701 kg/s m^2 for the drying air, 80 °C heater temperature, and 7.01 g/kg d.a. specific humidity. In this study, the lowest drying rate constant value occurred with an air mass flux of 0.729 kg/s m^2 for the drying air, 60 °C heater temperature, and without using a refrigeration system. This value was 5.3 × 10^{-5} s^{-1}. Increasing the drying rate constant will affect the mass transfer of water vapor from the coffee beans to the environment.

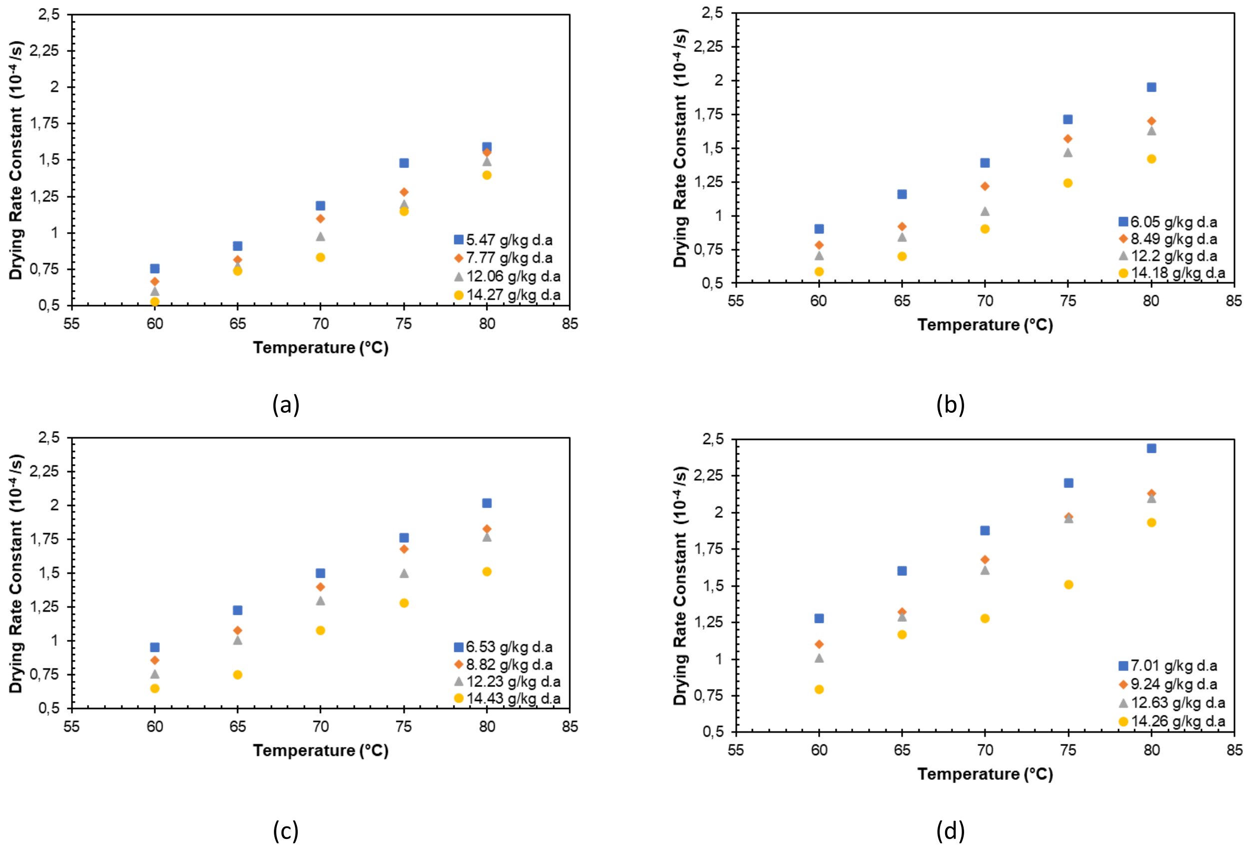


Fig. 8. Drying rate constant vs heater temperature (a) 0.729 kg/s m^2, (b) 0.972 kg/s m^2, (c) 1.336 kg/s m^2, and (d) 1.701 kg/s m^2

The next stage is to obtain the activation energy value. The activation energy is obtained by plotting the ln k data against $1/T$ (as shown in Figure 9), and then looking at the trendline; the gradient displayed from the existing data shows the value of Ea/R. The R^2 value of the existing trendline has an average value above 95%, indicating that this value is good. It can be seen that the higher the specific humidity, the higher the Ea/R value, and vice versa.

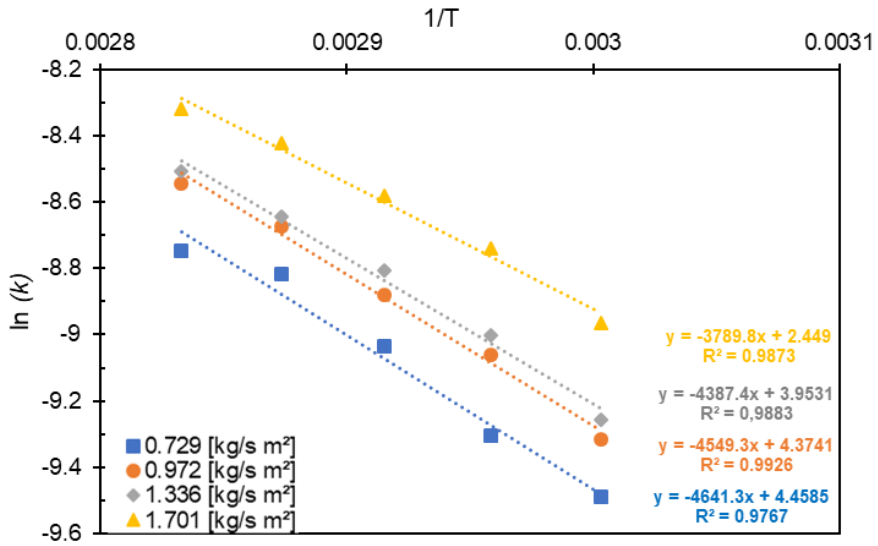


Fig. 9. Ln (k) vs 1/T at 6.27 g/kg d.a specific humidity at various mass flux

The value of Ea is an indicator of the energy required to remove moisture from the sample during the drying process [38]. In this case, it is the reaction of water movement from inside the coffee beans to the surface of the coffee beans. Based on Figure 10, the activation energy values are obtained from all the variations used in the experiment. The air mass flux and the specific humidity significantly impact the activation energy's value. If the specific humidity of the drying air is lower, the activation energy value will be lower at the same air mass flux, and vice versa. In this experiment, the lowest activation energy value was 31.88 kJ/mol at the drying air's 1.701 kg/s m^2 air mass flux. The drying air's specific humidity condition averaged 7.01 g/kg d.a. At the same time, the highest activation energy value was 47.10 kJ/mol at 0.729 kg/s m^2 air mass flux, and the drying air's specific humidity averaged 14.27 g/kg d.a (without the refrigeration system).

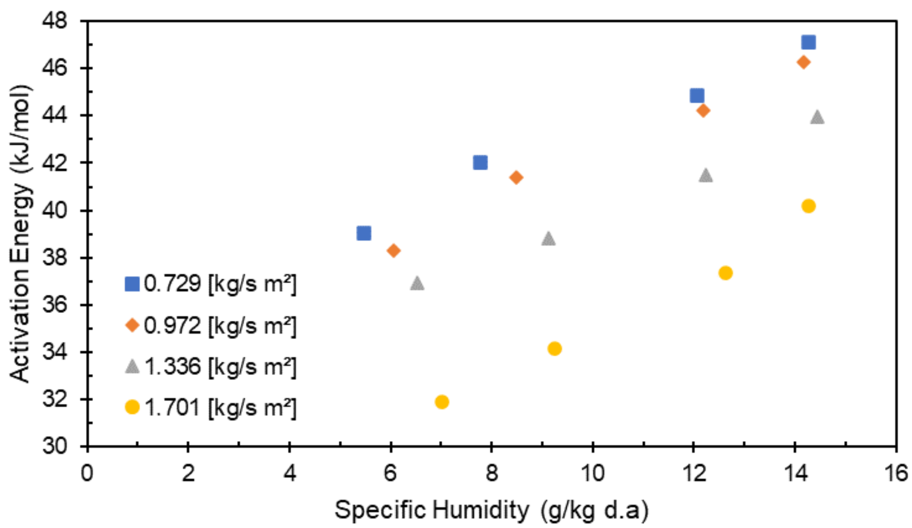


Fig. 10. The activation energy vs specific humidity at various air mass flux rates

Figure 11 indicates the value of pre-exponential factor (A) obtained at variations in the airflow rate, which has a tendency similar to the activation energy. The value of A will increase when the specific humidity is higher. The value of A will get smaller when the airflow rate gets lower. The highest A value was obtained at 1087.57 s^{-1} with an air mass flux of 0.729 kg/s m^2 for the drying air and a specific humidity of 14.27 g/kg d.a. The lowest A value was obtained at 11.58 s^{-1} at an air mass flux of 1.701 kg/s m^2 and a specific humidity of 7.01 g/kg d.a. The value of A will be close to the value of k if the drying temperature is very high, so the exp value ($^{-Ea}/_{RT}$) is close to 1. By performing multivariable regressions, the equations $\ln Ea$ and $\ln A$ can be obtained as follows.

$$\ln Ea = 3.210 - 0.244\ \phi_{am} + 0.225\ \omega \tag{9}$$

where Ea is the activation energy (kJ/mol), ϕ_{am} is the air mass flux (kg/s m^2), and ω is the specific humidity (g/kg d.a). Based on Eq. (9), the regression equation is obtained with an R^2 value of 0.904 and a standard deviation of 3.60 × 10^{-2}. The Eq. (9) can also be simplified into the following Eq. (10).

$$Ea = 24.767\ {\phi_{am}}^{-0.244}\ \omega^{0.225} \tag{10}$$

Furthermore, for the equation, $\ln A$ can be obtained by multivariable regression as shown in Eq. (11).

$$\ln A = -0.968 - 2.796\ \phi_{am} + 2.766\ \omega \tag{11}$$

where A is the pre-exponential factor (s^{-1}), ϕ_{am} is the air mass flux (kg/s m^2), and ω is the specific humidity (g/kg d.a). Based on equation 11, the regression equation is obtained with an R^2 value of 0.917 with a standard deviation of 3.960 × 10^{-1}. Eq. (11) can also be simplified as Eq. (12).

$$A = 0.380\ {\phi_{am}}^{-2.796}\ \omega^{2.766} \tag{12}$$

According to the experimental results that have been carried out, there are two empirical correlation equations to predict the value of Ea (Eq. (10)) and the value of A (Eq. (12)). The values of Ea and A in the coffee bean drying process can be predicted by knowing the air mass flux (ϕ_{am}) and the specific humidity (ω) value. These equations are also helpful in predicting the coffee bean drying rate constant and drying time when the drying temperature is known.

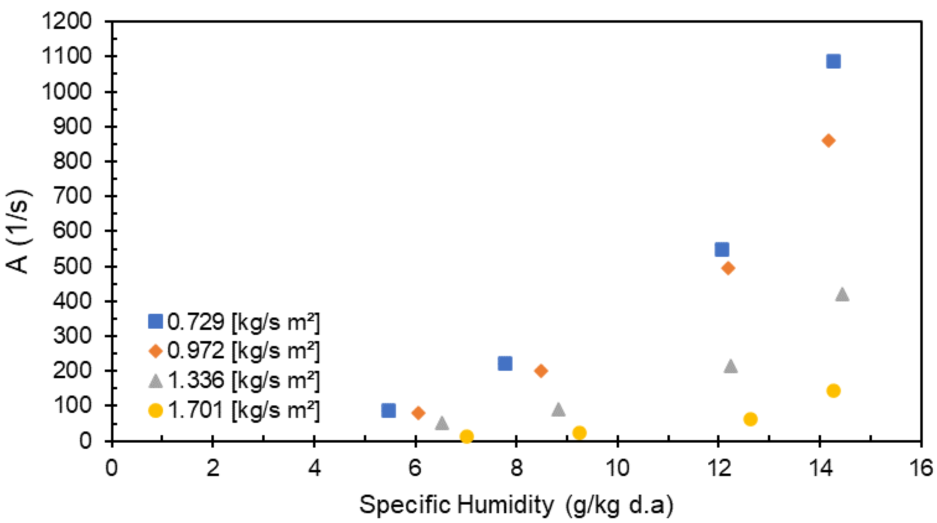


Fig. 11. The A value vs specific humidity at various air mass flux rates

4. Conclusions

Several conclusions are based on the experiments on thin layer coffee beans drying that has been carried out under various conditions of air mass flux, specific humidity, and drying air temperature. The lower specific humidity value of the drying air can bind the drying rate constant value. Evaporator in refrigeration system act as a dehumidifier, and the specific humidity value of the drying air can be reduced on average by up to 5.47 g/kg d.a. The drying rate constant was greatly affected by air mass flux, specific humidity, and drying air temperature. The drying rate constant value increased when the drying air temperature and air mass flux were increased. Under conditions of an air mass flux of 1.701 kg/s m^2 for the drying air, 80 °C heater temperature, and 7.01 g/kg d.a specific humidity, the highest drying rate was obtained at 2.44×10^{-4} s^{-1}. The lowest drying rate value, 5.3×10^{-5} s^{-1}, was obtained at an air mass flux of 0.729 kg/s m^2 for the drying air, a heater temperature of 60 °C, and no refrigeration system. The value of the activation energy is directly proportional to the specific humidity and airflow rate but inversely proportional to the drying rate constant. The highest activation energy value was 47.1 kJ/mol, obtained at an air mass flux of 0.729 kg/s m^2 for the drying air, 60 °C heater temperature, and no refrigeration system. The lowest activation energy value was 31.88 kJ/mol, obtained at an air mass flux of 1.701 kg/s m^2 for the drying air, a heater temperature of 80 °C, and a specific humidity of 7.01 g/kg d.a. In this work, the developed correlation is proposed for predicting the values of Ea and A practically. The correlation between air mass flux and specific humidity contributes to predicting the constant drying rate and drying time required for coffee beans, so that it can be used as a reference in designing bed-type coffee dryers on a larger scale.

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