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Comparative study of modelling, drying kinetics and specific energy consumption of desiccated coconut during convective and infrared drying

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Abstract

White coconut shreds were dried in this study utilizing convective (CD) and infrared (IR) drying methods to produce desiccated coconuts. The drying duration, drying rate, effective moisture diffusivity, activation energy, and specific energy consumption of desiccated coconuts were examined and compared between convective and infrared drying. The experiments were carried out at three levels of air temperatures (50, 60 and 70°C) for convective drying and the same heating temperature was used for infrared drying. Air velocity of (1.5, 2.3 and 3.0 m/s) was supplied at every temperature for both drying methods. In order to determine the ideal model for desiccated coconuts, six mathematical models were fitted to both drying techniques with the Page model providing a better fit than other models in all drying parameter ranges. Experimental drying curves displayed only a falling drying rate period. The experimental findings demonstrated that drying temperature, air velocity, and drying techniques had a substantial impact on drying kinetics. The highest effective moisture diffusivity value of desiccated coconuts was 1.66×10^{-9} m^2/s at 70°C and 3.0 m/s and 2.79×10^{-9} m^2/s at 70°C and 1.5 m/s from convective and infrared drying, respectively. For convective and infrared drying, respectively, the specific energy consumption varied from 64.80 to 112.54 kWh/kg and 18.68 to 37.72 kWh/kg. The drying time between convective and infrared drying was inversely influenced by higher air velocity at the same temperature. Air velocity had a substantial effect during infrared drying whereby the activation energy of 9.42 kJ/mol was the lowest at 2.3 m/s. Infrared drying proved to have a better synergistic effect by providing a higher drying rate and effective moisture diffusivity with the shortest drying time when compared to convective drying.

1. Introduction

In the tropical part of the world, coconut is one of the most significant tree crops, providing food and shelter for millions of people as well as supporting the local economy. For several nations in this region, especially those in Southeast Asia, it is also a significant export with a large number of products derived from coconut (Pham, 2016). It is undoubtedly that the human diet heavily relies on coconuts which are used as a raw material in the food, drug and cosmetics sectors (Lamdande *et al.,* 2018). In coconut fruit, the three portions known as the exocarp, mesocarp, and endocarp protect the flesh and water (endosperm) of the coconut. In other words, its structural components include husk, kernel, and water, which vary depending on the coconut's maturity (Kumar, 2019). Coconut kernels have been used for a variety of purposes and can be consumed in raw, processed, or cooked forms. Copra, desiccated coconut, coconut flakes and chips are examples of coconut kernel-based products available in the market. As a matter of fact, coconut kernel is considered perishable with high in fat, sugar, and moisture content, making it difficult to keep in fresh condition for an extended period of time (Lamdande *et al.,* 2018). To avoid microbiological degradation, fresh coconut kernel that contains 50–55% moisture needs to be dried as soon as possible (Jongyingcharoen *et al.,* 2019). Therefore, it is predominantly important to ensure that losses in coconut kernel processing are minimized through proper and right preservation techniques. Among them, drying is one of the most popular and practical methods for

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making products in dried form enabling long-term storage (Sarkar *et al.,* 2020). Desiccated coconut, which is already dried has a very low moisture content of about 3% on a dry weight basis and thus can be used to flavour chocolate bars, candies, and biscuits as well as to decorate ice cream, cake, and doughnuts (Madhiyanon *et al.,* 2009; Agarry and Aworanti, 2012).

Fruits, vegetables, and other foods can be preserved using the most popular drying technique, hot air drying or convective drying, but it has significant downsides, such as shrinkage, a reduced rehydration ratio, and unfavourable changes to colour, texture, taste, and nutritional value (Salimi and Hoseinnia, 2020). For instance, Doymaz and Pala (2002) also reported that red pepper's drying period can be reduced to about 20 to 30 hours with hot air drying, although this method's prolonged duration and high temperature usually result in significant nutrient loss, significant shrinkage, or inadequate rehydration. Similar results and findings were also noticed for other dried agricultural products mentioned by (Inyang *et al.,* 2017). To date, numerous studies using convective and hot air drying have been conducted on coconut kernel products, either in laboratories or on a pilot scale (Madamba, 2003; Madhiyanon *et al*., 2009; Prieto *et al*., 2011; Agarry and Aworanti 2012; Zainal Abidin *et al*., 2014; Wutthigarn *et al*., 2018; Jongyingcharoen *et al*., 2019; Kurniawan *et al*., 2020; Yahya *et al*., 2020). Although convection or hot air drying is frequently employed in the food industries, it still requires more time and energy than other drying methods. Therefore, application of more improved drying technologies may be the tendency for agricultural product dehydration from the perspectives of drying kinetics, drying rate, energy consumption, and final product quality.

One of the newest drying methods that is now getting a lot of interest is infrared drying. Since it operates without heating the surrounding air, it differs noticeably and fundamentally from conventional drying. During IR heating, IR is absorbed by food, penetrating the product and converting it into thermal energy via molecular vibration. Due to its inherent benefits, IR heating-based drying is receiving more attention than conventional drying techniques in the food processing business (Delfiya *et al*., 2021; Huang, Li, Wang *et al*., 2021). In general, the wavelength range for IR radiation technology is 0.75 to 100 μm and it is further split into short-wave IR (0.75-2 μm), medium-wave IR (2-4 μm), and long-wave IR (4-100 μm) (Salehi and Satorabi, 2021). High heat transfer coefficients, quick processing times, and low energy costs are benefits of IR radiation over convective heating (Zhang *et al*., 2017). However, it is probable that the amount of energy that is absorbed, reflected, or transmitted changes depending on the infrared radiation's wavelength, various materials, and surface circumstances (Pan, 2021). Furthermore, the surface temperature and the material's emissivity are directly related to how much radiant energy is released from a heat source (Pawar and Pratape, 2017; Pan, 2021). Electric heaters and gas-fired heaters are the two commonly utilized types of IR heaters. When using IR and IR-assisted drying technologies, the following factors can significantly affect how quickly food items dry: IR power, drying temperature, IR heater to sample distance, material thickness, and air velocity (Delfiya *et al*., 2021). For high moisture products such as kiwi, cantaloupe, carrot and longan, medium and short infrared radiation has shown advantages with good performances (Wu *et al*., 2014; Sadeghi *et al*., 2019; Chang *et al*., 2022). To date, no research on the application of infrared drying of coconut kernel products has been reported. Therefore, the goal of this study was to learn more and offer solid evidence on the impact of infrared drying on desiccated coconuts as opposed to convective drying. The drying time, drying rate, drying kinetics, modelling, and specific energy consumption were the study's key areas of interest.

2. Materials and methods

2.1 Materials and sample preparation

Newly harvested local variety of de-husked coconuts were obtained and purchased from a local market in Senawang, Negeri Sembilan. In this experiment, only intact and matured coconut was chosen while sprouted coconut was discarded to ensure product homogeneity throughout the drying process. The coconut was further processed on an experiment basis therefore, the freshness of the coconut was well preserved and maintained. The de-husked coconut must first go through a few stages before being processed into coconut shreds. Using a sharp knife, the coconut was first manually cracked open to remove the shell. Then the de-shelled coconut was pared using a special scraper to remove the brown skin or so-called testa. The coconut water was drained from the white peeled coconut kernel balls which were then carefully cleaned and washed with filtered tap water. Finally, a 1.5 hp mechanical shredder (Brand: Anson) with the dimension of 457.2 × 431.8 × 939.8 mm (L × W × H) was used to shred the cleaned white coconut kernels into uniform coconut shreds. The average thickness of the coconut shreds was 4.06±0.89 mm, with an initial moisture level of 51.35±4.0% wet basis (w.b) or 106±4% dry basis (d.b). Figure 1 illustrates the flow of desiccated coconut processing prior to convective and infrared drying. A thin layer of about 40 g of white coconut shreds was used in every run of the drying experiment. One layer of sample particles or slices is

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usually applied to this thin layer drying (Erbay and Icier, 2010).

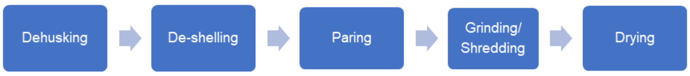

Figure 1. Processing flow of desiccated coconuts.

2.2 Convective drying set up

The stainless-steel drying chamber's dimension was 510 × 550 × 570 mm (L × W × H) and was highly insulated to avoid heat loss. The convective dryer consisted of a 3-kW electric heater, an axial blower, fresh air intake and exhaust air outlet. The dryer design allows the hot air to circulate and recycle the exhaust air hence reduce the energy consumption of the dryer. This was proven by (Djaeni *et al.*, 2021) as the heat load of the dryer could be reduced. The Shinko Denshi AJ 820E (820±0.01 g) underhook weighing scale was configured to track and measure the sample's mass loss during the drying process. The inlet hot air temperature was measured by a K-type thermocouple while air velocity was determined by a vane Anemometer (TESTO 416, Germany) with a reading accuracy of ±0.2 m/s. The schematic diagram of convective drying is illustrated in Figure 2.

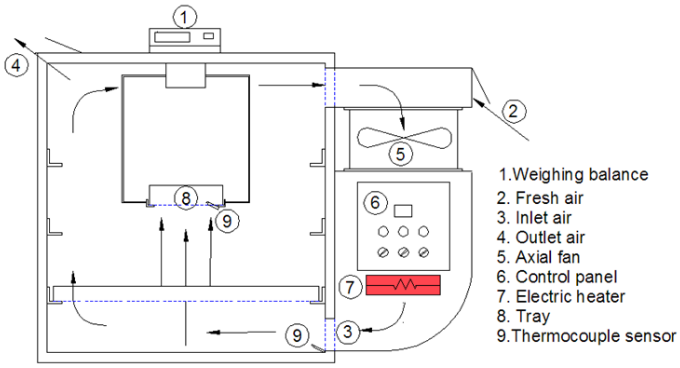

Figure 2. Schematic diagram of convective drying.

2.3 Infrared drying set up

The same unit of the dryer was used for infrared drying as the dryer was also equipped with an electrical ceramic emitter. Since ceramic heaters emit up to 3 µm of heat, they are frequently employed for drying food products (Aboud *et al.*, 2019). Figure 3 shows the schematic diagram of an experimental infrared drying set-up that was used in this study. Inside the dryer, a ceramic infrared heater with a measurement of 245 × 60 mm (L × W) and a radiation power of 600 W was mounted in the top position. The output power and infrared drying temperature can both be adjusted using the dryer's control panel. A round sample tray composed of woven wire mesh with a diameter of 140 mm was positioned beneath the infrared heater at a fixed distance of 150 mm. In addition, a thermocouple sensor was additionally positioned on the tray to gauge the product's surface drying temperature. To track the overall amount of energy used by the electric fan and infrared heater, a Watt-hour metre was additionally mounted to the control panel.

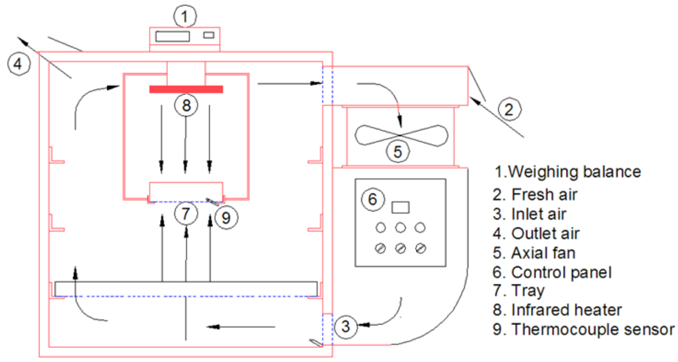

Figure 3. Schematic diagram of infrared drying.

2.4 Experimental procedure

To perform convective and infrared drying, a single layer of white coconut shreds sample weighing roughly 40 g was put evenly on a sample tray. Hot air at 50, 60, and 70°C and air velocity at 1.5, 2.3 and 3.0 m/s were used for convective drying. The radiation power used in the infrared drying process was set at 600 W or 3.90 W/cm^2. Target surface product temperature (50, 60 and 70°C) and air velocity (1.5, 2.3 and 3.0 m/s) were the two factors in infrared drying. Prior to the experiment, the convective and infrared drying were scheduled to run for roughly 15-30 mins to achieve steady state temperature. The experiment was terminated when the sample's moisture content decreased to less than 3% (w.b), as noted by the continuous recording of the sample's moisture content reduction (Asian and Pacific Coconut Community, 2009). The moisture content was assessed and recorded for the convective drying process every 10 mins for the first 30 mins, every 5 mins for the next 30 mins, and then every 2 mins for the remaining time. For the first 20 mins of infrared drying, the moisture reduction was monitored every 5 mins; for the following 20 mins, it was measured every 2 mins. All experiments were repeated twice in order to calculate the average and minimise error. Table 1 summarizes the experimental parameters involved in this study.

2.5 Determination of moisture ratio and drying rates

Moisture ratio (MR) is another way to express moisture content of product whereby it is dimensionless and can be determined using the equation given below:

$$MR = \frac{M(t) - M_{eq}}{M_0 - M_{eq}} \qquad (1)$$

Where M_o, $M_{(t)}$ and M_{eq} are initial, at any time (t) and equilibrium moisture content respectively. As the M_{eq}

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Table 1. Experimental parameters during convective and infrared drying.

Drying method	Temperature (°C)	Air velocity (m/s)	Irradiation distance (mm)
Convective drying (CD)	50	1.5, 2.3, 3.0	-
	60	1.5, 2.3, 3.0	-
	70	1.5, 2.3, 3.0	-
Infrared drying (IR) Radiation power: 600 Watt (3.90 W/cm^2)	50	1.5, 2.3, 3.0	150
	60	1.5, 2.3, 3.0	150
	70	1.5, 2.3, 3.0	150

value is normally approach zero and extremely small compared to M_o and $M_{(t)}$ it may be excluded from the MR definition. This MR value was supposed to generate the drying curve of the final dried product. Besides the drying curve, the drying rate can also be calculated by the formula given below:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (2)$$

Where M_t is the moisture content at any time, $M_{t+\Delta t}$ is the moisture content at $t+\Delta t$ (kg water/kg dry matter) and t is time (mins).

2.5 Mathematical modelling of thin layer drying kinetics

According to Table 2, six different drying kinetic models were selected and fitted to the experimental convective and infrared drying curve data. The projected and experimental moisture ratios were compared following the non-linear regression analysis using Microsoft Excel Solver®. The constant values for the models that were tested were obtained at the conclusion of the fitting investigation.

2.5.1 Statistical analysis

The mathematical model with the highest correlation coefficient (R^2) (Equation 3) and the lowest values of chi -squared (χ^2) (Equation 4) and relative mean square error (RMSE) was statistically tested to support the fitting analysis (Equation 5).

$$R^2 = 1 - \left[\frac{\sum(MR_{prd} - \sum MR_{exp})^2}{\sum(\overline{MR}_{prd} - \sum MR_{exp})^2}\right] \quad (3)$$

$$\chi^2 = \frac{\sum(MR_{exp} - MR_{prd})^2}{N-n} \quad (4)$$

$$RMSE = \left(\frac{\sum(MR_{prd} - MR_{exp})^2}{N}\right)^{1/2} \quad (5)$$

Where MR_{exp}, MR_{prd} and $\overline{MR}_{prd}$ are the experimental, predicted moisture ratio and average predicted moisture ratio respectively while N is the number of observations and n is the number of constants.

2.5.2 Determination of effective moisture diffusivity

Fick's unsteady state law of diffusion has a basic equation of the type Equation (6). Since the white coconut shreds were dried in the form of slabs having a thickness of slab 4.06 mm on average, the integrated equation for long time periods and infinite slab geometry was used hence representing the first term of the development of the series (Crank, 1975). The diffusion equation can be used to compute the moisture diffusion coefficient, which reflects moisture movement within a substance being dried (Equation 7).

$$\frac{\partial M}{\partial T} = D\frac{\partial^2 M}{\partial r^2} \quad (6)$$

$$MR = \frac{8}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{(2i-1)^2}\, exp\left[\frac{(2i-1)^2\pi^2 D_{eff}t}{4L^2}\right] \quad (7)$$

The experimental data were run through Equation (8), and the values of D_{eff} were calculated using linear regression analysis. This equation was also applied in other previous studies on coconut strips done by (Madamba, 2003; Agarry and Aworanti, 2012).

$$MR = \frac{M-M_e}{M-M_o} = \frac{8}{\pi^2}\, exp\left(-\frac{\pi^2 D_{eff}}{4L^2}t\right) \quad (8)$$

where t is the drying time (s), L is the half thickness of the slab (m) and i can be a positive integer. Equation (7) can be simplified by taking the first term for the case of a long drying duration as also mentioned by (Onwude *et al*., 2018; Li *et al*., 2019; Kaveh *et al*., 2021). Taking the natural logarithm of both sides of equation (8), we could obtain Equation (9) as given below:

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \quad (9)$$

Ln MR versus time was drawn hence the D_{eff} can be determined from the slope (Equation 10).

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4L^2} \quad (10)$$

2.5.3 Determination of activation energy

Using an Arrhenius equation 11, the lowest amount of energy needed to dry coconut shreds or so-called activation energy (Ea), was calculated from the relationship between effective moisture diffusivity and the sample's average temperatures. This equation was also used by a number of previous researchers with regard to infrared drying with specified infrared temperatures of various products (Touil *et al*., 2014; Wu *et al*., 2014; Selvi, 2020; Praneetpolkrang and Sathapornprasath, 2021).

$$D_{eff} = D_o\, exp\left(\frac{E_a}{RT_{abs}}\right) \quad (11)$$

Table 2. Drying kinetic models.

No.	Model	Equation	References
1	Page	$y = exp(-kt^n)$	Singh *et al*. (2021)
2	Modified Page	$y = exp(-(kt)^n)$	Cai *et al*. (2017)
3	Newton	$y = exp(-kt)$	Hasibuan and Bairuni (2018)
4	Henderson and Pabis	$y = a\ exp(-kt)$	Hashim *et al*. (2014)
5	Two-term	$y = a\ exp(-k_o t) + b\ exp\ (k_1 t)$	Nag and Dash (2016)
6	Logarithmic	$y = a\ exp(-c(t\ /\ L\char`^2\ ))$	Zhu *et al*. (2020)

where D_o is the diffusion factor (m^2/s), R is the universal gas constant (8.31451×10^{-3} kJ/mol K), E_a is the activation energy (kJ/mol) and T_{abs} is the absolute temperature of the sample in Kelvin. To simplify the equation, a natural logarithm is included hence the equation becomes a linear form and the activation energy can be calculated from the slope of the equation as follows:

$$ln(D_{eff}) = \ln(D_o) - \frac{E_a}{R}\frac{1}{T_{abs}} \quad (12)$$

2.6 Energy utilization and specific energy consumption during convective drying

Equation (13) and equation (15) were used to compute the convective drying energy consumption and the specific energy consumption necessary for drying a kilogram of white coconut shreds (Okoro and Isa, 2021).

$$E_t = Av\rho_a C_a \Delta T t \quad (13)$$

Where E_t is the total energy consumption, A is the cross-sectional area of the drying sample tray, v is the air velocity supplied, ρ_a is the air density, C_a is the specific heat capacity, ΔT is the temperature difference and t is the total drying time.

The air density was calculated using equation (14):

$$\rho_a = \frac{101.325}{0.28\,T} \quad (14)$$

$$SEC = \frac{E_t}{M_W} \quad (15)$$

where SEC is the specific energy consumption and M_w is the weight of loss water.

2.7 Energy utilization and specific energy consumption during infrared drying

The energy utilization and specific energy consumption can be determined by equations (16) and (17) respectively

$$E_T = (E_{IR+fan}).t \quad (16)$$

$$SEC = \frac{E_T}{m_w} \quad (17)$$

Where E_{IR+fan} is the total IR emitter and fan power (Watt), t is the time (hour), E_T is the total energy utilization (kWh), SEC is the specific energy consumption (kWh/kg) and m_w represents the weight loss of water evaporated (kg).

3. Results and discussion

3.1 Drying curve and drying rate

Figures 4, 5 and 6 show the reduction in moisture ratio with drying time at various hot air temperatures and IR temperatures with varies in air velocities. The white coconut shreds moisture ratio decreases with increasing time of drying. There was a clear and obvious difference between the drying curve of convective and infrared drying at every temperature whereby the infrared drying curve was steeper than the convective drying. Similar results have also been reported for the drying of some agricultural products (Kumar *et al*., 2005; Prakash, 2011; Tirawanichakul *et al*., 2011; Samadi, 2013; Moon *et al*., 2014; Nozad *et al*., 2016; Miraei Ashtiani *et al*., 2017). Both drying curves observed were in the falling rate drying stages. It is simpler to understand how air velocity influences convective drying since greater air velocities result in a higher drying rate and improved heat and mass transfer coefficients between coconut shreds and the surrounding hot air. Under all experimental circumstances in infrared drying, there was never a time when the rate of moisture loss was constant as the moisture removal rate decreased in a short period of time hence triggering the falling rate period. This is probably due to the higher heating temperature of the infrared emitter causing increases in vapour pressure of the

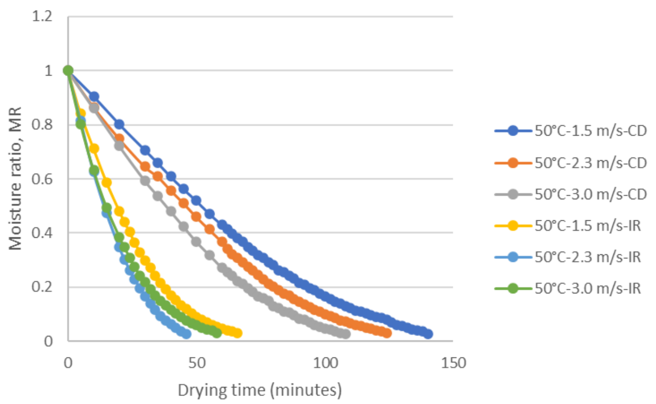

Figure 4. Comparison of convective and infrared drying at 50°C with varied air velocity.

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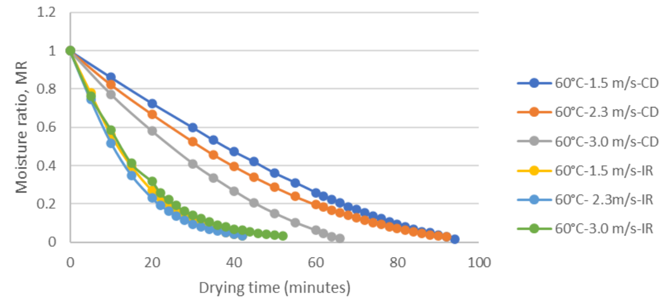

Figure 5. Comparison of convective and infrared drying at 60°C with varied air velocity.

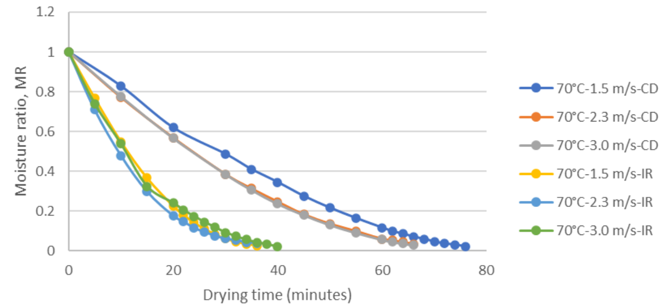

Figure 6. Comparison of convective and infrared drying at 70°C with varied air velocity.

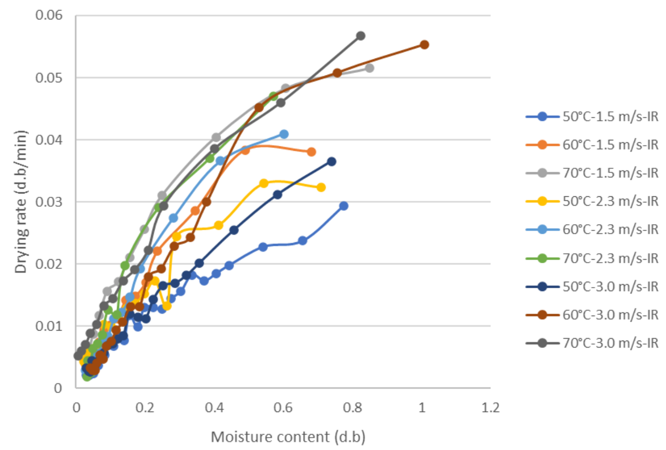

Figure 7. Drying rate of desiccated coconuts under different infrared drying temperatures and air velocity.

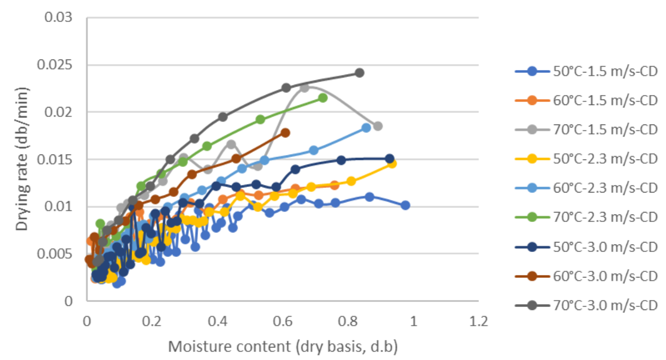

Figure 8. The drying rate of desiccated coconuts under different convective drying temperatures and air velocity.

sample moisture content (Miraei Ashtiani *et al.*, 2017; Onwude *et al.*, 2018).

Figures 7 and 8 illustrate the drying rate of both convective and infrared drying across the drying parameters range. It was clearly shown that the highest drying rate (0.0567 d.b/min) was from infrared drying at 70°C and 3.0 m/s whereas only 0.024 d.b/min for convective drying at 70°C and 3.0 m/s of hot air. Interestingly, the drying rate at 50°C and 1.5 m/s from both drying methods encountered the lowest throughout the drying process.

3.2 Drying time

Figure 9 displays the convective and infrared drying times for desiccated coconuts within specified drying parameters. It is obvious that, for a certain temperature for convective drying, drying time decreases as air velocity increases. The drying time decreases by approximately (45.72%, 46.78% and 38.89%), respectively, at fixed air velocity (1.5, 2.3 and 3.0 m/s) during convective drying with rising temperatures from 50°C to 70°C. The same pattern was shown in infrared drying, where the drying time falls by about (45.46%, 21.74% and 31.04%) at constant air velocities (1.5, 2.3 and 3.0 m/s) with increased temperatures respectively. The drying time of convective drying showed a declining pattern at constant temperature and increased air velocity. As opposed to convective drying at constant temperature and varying air velocity, the infrared drying time pattern was distinct. It is worth noting when air velocity was raised from 2.3 to 3.0 m/s at each drying temperature, the drying time of infrared drying rose. This behaviour could be due to the cooling effect as a result of an increase in air velocity which would lower the product's temperature and water vapor pressure hence extending the drying time. A similar phenomenon was also reported by (Sadeghi *et al.*, 2019; Jafari *et al.*, 2020). In addition, it can be shown that at 50°C and 1.5 m/s, both drying methods had the longest drying times. Figure 10 illustrates the significant difference ($p<0.05$) in drying time within the drying parameters between convection and infrared drying of desiccated coconuts. When compared to convective drying, the overall drying time of desiccated coconuts can be reduced by around 50% when using infrared drying. This was demonstrated

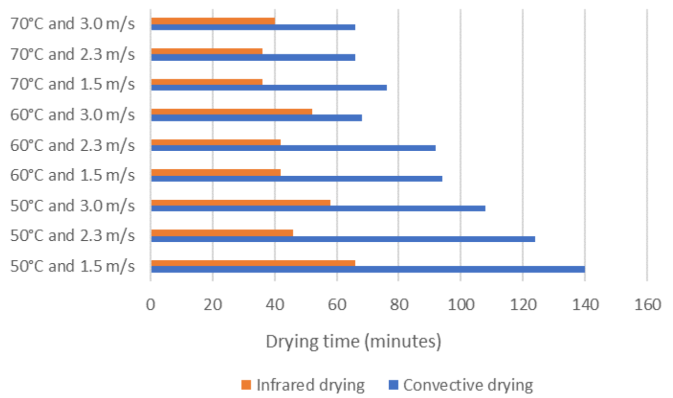

Figure 9. Comparison of drying time between convective and infrared drying with varies in temperature and air velocity.

by the fact that the highest drying rate achieved by infrared drying, 0.0567 d.b/min, was only half that of convective drying at the same conditions. The same findings were also reported by (Hebbar *et al*., 2004; Riadh *et al*., 2015) when infrared drying was proven to reduce the drying time of carrots and potatoes by 48%.

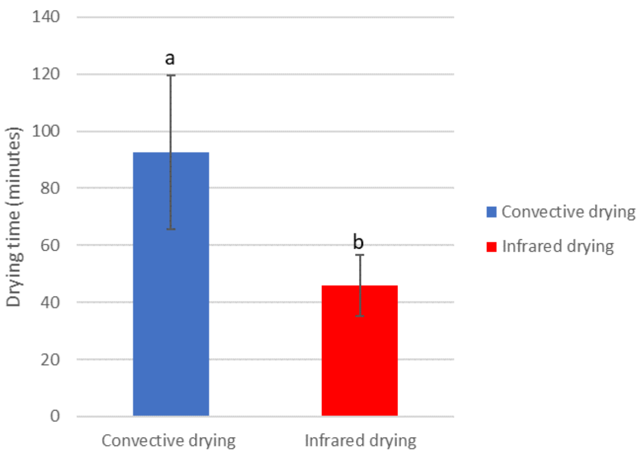

Figure 10. Comparison of drying time between convective and infrared drying. Bar with different notations differ significantly from each other at p<0.05 as determined by ANOVA (Turkey's test).

3.3 Evaluation of mathematical models

For the purpose of thin-layer drying of desiccated coconuts, certain mathematical models were fitted to the experimental data of convective and infrared drying as shown in Tables 3 and 4, respectively. Performances of the models were assessed using R^2, χ^2 and RMSE of non-linear regression analysis. The general principle of the analysis is that the goodness of fit is better by higher values of R^2, lower values of χ^2 and RMSE. For convective drying, the Page model gave the highest R^2 with an average value of (0.994775, 0.996231 and 0.995864), the lowest χ^2 (0.000431, 0.00030, 0.000419) and RMSE (0.01964, 0.016841, 0.018914) at every air velocity (1.5, 2.3 and 3.0 m/s) with a range of temperatures, respectively. Interestingly, Page model also performed well under the infrared drying condition for desiccated coconuts. This could be seen by the average value of R^2 (0.999171, 0.999494, 0.999197), the lowest χ^2 (0.000075, 0.000046, 0.000071) and RMSE (0.007886, 0.005566, 0.007867) across the drying parameter range as displayed by Table 4. Therefore, the Page model was chosen as the most suitable and adequate drying model to represent the drying behaviour of desiccated coconuts in both convective and infrared drying within the experimental parameters range. In relation to this study, some previous researchers also found that the Page model was well-suited for coconut kernel products (Madamba, 2003; Agarry and Aworanti, 2012; Pestaño, 2015). Figures 11 and 12 show the drying curves and the goodness of fit of the Page model for convective and infrared drying between predicted and experimental data. Table 5 also compared the drying constants of desiccated coconuts with regard to the Page model between convective and infrared drying.

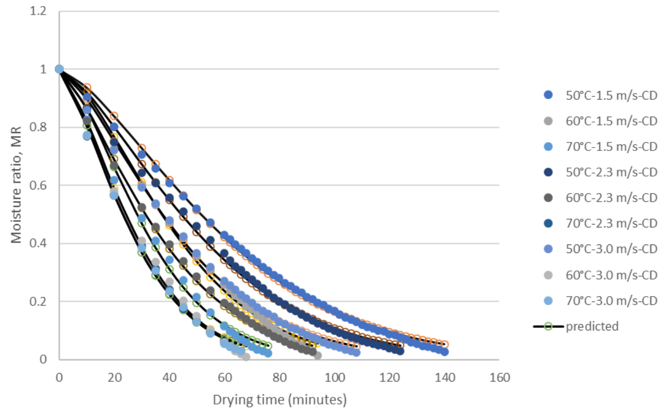

Figure 11. Fitting of drying curves between the measured and predicted MR values from the Page model with drying time at different temperatures and air velocities of convective drying.

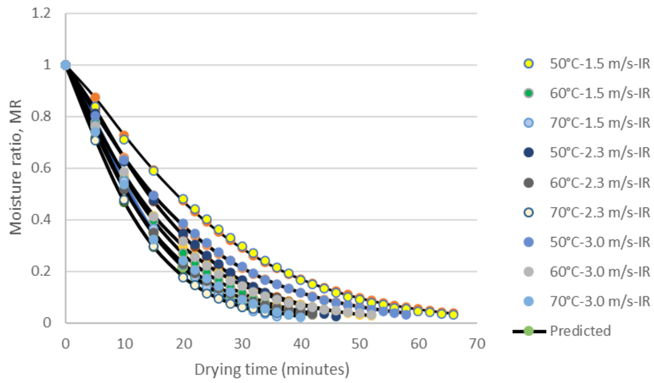

Figure 12. Fitting of drying curves between the measured and predicted MR values from the Page model with drying time at different temperatures and air velocities of infrared drying.

3.4 Effective moisture diffusivity

From the plot of the ln (MR) versus drying time (s), the equations were obtained for convective and infrared drying respectively as shown in Table 6.

For further analysis, the value of effective moisture diffusivity, D_{eff} of each drying method and parameter can be estimated and calculated through the slope of the equation. Figure 13 shows the comparison of effective moisture diffusivity value between convective and infrared drying. It is generally known that during convective drying, the value of D_{eff} increased as air velocity increased at a constant temperature. Interestingly, the D_{eff} was happened to be almost proportionate to the drying time. This is shown by the fact that the drying time was the longest at the lowest value of effective moisture diffusivity (50°C and 1.5 m/s), whereas the drying time was the fastest at the maximum value of D_{eff} at (70°C and 3.0 m/s). Convective drying raised the effective moisture

Table 3. Estimated statistical results obtained from different drying models using convective drying.

Model	Temperature (°C)	Air velocity (m/s)	RMSE	Chi-squared, χ^2	R-squared, R^2
Page	50	1.5	0.012471	0.000159	0.997391
	60		0.023204	0.000560	0.992845
	70		0.023245	0.000574	0.994088
	Average		0.019640	0.000431	0.994775
	50	2.3	0.017177	0.000302	0.995178
	60		0.015433	0.000248	0.996645
	70		0.017912	0.000350	0.996869
	Average		0.016841	0.000300	0.996231
	50	3.0	0.013738	0.000195	0.997093
	60		0.026737	0.000774	0.993047
	70		0.016267	0.000289	0.997453
	Average		0.018914	0.000419	0.995864
Modified page	50	1.5	0.051584	0.002716	0.979861
	60		0.064112	0.004275	0.966589
	70		0.063067	0.004226	0.972315
	Average		0.059588	0.003739	0.972922
	50	2.3	0.050679	0.002633	0.976480
	60		0.046042	0.002208	0.982313
	70		0.052649	0.003024	0.982139
	Average		0.049790	0.002622	0.980311
	50	3.0	0.048426	0.002418	0.980499
	60		0.060229	0.003930	0.975723
	70		0.053447	0.003116	0.982079
	Average		0.054034	0.003155	0.979434
Newton	50	1.5	0.051584	0.002716	0.979861
	60		0.064112	0.004275	0.966589
	70		0.063067	0.004226	0.972315
	Average		0.059588	0.003739	0.972922
	50	2.3	0.050679	0.002633	0.976480
	60		0.046042	0.002208	0.982313
	70		0.052649	0.003024	0.982139
	Average		0.049790	0.002622	0.980311
	50	3.0	0.048426	0.002418	0.980499
	60		0.060229	0.003930	0.975723
	70		0.053447	0.003116	0.982079
	Average		0.054034	0.003155	0.979434
Henderson and Pabis	50	1.5	0.043052	0.001892	0.970303
	60		0.057434	0.003431	0.957725
	70		0.057542	0.003518	0.965925
	Average		0.052676	0.002947	0.964651
	50	2.3	0.050679	0.002633	0.976480
	60		0.041285	0.001775	0.977346
	70		0.048654	0.002582	0.978424
	Average		0.046873	0.002330	0.977417
	50	3.0	0.042298	0.001845	0.973807
	60		0.056347	0.003440	0.971042
	70		0.049168	0.002637	0.978205
	Average		0.049271	0.002641	0.974351

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Table 3 (Cont.). Estimated statistical results obtained from different drying models using convective drying.

Model	Temperature (°C)	Air velocity (m/s)	RMSE	Chi-squared, χ^2	R-squared, R^2
Two-term	50	1.5	0.035578	0.001292	0.979531
	60		0.047164	0.002313	0.971106
	70		0.043720	0.002031	0.979940
	Average		0.042154	0.001879	0.976859
	50	2.3	0.038246	0.001499	0.976552
	60		0.032355	0.001090	0.985776
	70		0.034477	0.001297	0.988864
	Average		0.035026	0.001295	0.983731
	50	3.0	0.033484	0.001156	0.983337
	60		0.044189	0.002115	0.981707
	70		0.033505	0.001225	0.989630
	Average		0.037059	0.001499	0.984891
Logarithmic	50	1.5	0.043052	0.001892	0.970301
	60		0.057434	0.003431	0.957725
	70		0.057542	0.003518	0.965925
	Average		0.052676	0.002947	0.964650
	50	2.3	0.044618	0.002041	0.968555
	60		0.041285	0.001775	0.977343
	70		0.048654	0.002582	0.978424
	Average		0.044852	0.002133	0.974774
	50	3.0	0.042298	0.001845	0.973807
	60		0.056347	0.003440	0.971042
	70		0.049168	0.002637	0.978205
	Average		0.049271	0.002641	0.974351

Table 4. Estimated statistical results obtained from different drying models using infrared drying.

Model	Temperature (°C)	Air velocity (m/s)	RMSE	Chi-squared, χ^2	R-squared, R^2
Page	50	1.5	0.009920	0.000102	0.998618
	60		0.003905	0.000016	0.999824
	70		0.009834	0.000106	0.999072
	Average		0.007886	0.000075	0.999171
	50	2.3	0.010142	0.000109	0.998775
	60		0.001737	0.000003	0.999964
	70		0.004818	0.000025	0.999744
	Average		0.005566	0.000046	0.999494
	50	3.0	0.005865	0.000036	0.999498
	60		0.007026	0.000052	0.999281
	70		0.010711	0.000125	0.998813
	Average		0.007867	0.000071	0.999197
Modified page	50	1.5	0.031879	0.001055	0.992510
	60		0.029073	0.000906	0.994607
	70		0.045559	0.002264	0.987513
	Average		0.035504	0.001408	0.991543
	50	2.3	0.036213	0.001393	0.991296
	60		0.020519	0.000451	0.997059
	70		0.024667	0.000664	0.995868
	Average		0.027133	0.000836	0.994741
	50	3.0	0.018256	0.000348	0.997490
	60		0.018116	0.000345	0.997090
	70		0.034473	0.001296	0.992405
	Average		0.023615	0.000663	0.995662

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Table 4 (Cont.). Estimated statistical results obtained from different drying models using infrared drying.

Model	Temperature (°C)	Air velocity (m/s)	RMSE	Chi-squared, χ^2	R-squared, R^2
Newton	50	1.5	0.031879	0.001055	0.992510
	60		0.029073	0.000906	0.994607
	70		0.045559	0.002264	0.987513
	Average		0.035504	0.001408	0.991543
	50	2.3	0.036213	0.001393	0.991296
	60		0.020519	0.000451	0.997059
	70		0.024667	0.000664	0.995868
	Average		0.027133	0.000836	0.994741
	50	3.0	0.018256	0.000348	0.997490
	60		0.018116	0.000345	0.997090
	70		0.034473	0.001296	0.992405
	Average		0.023615	0.000663	0.995662
Henderson and Pabis	50	1.5	0.028091	0.000819	0.989781
	60		0.025520	0.000698	0.993068
	70		0.041442	0.001874	0.984729
	Average		0.031685	0.001130	0.989192
	50	2.3	0.032095	0.001094	0.988650
	60		0.017978	0.000346	0.996376
	70		0.022469	0.000551	0.995084
	Average		0.024181	0.000664	0.993370
	50	3.0	0.016180	0.000274	0.996587
	60		0.016194	0.000276	0.996522
	70		0.031537	0.001085	0.990710
	Average		0.021304	0.000545	0.994606
Two-term	50	1.5	0.022955	0.000547	0.993010
	60		0.075313	0.006077	0.930391
	70		0.024714	0.000666	0.994411
	Average		0.040994	0.002430	0.972604
	50	2.3	0.038246	0.001499	0.976552
	60		0.006344	0.000043	0.999537
	70		0.003524	0.000014	0.999867
	Average		0.016038	0.000519	0.991985
	50	3.0	0.012284	0.000158	0.997966
	60		0.011067	0.000129	0.998286
	70		0.019820	0.000429	0.996171
	Average		0.014390	0.000238	0.997474
Logarithmic	50	1.5	0.028091	0.000819	0.989780
	60		0.025520	0.000698	0.993067
	70		0.041442	0.001874	0.984729
	Average		0.031685	0.001130	0.989192
	50	2.3	0.032095	0.001094	0.988650
	60		0.017978	0.000346	0.996376
	70		0.022469	0.000551	0.995084
	Average		0.024181	0.000664	0.993370
	50	3.0	0.016180	0.000274	0.996587
	60		0.016194	0.000276	0.996522
	70		0.031537	0.001085	0.990710
	Average		0.021304	0.000545	0.994606

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Table 5. Drying constants of desiccated coconuts from Page model between convective and infrared drying.

Model	Temperature (°C)	Air velocity (m/s)	Infrared drying		Convective drying	
			Model constants			
			k	*n*	*k*	*n*
Page	50	1.5	0.0182	1.2399	0.0023	1.4479
	60		0.0342	1.2190	0.0026	1.5422
	70		0.0275	1.3432	0.0046	1.4995
	50	2.3	0.0241	1.2714	0.0030	1.4348
	60		0.0461	1.1550	0.0060	1.3743
	70		0.0499	1.1808	0.0087	1.3927
	50	3.0	0.0327	1.1330	0.0041	1.4145
	60		0.0410	1.1311	0.0071	1.4387
	70		0.0369	1.2435	0.0084	1.4048

Table 6. Equations for convective and infrared drying within drying parameters.

Drying method	Air velocity (m/s)	Temperature (°C)	Equation	R^2
Convective drying	1.5	50	ln MR = -0.000421x + 0.577883	0.944
		60	ln MR = -0.000654x + 0.675077	0.875
		70	ln MR = -0.000829x + 0.580590	0.922
	2.3	50	ln MR = -0.000483x + 0.556154	0.952
		60	ln MR = -0.000651x + 0.492801	0.943
		70	ln MR = -0.000859x + 0.391169	0.956
	3.0	50	ln MR = -0.000568x + 0.552999	0.945
		60	ln MR = -0.000904x + 0.440417	0.948
		70	ln MR = -0.001024x + 0.671507	0.871
Infrared drying	1.5	50	ln MR = -0.000910x + 0.312522	0.986
		60	ln MR = -0.001377x + 0.240072	0.988
		70	ln MR = -0.001724x + 0.349718	0.973
	2.3	50	ln MR = -0.001291x + 0.358623	0.966
		60	ln MR = -0.001372x + 0.125668	0.998
		70	ln MR = -0.001585x + 0.125480	0.997
	3.0	50	ln MR = -0.000967x + 0.152317	0.994
		60	ln MR = -0.001138x + 0.099777	0.998
		70	ln MR = -0.001543x + 0.280219	0.974

diffusivity of desiccated coconuts from 6.823×10^{-10} to 1.659×10^{-9} m^2/s at a given parameter range, demonstrating that the drying air temperature and air velocity had a significant impact on the moisture diffusivity as described by previous Arrhenius equation. The results were comparable to those of the earlier work on coconut strips conducted at various temperatures and published by (Agarry and Aworanti, 2012). In another attempt, the usage of significantly greater air temperature (120°C) and air velocity was applied to chopped coconut which was also reported by Madhiyanon *et al*. (2009) and as a result, the value of moisture diffusivity turned out to be much higher than this present study. This might be because greater air temperatures would cause water molecules to be more active throughout the drying phase of the desiccated coconuts, leading to higher moisture diffusivity (Hasibuan and Bairuni, 2018; Md Saleh *et al*., 2020).

Similar upward trends in the effective moisture diffusivity value were seen during the infrared drying of desiccated coconuts at constant air velocity and elevated temperature, demonstrating the larger influence of using higher temperatures. However, the trend was different for constant temperature and different air velocities during infrared drying. Figure 13 demonstrates that when air velocity rose from 1.5 to 3.0 m/s, D_{eff} values decreased, especially at constant temperatures of 60°C and 70°C. Given that the samples' temperature is higher than the temperature of the surrounding air, this may be because the samples were cooled by the faster airflow (Younis *et al*., 2018). In comparison, Figure 14 clearly shows that the average effective moisture diffusivity value of infrared drying ($2.144\times10^{-9} \pm 4.496\times10^{-10}$ m^2/s) was greater with significant differences ($p<0.05$) than convective drying ($1.151\times10^{-9} \pm 3.314\times10^{-10}$ m^2/s) within the parameter range. The estimated moisture

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diffusivity values of desiccated coconuts are within the typical range for drying food materials of 10^{-11} to 10^{-9} m^2/s (Madamba, 2003; Kaleemullah and Kailappan, 2006; Agarry and Aworanti, 2012; Isik *et al.*, 2019).

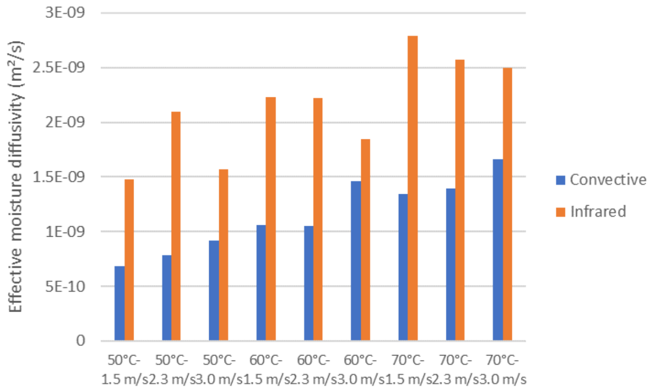

Figure 13. Comparison of effective moisture diffusivity between convective and infrared drying.

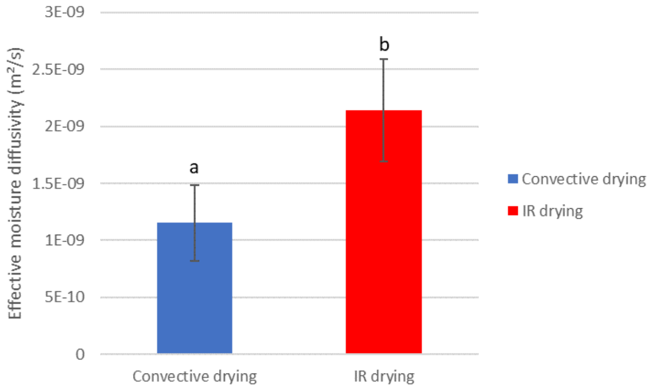

Figure 14. Comparison of effective moisture diffusivity between convective and infrared drying. Bar with different letter differ significantly from each other at $p<0.05$ as determined by ANOVA (Turkey's test).

3.5 Activation energy

As shown in Figures 15 and 16, the plot illustrating the relationship between ln (D_{eff}) and 1/T(K) was discovered to be a straight line within the range of temperatures (50, 60, 70°C) in order to determine the activation energy of desiccated coconuts for both infrared and convective techniques, respectively. The comparison of the effects of air velocity on activation energy is also shown in the plot. The activation energy of desiccated coconuts was in the range (of 9.42 to 29.53 kJ/mol) and (26.54 to 31.32 kJ/mol) for infrared drying and convective drying respectively. These values are within the range of 12 to 130 kJ/mol for food and agricultural products (Delfiya *et al.*, 2021). As far as previous works on far-infrared drying are concerned, the activation energy of mushroom (21.85 kJ/mol), stevia leaves (28.79 kJ/mol), linden leaves (16.339 kJ/mol) and kiwi slices (21.36 kJ/mol) were all in agreement and within the range of this study (Darvishi *et al.*, 2013; Sadeghi *et al.*, 2019; Selvi, 2020; Huang, Yang, Tang *et al.*, 2021). Younis and his colleagues (2018) also studied infrared drying on garlic whereby the activation energy ranged from 3.05 to 45.13 kJ/mol. Meanwhile, the activation energy of chopped coconut (25.92 kJ/mol) dried in a fluidized bed dryer, as reported by Madhiyanon *et al.* (2009) was somewhat close to that of the current study. The activation energy value of beetroot strips (30.08 kJ/mol) utilising convective drying, according to Manjunatha and Raju (2019), was also within the parameters of the current investigation. Of all experiments conducted, convective drying at 1.5 m/s produced the highest activation energy value of 31.32 kJ/mol, whereas infrared drying at 2.3 m/s produced the lowest activation energy value of 9.42 kJ/mol. It is notable that during convective and infrared drying, the activation energy value was highest at 1.5 m/s and lowest at 2.3 m/s. The higher value of activation energy of convective and infrared drying at 1.5 m/s shows that more energy is needed to initiate moisture diffusion and remove the water from white coconut shreds. A greater drying rate is demonstrated by the observation that both drying methods' activation energies decreased when air velocity rose from 1.5 m/s to 2.3 m/s. The activation energy of desiccated coconuts during infrared drying increased with the increase of air velocity from 2.3 m/s to 3.0 m/s. This shows that as air velocity increased, the drying rate reduced as a result of the cooling effect of the sample hence the average energy of the molecules to

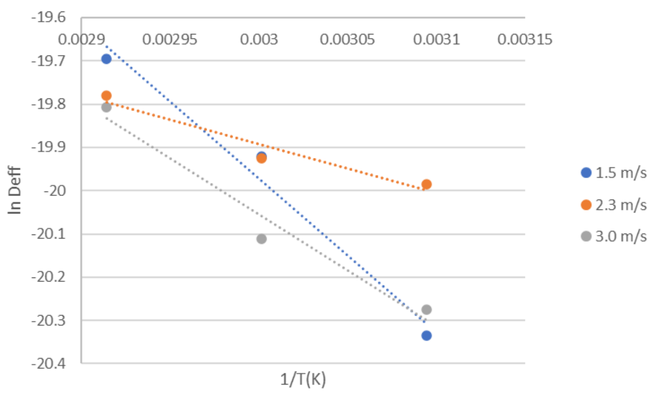

Figure 15. Ln(D_{eff}) versus the reciprocal of the absolute temperature ($1/T_{abs}$) of infrared drying.

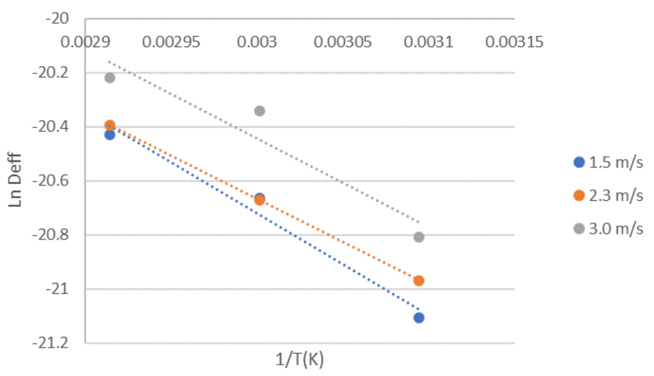

Figure 16. Ln(D_{eff}) versus the reciprocal of the absolute temperature ($1/T_{abs}$) of convective drying.

release the moisture increased. However, a slight increase in activation energy in convective drying from 2.3 to 3.0 m/s may be brought on by hot air making less contact with the sample as a result of higher air velocity and a corresponding decrease in drying rate. According to the activation energy, infrared drying was shown to have higher thermal sensitivity for desiccated coconuts than convective drying, as illustrated in Figure 17.

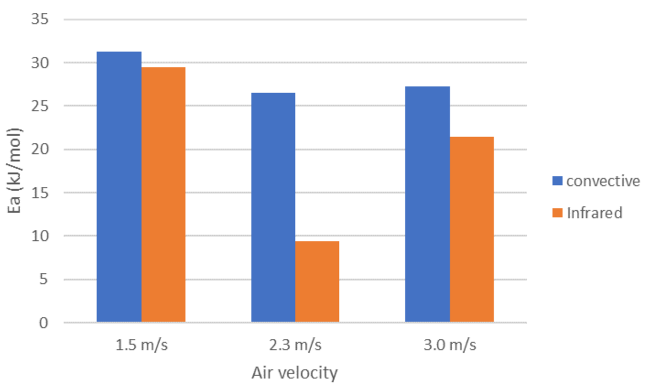

Figure 17. Comparison of activation energy between convective and infrared drying.

3.6 Specific energy consumption

Figure 18 shows the value of energy needed to remove one kilogram of moisture from white coconut shreds for both drying methods at every drying parameter. For convective drying, the minimum specific energy consumption of 64.80 kWh/kg was required to dry one kilogram of white coconut shreds at 70°C and an air velocity of 1.5 m/s whereas a maximum SEC of 112.54 is needed at 70°C and 3.0 m/s. At 50°C and 60°C, the SEC trend continued to decline, indicating that air velocity has a greater impact on energy use since the heated air needs to be continuously moved and recycled. The same phenomenon was also described by Koyuncu and his colleagues (2007) on cornelian cherry fruits. For infrared drying, a minimum SEC of 18.67 kWh/kg was calculated at 70°C and 1.5 m/s while a maximum SEC of 37.72 kWh/kg was recorded at 50°C and 1.5 m/s. The lowest SEC of infrared drying was predominantly caused by the use of a low temperature of 50°C, hence increasing the drying time and specific energy consumption. Nevertheless, the cooling effect on the product temperature which extended the drying time can also be seen as the SEC increased when increasing air velocity. Many studies (El-Mesery and Mwithiga, 2015; EL-Mesery and Mao, 2017; Ye *et al.*, 2021) involved in the infrared drying of agricultural products also experienced and reported the same behaviour. As shown in Figure 19, the average SEC of drying desiccated coconuts can be lowered by up to 71% using infrared drying compared to convective drying, thus the cost of energy could be reduced significantly.

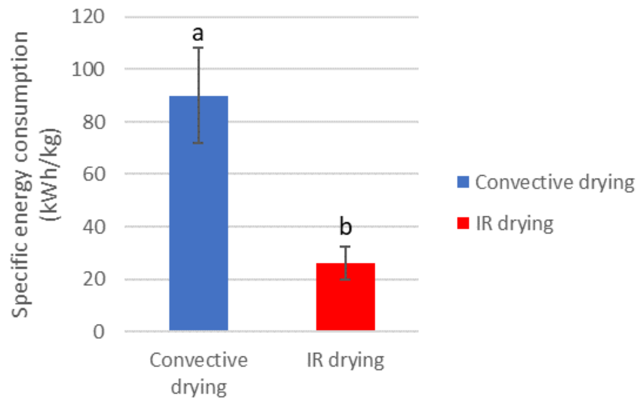

Figure 19. Comparison of specific energy consumption between convective and infrared drying. Bar with different letter differ significantly from each other at $p < 0.05$ as determined by ANOVA (Turkey's test).

4. Conclusion

The comparison concerned modelling, drying kinetics and the amount of energy used to dry white coconut shreds at temperatures between (50 - 70°C) and air velocity between (1.5 - 3.0 m/s). It was concluded that every drying process had shown a falling rate period and the Page model was chosen as the best to describe the drying behaviour of desiccated coconuts in both drying methods. This can be justified by a strong agreement with experimental data obtained from

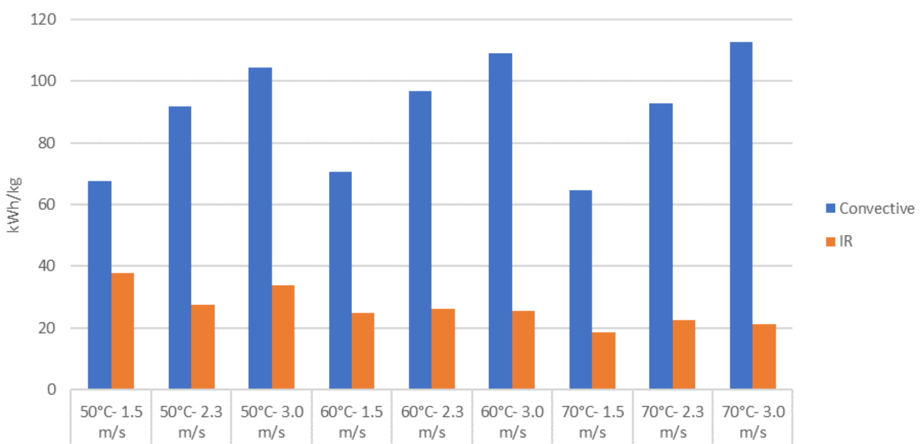

Figure 18. Comparison of specific energy consumption between convective and infrared drying.

experiments. It was discovered that drying techniques had a considerable impact on the drying kinetics and specific energy consumption. The total drying time for desiccated coconuts using convective drying was shortened by about 50% when using infrared drying. In comparison to convective drying, infrared drying produced the highest effective moisture diffusivity values across the whole temperature and air velocity range. Consequently, a lower value of activation energy during infrared drying indicates less amount of energy required for the drying process to happen as opposed to convective drying. Nonetheless, the cooling effect of increased air velocity at a constant temperature during infrared drying led to longer drying times, lower effective moisture diffusivities, and higher activation energies. Infrared drying proved to be more efficient than convective drying with a significant reduction of 71% in specific energy consumption. Overall, it can be concluded that infrared drying offers a better alternative drying method for desiccated coconuts which provides less drying time and energy consumption with higher in mass and heat transfer rate. Future research is recommended to examine the effects of infrared drying optimization on drying time, SEC, and quality attributes of desiccated coconuts.

Conflict of interest

The authors declare no conflict of interest.

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