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Determination of moisture diffusivity and activation energy on fixed bed drying of red pepper (*Capsicum annum*) on convective solar drying

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KEYWORDS

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ABSTRACT

Moisture diffusivity and activation energy are two important variables in a drying process to understand a certain product's drying behavior. This study aimed to determine the value of effective moisture diffusivity and the activation energy of red pepper in a conventional forced convective drying based on electricity (conventional convective drying/CCD) and forced convective drying based on solar energy (convective solar drying/CSD). The value of effective moisture diffusivity was determined using the equation, which refers to Fick's second law. The Arrhenius equation determines the activation energy value as a model of the relationship of inverse temperature and the normal logarithmic value of effective moisture diffusivity. The results showed that the values of effective moisture diffusivity of CCD 70 °C were the highest. The regression analysis between the drying layers (X), and effective moisture diffusivity (Y) showed a polynomial pattern with a coefficient determination R^2 value of 0.85 (CCD 70 °C), 0.81 (CCD 60 °C), 0.88 (CCD 50 °C), and 0.48 (CSD). (R^2) The higher moisture diffusivity values in CCD indicated that the drying systems are more stable than CSD. The drying activation energy calculation showed that the value of CCD's activation energy was 36.36 kJ/mol.K, while the value of CSD's activation energy was 31.28 kJ/mol.K. Those results were consistent with the results of the previous studies.

Introduction

The primary mechanism for drying agricultural products, including horticulture, is a diffusion process in the surface pores of drying material to the air due to concentration difference and capillary action in the granular and tissue material. According to Babu et al. (2018), a drying process removes unbound moisture from the surface, continued by bound moisture from the product interior until it reached its defined limit. This process is influenced by the thermal properties and causing flow hydrodynamics phenomena. The diffusion mechanism as the dominant mechanism in a drying process is a function of moisture content and the drying products' structure. The mechanism would change dynamically along the drying process. The changing pattern can be predicted by developing mathematical drying models (Majdi and Esfahani, 2019). According to Chen et al. (2020) understanding the drying mechanism is essential due to its practical value for optimizing the operational conditions in the drying industry.

Drying rates in horticultural products are constant at the beginning, then decrease and stop at the balancing point of the moisture of material and the air. The implementation of red pepper drying using a solar tunnel dryer carried out by Hossain and Bala (2007) showed a logarithmic function on the relationship between moisture content and drying rate. This function indicated a constant phase at the beginning of drying. Some of the external conditions that influence the diffusion rate are the surface temperature, the airflow dryer, the relative humidity, the drying media, and the dry material's physical form (Majdi and Esfahani, 2019). At the end of the constant period, the water in the material was transferred to the surface by capillary action.

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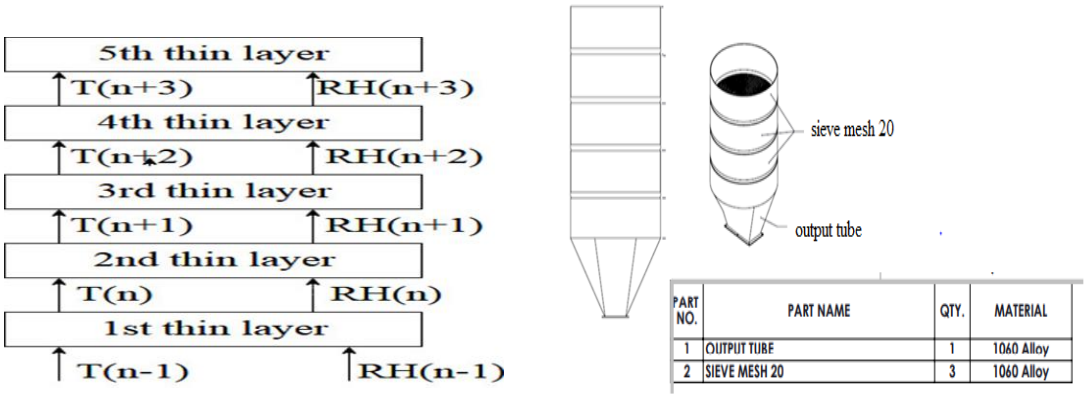


Figure 1. The thick layer drying process modeled as a pile of five thin layers

The drying rates remains constant until the water level reaches a critical point, followed by a decrease in the velocities of drying as the drying process begins. A critical point is the condition of moisture content at which the drying rate first begins to drop (Mujumdar and Dehavastin, 2000). Although in general, the speed of drying is low, the rate of moisture diffusion of the drying material from the inner part to the surface is relatively constant. In this phase, the most dominant diffusion mechanism is the diffusion of fluid due to differences in the concentration of the liquid material (Salehi, 2020). According to Henderson and Perry (1976) in the first stage of drying, liquid diffusion of moisture is the primary mechanism of moisture transport. It continued by vapor diffusion as the dominant mode of moisture diffusion in the latter part of drying. It is also influenced by the material's internal condition, such as the temperature and chemical content of the materials (Natesan et al., 2020). When all the water content on the surface evaporates completely, water vapor diffusion begins as the most dominant diffusion process.

Minaei et al. (2012) stated that moisture diffusivity depends on temperature, the tissue, and the material's structure. The moisture of the dried material decreases alongside with increasing temperature and air velocity of the air chamber. Nagata et al. (2020) explained that the mechanism of mass transfer in biological materials is involved. The dehydration process in the falling rate period is controlled by diffusion (Crank, 1975). Jayatunga and Amarasinghe (2019) stated that the increase in drying temperature would increase the effective moisture diffusivity. According to Zhang et al. (2016) the different coefficients could be determined using Fick's second law. For red pepper, it is assumed that the geometry is in a slab form. The physical and thermal properties of agricultural products are essential information for an ideal dryer design. The value of some moisture diffusivity and energy activation of agricultural products has been conducted by some researchers (Babalis et al., 2017). This study aimed to determine the value of effective moisture diffusivity and the activation energy of red pepper (*Capsicum annum*) in a conventional forced convective drying based on electricity (i.e. conventional convective drying/CCD) and forced convective drying based on solar energy (i.e. convective solar drying/CSD).

Research Methods

Drying Implementation

Red pepper samples were selected manually as they must be homogeneous in size, shape, and color. Each red pepper used in this study had a total weight of 12.95 g, a length of 13.27 cm, and a diameter of 1.72 cm. The red peppers were dried using a convective fixed bed dryer with an experimental apparatus fixed bed dryer at the Post-Harvest and Food process Engineering Laboratory, Universitas Brawijaya,. The temperature applied were 50°, 60°, and 70 °C with 1.8 m/s air flow rates. There were five layers in the drying columns. The thick layer drying process modeled as a pile of 5 thin layers is described in Figure 1. The thickness of each layer was 5 cm, with a 20 cm diameter. Similar steps were taken in the red pepper drying process using a solar dryer based on solar collectors and solar photovoltaic panels consisting of four main parts: a collector, a solar photovoltaic, a drying unit in a silo model, and a blower. This study's measuring tools were a thermometer, hygrometer, lux meter, wind meter, and digital balance.

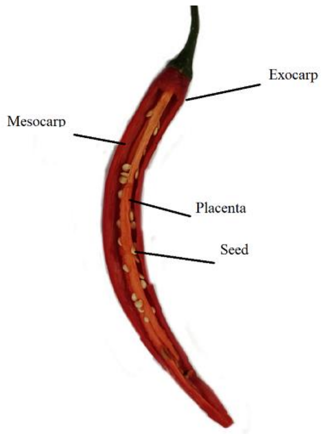


Figure 2. Inner part of red pepper

The solar collector is made from a V-groove iron plate (0.55 mm thick) and painted in black. A 4 mm transparent glass was placed on the absorber's top to create a greenhouse effect in the collector. The drying implementation was conducted on 25−31 July 2018. The intensity of the sunlight gradually increased from 465.6 W/m^2 in the morning to 1131 W/m^2 between 10.00 and 12.00 a.m. The average air temperature was 30.92±3.59 °C, with a relative humidity of 50.08±10.72%. As a comparison, a drying process using the open sun drying (OSD) model was done alongside with CSD application. The temperature of inlet temperature on CSD was 45-55 °C depending on the environmental condition. The airflow of CSD was relatively stable at 3 m/s. OSD drying was accomplished by placing red peppers on a tray and exposing it to direct sunlight.

Determination of Moisture Diffusivity and Energy Activation

Red peppers consist of exocarp, mesocarp placenta/core, and seeds. The largest part of red pepper is exocarp and mesocarp/flesh (90%), while the proportion of placenta and the seed is only 10% (Figure 2). Therefore, those parts determine the value of moisture diffusivity. Mass diffusion occurs during drying from the inside mesocarp into the exocarp's outer layer and from the exocarp to the surrounding environment. In calculating this modeling, red pepper was assumed as a homogeneous slab. Determination of the moisture diffusivity in this study refers to the diffusion equation of Fick's second law (Henderson and Perry, 1976) in a simple form as follows:

$$\frac{M-Me}{M0-Me} = \frac{8}{\pi^2} e[\frac{\text{Deff.t}}{4L^2}] \quad (1)$$

In the form of logarithms, equation (1) can be written as:

$$\ln(\frac{M-Me}{M0-Me}) = ln\frac{8}{\pi^2} - (\frac{\text{Deff.}}{4L^2})t \quad (2)$$

Effective diffusivity value is determined by making data plot of:

$$\ln(\frac{M-Me}{M0-Me}) \quad (3)$$

with time (t), so the slope is obtained that describes the value of K (constant drying)

$$K = \frac{\pi^2 Deff}{4L^2} \quad (4)$$

Where:

M : Moisture content, dry basis after a period of time (%);
M_e : Equilibrium moisture content, determined from the RH of the drying air (%)
M_0 : Moisture content, dry basis at the beginning of the drying period at time zero (%)
L : Half slab thickness (m);
Deff : Moisture Diffusivity (m²/s);
K : Drying Constant ;
T : Time (second).

The activation energy values of drying were determined by the Arrhenius equation (Lopez et al., 2000) as follows:

$$Deff = D_0\, e[\frac{E_a}{RT_a}] \quad (5)$$

Where:

D (0) : Constants diffusivity;
Ea : Energy activation (J/mol);
R : The value of the ideal gas constant (8.1345 J/mol.K);
T : Absolute temperature (K).

The slope of the regression equation between the logarithmic value of *Deff* with 1/T produces an Arrhenius relationship which describes the relationship between the moisture diffusivity with temperature. The Arrhenius equation was used to determine the value of the constant diffusivity and activation energy of each drying system.

Table 1. Moisture diffusivity of Red Peppers in layer 1-5 of Various Drying Model

Drying Model	Layers	Effective Diffusivity (m²/s)
CCD 50 °C	1st layer	6.40943E-09
	2nd layer	6.05727E-09
	3rd layer	6.40943E-09
	4th layer	5.84597E-09
	5th layer	4.76129E-09
CCD 60 °C	1st layer	8.0294E-09
	2nd layer	8.0294E-09
	3rd layer	8.52243E-09
	4th layer	8.31113E-09
	5th layer	7.04333E-09
CCD 70° C	1st layer	1.27484E-08
	2nd layer	1.33119E-08
	3rd layer	1.37345E-08
	4th layer	1.37345E-08
	5th layer	1.06354E-08
CSD	1st layer	7.03629E-09
	2nd layer	7.59976E-09
	3rd layer	6.3883E-09
	4th layer	5.59241E-09
	5th layer	6.44465E-09
OSD		4.12739E-09

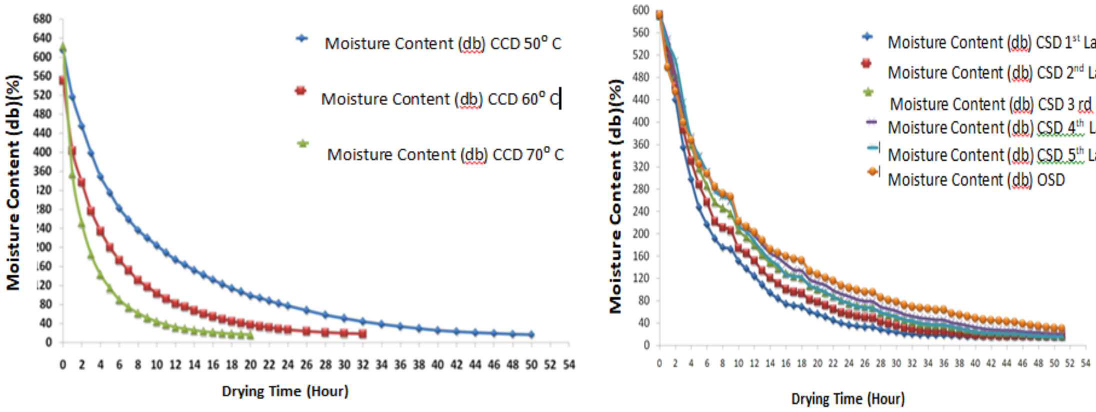


Figure 3. Moisture content decreasing in CCD, CSD, and OSD drying systems

Results and Discussion

Effective moisture diffusivity values at each layer of the drying system were determined using equations 1-3. Table 1 shows that the effective diffusivity values of CSD at all levels are almost equal to the values of CCD 50 °C. This is verified by the data in Figure 3, which indicates that the drying time for CSD is between 50 and 52 hours, approximately identical to the drying time for CCD at 50 °C. Moisture diffusivity of CCD 70 °C was higher than the values of the other drying system. The temperature has a major role in determining the moisture diffusivity of agricultural products. The effective diffusivity values of CCD 50 °C ranged from 4.86 $\times 10^{-9}$– 6.54$\times 10^{-9}$ m² / s, CCD 60 °C ranged between 7.18$\times 10^{-9}$ – 8.69$\times 10^{-9}$ m² / s, CCD 70 °C ranged from 1.08 $\times 10^{-10}$ – 1.4$\times 10^{-8}$ m²/s, CSD 5.70$\times 10^{-9}$ – 7.75 x10^{-9} m²/s. The effective diffusivity value of open sun drying is the lowest (4.21$\times 10^{-9}$ m²/s). This result is slightly lower than the effective moisture diffusivity values (Agarry, 2017), who studied the drying characteristics and kinetics of hot air-drying of unblanched whole red pepper and blanched bitter leaf slices. The result showed that the moisture diffusivity tended to increase with the increase of temperature, which is in collinearly with the study conducted by Jayatunga and Amarasinghe (2019).

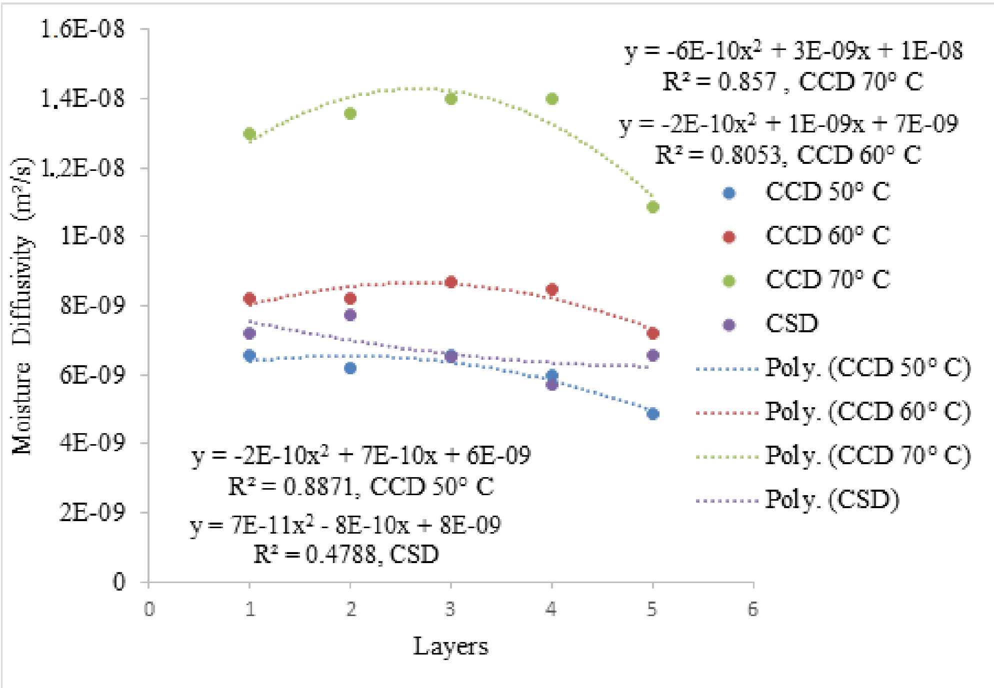
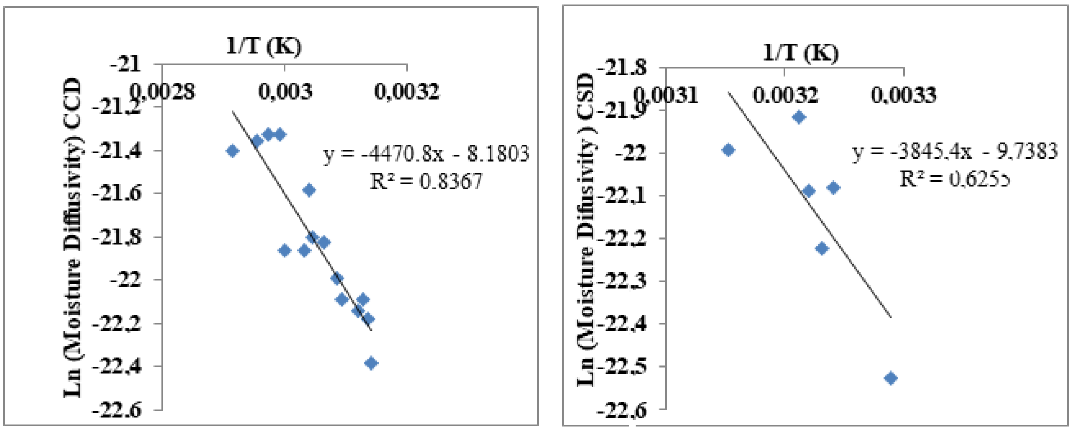


Figure 4. Polynomial relationship of moisture diffusivity and layers position of various drying model



(a) (b)

Figure 5. Arhennius relationship between Ln (*Deff*) and temperature absolute reciprocal value in CCD (a) and CSD (b) drying model.

Figure 4 shows that the relationship between the layers and moisture diffusivity has a polynomial pattern with R^2 value of 0.89 (CCD 50 °C), 0.81 (CCD 60 °C), 0.86(CCD 70 °C), and 0.48 on CSD. The R^2 value on CCD is relatively higher than the CSD. It shows that the CCD drying models are more stable than CSD drying models that rely entirely on drying environmental conditions. The figure also shows that the higher the temperature, the higher the effective diffusivity values are.

The value of the activation energy in the drying was obtained by plotting inlet temperature (1 / T (K)) in each of the drying systems at layers 1-5 and the value Ln (Diff). Figure 5 shows that the activation energy in CCD is 36.36 kJ/mol.K, while the value of the activation energy in the CSD drying system and the OSD is 31.28 kJ/mol.K. Activation energy value of agricultural products drying ranges from 12.7 to 110 kJ/mol.K. Activation energy value obtained in this study is not much different from the results of research by Agarry (2017) and Kaleemullah and Kailappan (2006) on the red pepper drying (37.6 kJ/mol.K) as well as the results obtained by Di Scala and Crapiste (2008) (33.83 kJ/mol). The lower the activation energy value, the higher the material's effective diffusivity value throughout the drying process. According to Olanipekun (2015), the lower the activation energy, the less energy is required to initiate moisture diffusion from integral parts of the material to the material's surface.

Conclusion

A study to determine the moisture diffusivity and activation energy of red pepper drying using conventional convective drying and convective solar drying was carried out on red chilies. The temperatures applied to CCD drying were 50°, 60°, and 70°C. Determination of moisture diffusivity was carried out using Fick's equation. The results showed that the higher the drying temperature, the moisture diffusivity values would be higher. Red peppers dried with CSD have a similar rate of diffusivity with dried red pepper with CCD 50º C. The red peppers dried in the second layer have the highest rate of diffusivity than the layers above or below in CCD drying system. While, red peppers in the second layer of CSD have the lowest moisture diffusivity value.

References

Agarry, S. E. (2017) 'Modelling the drying characteristics and kinetics of hot air-drying of unblanched whole red pepper and blanched bitter leaf slices', *Turkish Journal of Agriculture-Food Science and Technology*, 5(1), pp. 24–32

Babalis, S., Papanicolaou, E., and Belessiotis, V. (2017) *Fundamental mathematical relations of solar drying systems*. Singapore: Springer.

Babu, A. K., Kumaresan, G., Raj, V. A., and Velraj, R. (2018) 'Review of leaf drying: mechanism and influencing parameters, drying methods, nutrient preservation, and mathematical models', *Renewable and Sustainable Energy Reviews*, 90, pp. 536–556

Chen, C., Venkitasamy, C., Zhang, W., Khir, R., Upadhyaya, S., and Pan, Z. (2020) 'Effective moisture diffusivity and drying simulation of walnuts under hot air', *International Journal of Heat and Mass Transfer*, 150, pp. 1-10

Crank, J. (1975) *The mathematics of diffusion.* United Kingdom: Oxford University.

Darvishi, H., Asl, A. R., Asghari, A., Azadbakht, M., Najafi, G., and Khodaei, J. (2014) 'Study of the drying kinetics of pepper', *Journal of the Saudi Society of Agricultural Sciences*, 13(2), pp. 130–138

Di Scala, K., and Crapiste, G. (2008) 'Drying kinetics and quality changes during drying of red pepper', *LWT-Food Science and Technology*, 41(5), pp. 789–795

Henderson, S. M., and Perry (1976) *Agricultural engineering processing*. 3rd Edition. USA: Publishing Company Inc, Westport Conneticut.

Hossain, M.A. and Bala, B.K., (2007). Drying of hot chilli using solar tunnel drier' *Solar energy*, *81*(1), pp.85-92.

Jayatunga, G. K., and Amarasinghe, B. (2019) 'Drying kinetics, quality and moisture diffusivity of spouted bed dried sri lankan black pepper', *Journal of Food Engineering*, 263, pp. 38–45

Kaleemullah, S., and Kailappan, R. (2006) 'Modelling of thin-layer drying kinetics of red chillies', *Journal of Food Engineering*, 76(4), pp. 531–537

Lopez, A., Iguaz, A., Esnoz, A., and Virseda, A. (2000) 'Thin-layer drying behaviour of vegetable wastes from wholesale market', *Drying Technology*, 18(4–5), pp. 995–1006

Majdi, H., and Esfahani, J. A. (2019) 'Energy and drying time optimization of convective drying: taguchi and lbm methods', *Drying Technology*, 37(6), pp. 722–734

Minaei, S., Motevali, A., Ahmadi, E., Azizi, M. H. (2012) 'Mathematical models of drying pomegranate arils in vacuum and microwave dryers', *Journal Of Agricultural Science And Technology*, 14(2), pp. 311-325

Mujumdar, A. S., and Menon, A. S. (1995) *Drying of solids: principles, classification, and selection of dryers*. United States: CRC Press.

Mujumdar, A. S., and Devahastin, S. (2000) *Fundamental principles of drying*. Canada: Exergex.

Nagata, G. A., Costa, T. V., Perazzini, M., and Perazzini, H. (2020) 'Coupled heat and mass transfer modelling in convective drying of biomass at particle-level: model validation with experimental data', *Renewable Energy*, 149, pp. 1290–1299

Natesan, V. T., Mani, P., Prasad, T. J., Krishna, J. M., and Sekar, S. (2020) 'Applications of thin layer modelling techniques and advances in drying of agricultural products', *AIP Conference Proceedings*, 2311(1), pp. 090025

Olanipekun, B. F., Tunde - Akintunde, T. Y., Oyelade, O. J., Adebisi, M. G., and Adenaya, T. A. (2015) 'Mathematical modeling of thin - layer pineapple drying', *Journal of Food Processing and Preservation*, *39*(6), pp.1431-1441

Salehi, F. (2020) ‘Recent applications and potential of infrared dryer systems for drying various agricultural products: a review’, *International Journal of Fruit Science*, 20(3), pp. 586–602

Zhang, Q, A., Song, Y., Wang, X., Zhao, W, Q., and Fan, X, H. (2016) ‘Mathematical modeling of debittered apricot (*Prunus Armeniaca L.*) kernels during thin-layer drying’, *CyTA-Journal of Food*, 14(4), pp. 509–517