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Drying characteristics of robusta coffee beans using YSD-UNIB18 hybrid dryer based on thin-layer drying kinetics fitting model

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Abstract The YSD-UNIB's drying chamber temperature and relative humidity fluctuated changed due to the influence of the temperature of the heat exchanger and water. The temperature of the drying chamber was 38.3-78.6℃, averaging 61.5℃. It reached two times higher than the ambient temperature. The relative humidity of the drying chamber was 10-55%, averaging 17.5%. It reached 3-5 times lower than the relative ambient humidity. The moisture content was 60-65%wb, which was then reduced until it reached less than 12%. The drying time average increased by 25-30% for every increase of 2 cm of coffee thickness. YSD-UNIB18 dried the coffee bean until 33-72 hours for dry-processed coffee and 39-77 hours for semi-washed processed coffee. The drying rate decreased drastically in the first 20 hours and then constant until the end of the drying. The average drying rate decreased by 40-50% for every 20%wb decrease in moisture content. Except for the dry-processed coffee with a thickness of 4 cm, which experienced an average decrease of 28%. The treatment combinations of the coffee drying showed a significant difference in drying time, drying rate, and number of defects in each treatment combination ($p<0.05$). The Page Model is the best model to describe the behavior of coffee bean drying using the YSD-UNIB18 hybrid dryer with the highest R^2 and the lowest of SSE, RMSE, and X^2. Based on SNI 01-2907-2008, the dry and semi-washed processed coffee were in Grade IV and Grade II-III, respectively.

Keywords: Dry-processed; Henderson-Pabis; Newton; Page; Semi-washed processed

Introduction

Indonesia is the fourth largest coffee-producing country in the world after Brazil, Vietnam, and Colombia. In 2022/2023, coffee production in Indonesia was predicted to reach more than 11 million bags of 60 kilograms, coffee exports of more than 7 million bags of 60 kilograms, and total domestic consumption of 4.8 million bags of 60 kilograms. Robusta coffee produced by Indonesia is the third largest in the world, amounting to 10 million 60-Kilogram

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Bags (USDA, 2022). Indonesia's largest Robusta coffee productions are in Bengkulu, South Sumatra, and Lampung (Sustain Coffee, 2018). Besides the large production of robusta coffee in the world, it requires good post-harvest handling. Three main processes separate robusta coffee beans from fruit: dry, washed, and semi-washed (Franca and Oliveira, 2019; Gautz *et al.,* 2008).

Drying is post-harvest handling to maintain shelf life by reducing the moisture content of agricultural products so that enzyme and microbial activity also decrease (Agbede *et al*., 2020; Raaf *et al*., 2022; Strocchi *et al*., 2022). Drying is necessary to maintain coffee quality by inhibiting microbial spoilage and preventing spoilage before storage for further processing (Kulapichitr *et al.*, 2022). Bengkulu province's residents mostly use the traditional drying of coffee with sun drying which requires sufficient land to accommodate the coffee to be dried and is very dependent on sunlight and changes in weather so that the temperature and humidity are uncertain. The moisture content of coffee becomes non-uniform and causes much loss during the drying process due to dust, insects, and rain (Sastro *et al*., 2014; Yuwana *et al*., 2020). The hybrid dryer is one of the solutions to avoid the problem during sun drying. The hybrid dryer can work using more than one energy, such as biomass, hot water, and Liquid Petroleum Gas (Deeto *et al*., 2018; Manrique *et al.*, 2020; Shreelavaniya *et al*., 2021; Suherman *et al*., 2020).

Mathematical models can describe the drying process's characteristics (Younis *et al*., 2018). Thin layer mathematical modeling is a simple model that does not involve many parameters and can directly describe the drying process's behavior (Suherman *et al.*, 2020). Many studies have used thin-layer mathematical modeling to describe the behavior of the drying process (Biswas *et al*., 2022; Dasore *et al*., 2020). Newton, Page, and Henderson-Pabis are the commonly used thin-layer mathematical models. These three models can describe changes in moisture content in drying rice, fruit, vegetables, and coffee beans (Behera and Balasubramanian, 2021; Benseddik *et al.*, 2018; Biswas *et al.*, 2022; Kumar *et al*., 2022; Sadaka, 2022; Simha *et al*., 2016).

In a study by Suherman *et al.* (2020), a hybrid dryer produced higher temperatures, reducing the moisture content of the coffee faster. Shreelavaniya *et al.* (2021) also stated that a hybrid dryer solved the environmental pollution problems that interfere with the traditional drying process. According to Deeto *et al.* (2018), a hybrid dryer stored heat energy and used it at night without sunlight. The three studies used Newton, Page, and Henderson-Pabis thin layer mathematical models to describe changes in the water content of coffee with a high R^2 value and a low RMSE value.

The leading equipment of this study was YSD-UNIB18, a drying chamber with a capacity of 2 tons equipped with a chimney, a door, two metal heat collectors, and a glass roof, as shown in Figure 1. It has heat storage so that it can be used not only during the day but also at night. It is electricity free and uses natural solar and wood fuel energies.

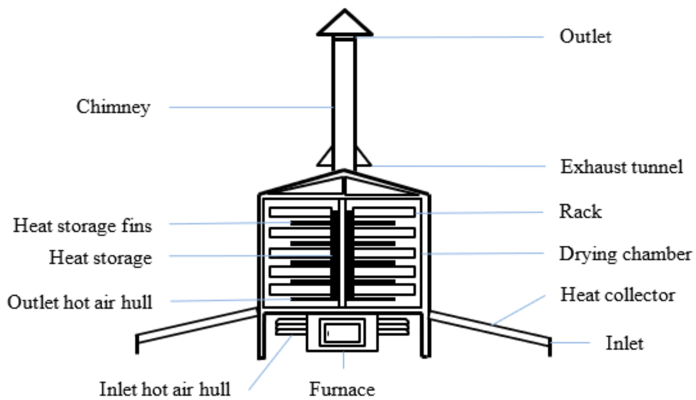


Figure 1. YSD-UNIB18 hybrid dryer

In this study, the YSD-UNIB18 was operated using a combination of solar energy and wood fuel simultaneously with a target temperature of 60-70℃ drying room to dry and semi-washed processed coffee cherries with various layer thicknesses. When it operated with a combination of solar energy and wood fuel, the coffee bean was put into racks and heat it with the solar energy from heat collectors that transferred it to the drying chamber. At the same time, the coffee bean also received heat from the fuel in the furnace. The heat stored in the heat storage was transferred through the heat storage and the heat conducting fins. The coffee bean also received heat from the hot air hull mounted on the furnace wall. The moist air in the coffee was removed from the drying chamber through the chimney. One of the requirements for coffee production in Indonesia is to maintain the physical quality of coffee beans following SNI 01-2907-2008. In this study, observations were made on the drying results using YSD-UNIB18 and the grouping of dried coffee beans based on the grade in the SNI (BSN, 2008).

There has been dound numerous research on the mathematical modeling of hybrid dryers, but not yet on YSD-UNIB18. Since there has been no research on modeling a thin layer of coffee beans on drying using YSD-UNIB18 for dry and semi-washed robusta coffee beans, it is necessary to investigate. The objective of study was to determine the characteristics of dry processed and semi-washed robusta coffee beans, model them with Newton, Page, and

Henderson-Pabis thin layer models, and determine the coffee quality based on the value of coffee defects.

Materials and methods

Time and place

The study was carried out in April 2020 in the Department of Agricultural Technology, Faculty of Agriculture, University of Bengkulu, Bengkulu Province, Indonesia.

Materials

The main ingredients of this study were: a) 200 kg of each dry and semi-washed processed Robusta Coffee from Rejang Lebong district, Bengkulu Province, Indonesia; b) water as the heat storage of the equipment; and c) firewood. The leading equipment of this study was YSD-UNIB18, a drying room with a chimney, a door, and two heat collectors from iron and a roof from glass.

Experimental design

The research was applied by Completely Randomized Design (CRD) with treatment combinations of coffee process and coffee layer thickness. The coffee processes were dry and semi-washed processed coffee. The coffee layer thickness were 4, 8, 12, and 16 cm.

Experimental procedure

The experiment was started by cleaning the drying chamber and putting the thermometer and thermo hygrometer inside and outside the drying chamber. The fruit peel was removed first by a grinder for the semi-washed processed coffee. Both dry and semi-washed processed coffee samples were put in the mesh wire to measure the weight and analyze the coffee's moisture content. The mesh wire is put in the middle of the coffee bed. The samples' moisture contents were analyzed first before the process to know the initial moisture content. The sample scales, temperature, and relative humidity were measured in periodical time. The water content samples for each thickness variation (4, 8, 12, and 16 cm) were weighed using a digital scale every 60 minutes. Air temperature, furnace, heat storage, and relative humidity were observed every

30 minutes. The moisture content of the coffee was analyzed until it reached 12.5%, as recommended by SNI 01-2907-2008 (BSN, 2008).

Analysis

The coffee beans' moisture contents were analyzed with wet-based and dry-based moisture content equations, as shown in Eqs 1:

$$M_{(wb)} = \frac{M_i - M_d}{M_i} x\, 100 \quad (1)$$

$$M_{(db)} = \frac{M_i - M_d}{M_d} x\, 100 \quad (2)$$

where M is moisture content on a wet basis and dry basis, M_i is the initial mass (g), and M_d is the mass after drying (g) (Deeto *et al*., 2018; Suherman *et al.*, 2020).

The coffee bean mass is analyzed the drying rate using Eqs 3:

$$Dr = \frac{M_i - M_d}{t} \quad (3)$$

where Dr is drying rate (g/h), t is drying time (h) (Suherman *et al*., 2020).

The thin-layer drying kinetics fitting models is determined by analyzing the moisture ratio (MR) using Eqs 4:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (4)$$

where M_0 is the initial moisture content, M_t is the moisture content at t time, and M_e is the equilibrium moisture content. However, in this study, having the fluctuating relative humidity for an extended drying time, the moisture ratio is simplified as Eqs 5 (Deeto *et al*., 2018; Huang *et al*., 2022; Shreelavaniya *et al*., 2021; Suherman *et al*., 2020; Susanti *et al*., 2021).

$$MR = \frac{M_t}{M_0} \quad (5)$$

Table 1. Thin-layer drying kinetics fitting models

Model	Model equation	Number equation
Newton	$MR = e^{-kt}$	(6)
Page	$MR = e^{-kt^n}$	(7)
Henderson-Pabis	$MR = a.e^{-kt}$	(8)

The finding used three thin-layer kinetics fitting models for coffee bean drying using a YSD-UNIB18 hybrid dryer, as shown in Table 1 (Agbede *et al*., 2020; Deeto *et al*., 2018; Gaikwad *et al*., 2022; Suherman *et al*., 2020; Susanti *et al*., 2021).

The accuracies of each thin-layer drying kinetics fitting model for the moisture ratio prediction were evaluated by the correlation coefficient (R^2), Sum-Square of Error (SSE), Root Mean Square Error (RMSE), and Chi-Square (X^2), as Eqs 9, 10, and 11 (Gaikwad *et al*., 2022; Huang *et al*., 2022; Shreelavaniya *et al*., 2021; Suherman *et al*., 2020; Susanti *et al*., 2021).

$$SSE = \sum_{i=1}^{n} \left(MR_{exp,1} - MR_{exp,i}\right)^2 \quad (9)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \left(MR_{exp,1} - MR_{pre,i}\right)^2} \quad (10)$$

$$X^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp,1} - MR_{pre,i}\right)^2}{N - z} \quad (11)$$

where MR_{exp}, MR_{pred}, N, and z are experimental moisture ratio, predicted moisture ratio, number of observations, and number of constant.

The number of defects to coffee beans from drying was determined by mixing the coffee bean sample, scaling the 300 grams weight, and counting the number of coffee defects. The investigation was classified according to SNI 01-2907-2008. There were some criteria of the defects such as black coffee seed, half black seed, broken black seed, brown seed, broken seed, young seed, one hole seed, and more than one hole seed. It was calculated in each variation to determine the grade of the coffee, as shown in Table 2 (BSN, 2008; Setyani *et al*., 2018).

Table 2. Coffee Quality Grade from SNI 01-2907-2008

Quality Grade	**The Number of Defect Requirement**
Grade I	≤11
Grade II	12 – 25
Grade III	26 – 44
Grade IV	45 – 80
Grade V	81 – 150
Grade VI	151 – 225

Statistical analysis

The data were analyzed using the analysis of variance (ANOVA) at the 5% level. Duncan's New Multiple Range Test (DMRT) was compared the significant differences between treatment combinations with p<0.05 was accepted as statistical differences.

Results

Drying characteristics

The drying time ranges were 32 to 67 hours and 36 to 74 hours for dry and semi-washed processed coffee, respectively. The drying rate ranges were 2.40 to 5.04 g/h and 1.89 to 3.85 g/h for dry and semi-washed processed coffee, respectively. The moisture ratio ranges were 0.06 to 0.14 for all dry and semi-washed processed coffee. The coffee defect ranges were 46.42 to 59.10 and 23.63 to 29.45 for dry and semi-washed processed coffee, respectively. The drying characteristics of robusta coffee beans using the YSD-UNIB18 are shown in Table 3.

Table 3. The drying characteristics of robusta coffee beans using the YSD-UNIB18 hybrid dryer

Coffee process	Coffee layer thickness (cm)	Drying time (h)	Drying rate (g/h)	Moisture ratio	Number of defects
Dry-processed	4	32^{a}	5.04^{h}	0.14	46.42^{b}
	8	54^{b}	3.22^{f}	0.06	50.18^{b}
	12	59^{bc}	2.94^{e}	0.07	59.65^{c}
	16	67^{de}	2.40^{c}	0.07	59.10^{c}
Semi-washed processed	4	36^{a}	3.85^{g}	0.09	23.63^{a}
	8	52^{b}	2.71^{d}	0.09	25.35^{a}
	12	64^{cd}	2.22^{b}	0.09	27.70^{a}
	16	74^{e}	1.89^{a}	0.07	29.45^{a}

In the same column, different superscripts show that the values are significantly different at p<0.05 DMRT test.

The profile of temperatures and relative humidity

The heat exchanger reached the temperature of 40.5-104℃, averaging 78.3℃. The water temperature was 45.8-117.6℃, averaging 80.2 ℃ (Figure 2). The temperature of the drying chamber was 38.3-78.6℃ which averaged of 61.5℃. The relative humidity of the drying chamber was 10-55% which averaged of 17.5%. The ambient temperature was 26.1-35.4℃ which averaged of 30.6°C. The relative ambient tehumidity was 43-89% which averaged of 65.1%.

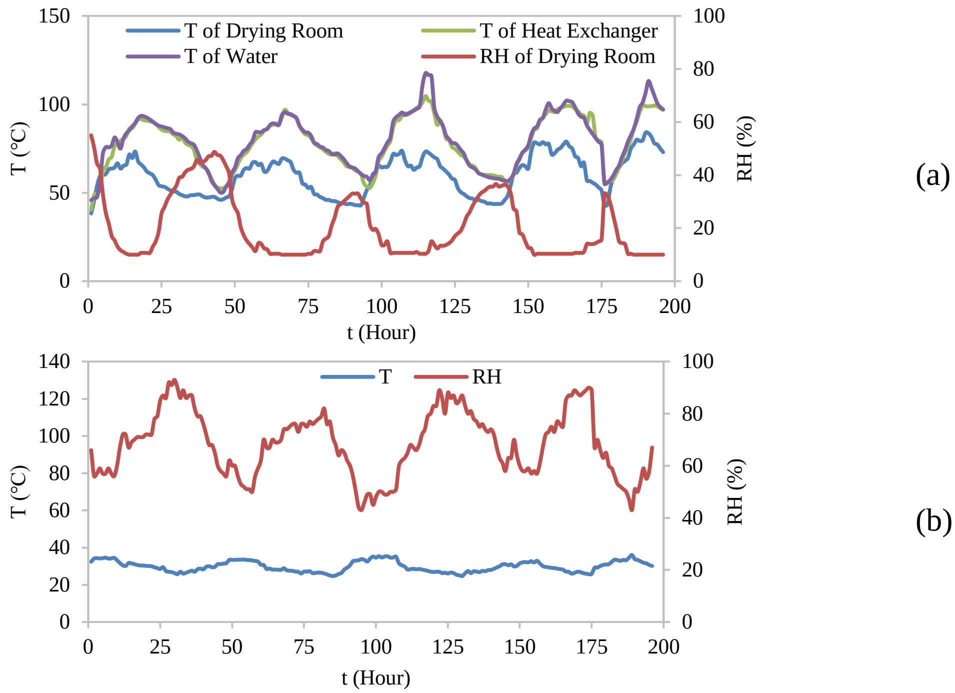


Figure 2. The temperatures and relative humidities during the drying process at (a) YSD-UNIB18 and (b) environment

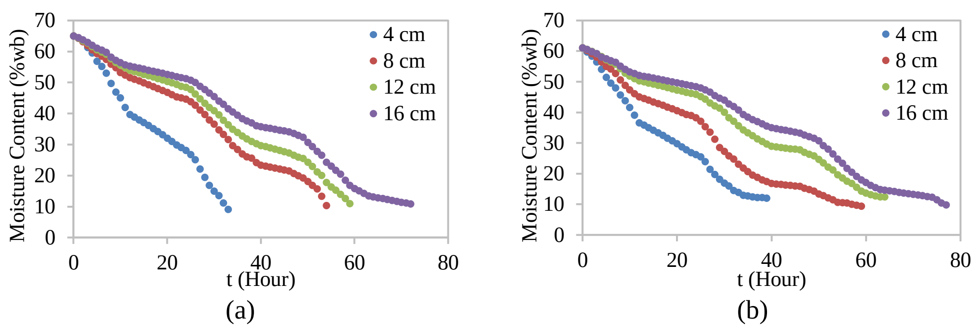
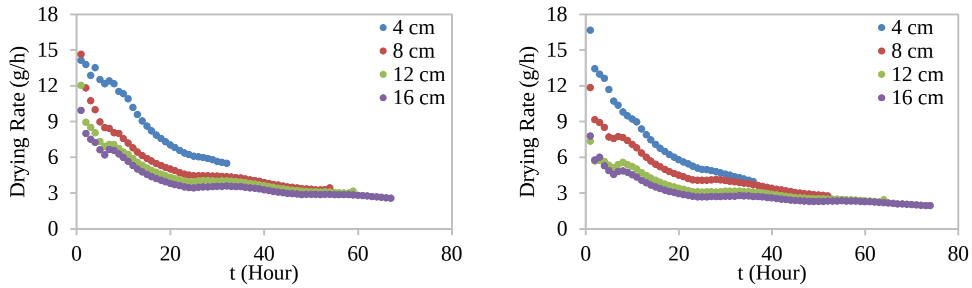


Figure 3. The moisture content versus drying time using YSD-UNIB18 hybrid dryer (a) for dry and (b) semi-washed processed coffee

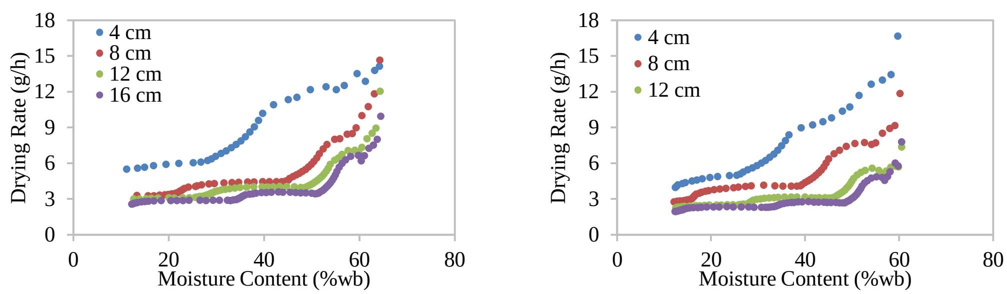
The profile of moisture content and drying rate

The initial moisture content was 60-65%wb, which was reduced until it reached less than 12%. YSD-UNIB18 dried the coffee bean until 33-72 hours for dry-processed coffee and 39-77 hours for semi-washed process coffee Figure 3. The drying rate versus drying time of coffee are shown in Figure 4. The drying rate versus moisture content of coffee during drying are shown in Figure 5.



(a) (b)

Figure 4. The drying rate versus drying time at YSD-UNIB18 (a) for dry and (b) semi-washed processed coffee



(a) (b)

Figure 5. The drying rate versus moisture content at YSD-UNIB18 (a) for dry and (b) semi-washed processed coffee

Mathematical modeling

Newton, Page, and Henderson-Pabis models were analyzed the moisture ratio prediction. The three models produced k, n, and a parameters. The accuracy of the three models was analyzed using R^2, SSE, RMSE, and X^2, as shown in Table 4. The range of R^2 for Newton, Page, and Henderson-Pabis models were 0.9696-0.9893, 0.9775-0.9898, and 0.9596-0.9880, respectively. The ranges of SSE for Newton, Page, and Henderson-Pabis models were 0.0009-0.0034, 0.0000-0.0017, and 0.0000-0.0055, respectively. The range of RMSE for Newton, Page, and Henderson-Pabis models were 0.0315-0.0527, 0.0005-0.0416, and 0.0003-0.0743, respectively. The range of X^2 for Newton, Page, and Henderson-Pabis models were 0.0892-0.6549, 0.0419-0.5894, and 0.0374-0.0711, respectively. The experimental and calculated moisture ratio by the Newton, Page, and Henderson-Pabis models at YSD-UNIB18 are shown in Figure 6.

Table 4. Parameter values from Newton, Page, and Henderson-Pabis models of coffee beans drying

Models	Coffee	Thickness	Parameters			R^2	SSE	RMSE	X^2
			k	n	a				
Newton	Dry Processed	4	0.0734			0.9871	0.0010	0.0318	0.1042
		8	0.0429			0.9860	0.0010	0.0315	0.1544
		12	0.0372			0.9828	0.0015	0.0383	0.2546
		16	0.0330			0.9719	0.0028	0.0527	0.6037
	Semi-washed Processed	4	0.0674			0.9893	0.0009	0.0318	0.0892
		8	0.0474			0.9880	0.0009	0.0315	0.1405
		12	0.0338			0.9821	0.0016	0.0383	0.2650
		16	0.0307			0.9696	0.0034	0.0527	0.6549
Page	Dry Processed	4	0.0464	1.1583		0.9807	0.0017	0.0410	0.1737
		8	0.0416	1.0037		0.9866	0.0009	0.0296	0.1329
		12	0.0321	1.0295		0.9853	0.0010	0.0313	0.0419
		16	0.0271	1.0350		0.9775	0.0017	0.0416	0.5894
	Semi-washed Processed	4	0.0678	1.0065		0.9898	0.0008	0.0291	0.0887
		8	0.0430	1.0269		0.9880	0.0000	0.0005	0.1393
		12	0.0252	1.0700		0.9851	0.0010	0.0319	0.1866
		16	0.0225	1.0619		0.9780	0.0017	0.0409	0.4863
Henderson & Pabis	Dry Processed	4	0.0766		1.0425	0.9875	0.0010	0.0309	0.1081
		8	0.0445		1.0566	0.9848	0.0014	0.0374	0.1709
		12	0.0398		1.1103	0.9793	0.0023	0.0480	0.0374
		16	0.0365		1.1710	0.9637	0.0048	0.0694	0.6427
	Semi-washed Processed	4	0.0650		1.0612	0.9880	0.0034	0.0585	0.2928
		8	0.0478		1.0066	0.9879	0.0000	0.0003	0.1423
		12	0.0363		1.1144	0.9786	0.0023	0.0483	0.2794
		16	0.0343		1.2048	0.9596	0.0055	0.0743	0.7011

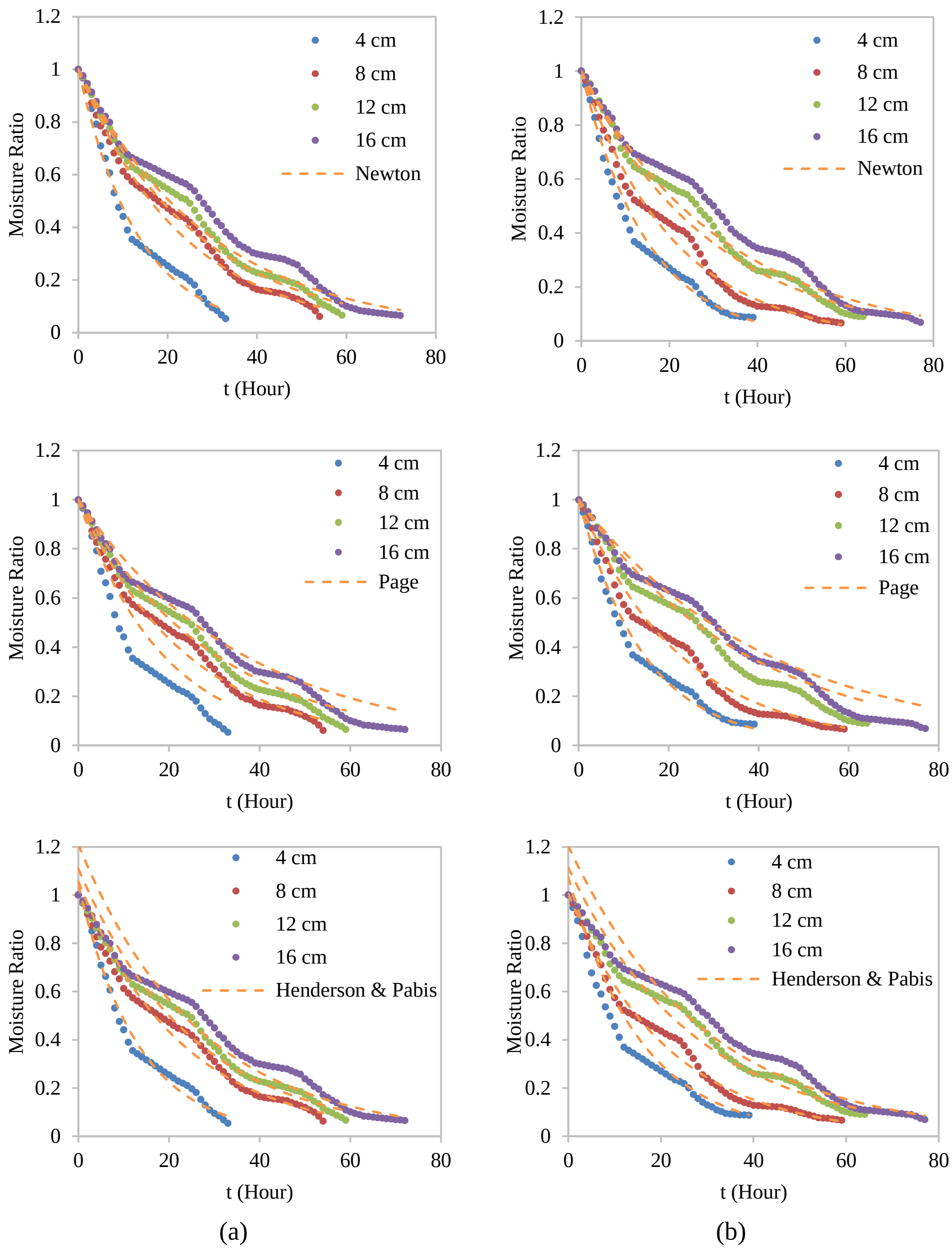


Figure 6. The experimental and calculated moisture ratio by the Newton, Page, and Henderson-Pabis models at YSD-UNIB18 (a) for dry and (b) Semi-washed processed coffee

Discussion

YSD-UNIB18 hybrid dryer produced fluctuating temperature and relative humidity due to the temperature of the water and heat exchanger. The stored heat in the water and heat storage expanded and increased the temperature of the dryer chamber. The temperature increased due to solar energy entering through the roof and dryer wall, heat from the heat collectors, and the combustion process from the furnace, hot hull, and heat conducting fins. It reached two times higher than the ambient temperature. The temperature in the dryer chamber was reduced due to some factors such as weather and time of sunshine. The fluctuating temperature affected the fluctuating humidity. When the temperature was high, the relative humidity was low. The relative humidity reached 3-5 times lower than the relative ambient humidity. The fluctuating temperature and relative humidity in the hybrid dryer were by the previous research conducted by Agbede *et al.* (2020), Chauhan *et al*. (2018), Shreelavaniya *et al.* (2021), and Suherman *et al*. (2020).

The treatment combinations of the coffee drying showed a significant difference in drying time and are shown in different superscripts ($p<0.05$). The drying time average increased 25-30% for every increase 2 cm of coffee thickness. The drying rate decreased drastically in the first 20 hours and then constant until the end of the drying. The average drying rate decreased by 40-50% for every 20%wb decrease in moisture content. Except for the dry-processed coffee with a thickness of 4 cm, which experienced an average decrease of 28%. These phenomena were by the previous research conducted Agarry (2014), Agbede *et al.* (2020), and Mugodo and Workneh (2021). In those studies, the drying time of the thin layer will increase, and the drying rate graphs demonstrated a decreasing drying rate with increasing layer thickness. The greater the thickness of the product, the longer the passage of water vapor will diffuse through the paste to its surface so that the moisture content in the product is removed more quickly through a smaller or thinner layer product.

The treatment combinations of the coffee drying showed a significant difference in drying rate and are shown in different superscripts ($p<0.05$). The drying rate increased in the lower thickness. It was by the previous research conducted by Mugodo and Workneh (2021) that the drying time increased. The drying rate graphs demonstrated a decreasing drying rate with increasing layer thickness. According to Fu *et al*. (2019), the low layer thickness will cause a decrease in moisture migration resistance. The drying rate is related to moisture content. The high moisture content and the low layer thickness will cause a decrease in moisture migration resistance. The drying rate is related to moisture content. With the high moisture content, the drying rate is also high. It was the same as the study by Agbede *et al.* (2020) and Younis (2018), that the drying rate decreased with increasing thickness.

The treatment combinations of the coffee drying showed a not significant difference in moisture ratio ($p<0.05$). The moisture ratio was analyzed to describe the behavior of coffee bean drying using Newton, Page, and Henderson-Pabis Model. The Page Model is the best model to describe the behavior of coffee bean drying using the YSD-UNIB18 hybrid dryer with the highest R^2 and the lowest of SSE, RMSE, and X^2. It was the same as the study from Suherman *et al*. (2020), which had the highest R^2 and lowest average of RMSE to describe the behavior of coffee bean drying using a hybrid dryer.

The treatment combinations of the coffee drying show a significant difference in the number of defects of coffee after drying and are shown in different superscripts ($p<0.05$). The coffee defect value analysis was also carried out by Setyani *et al.* (2018) in the form of black coffee beans, half black beans, broken black beans, cocoa beans, broken beans, young beans, seeds with one hole, and beans with more than one hole. Black beans are usually caused by diseases that attack coffee and can affect pH. Brown beans and holes will affect the taste. The age of the coffee beans causes cracked beans are still too young. Based on SNI 01-2907-2008, the dry and semi-washed processed coffee were in Grade IV and Grade II-III, respectively (BSN, 2008).

In summary, this study shows the signifantly difference of drying times, drying rates, and number of defects in each treatment combination. Thin layer mathematical modeling shows that Page's model best describes the behavior of coffee bean drying using the YSD-UNIB18 hybrid dryer. Based on SNI 01-2907-2008, the dry and semi-washed processed coffee were in Grade IV and Grade II-III, respectively.

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References

Agarry, S. E. (2014). Thin Layer Drying Kinetics and Modelling of Okra (Abelmoschus Esculentus (L.) Moench) Layers under Natural and Forced Convective Air Drying Wetland Treatment of oil refinery wastewaters using marine plants View project, 35-50. https://www.researchgate.net/publication/333172440

Agbede, O. O., Oke, E. O., Akinfenwa, S. I., Wahab, K. T., Ogundipe, S., Aworanti, O. A., Arinkoola, A. O., Agarry, S. E., Ogunleye, O. O., Osuolale, F. N. and Babatunde, K. A.

(2020). Thin layer drying of green microalgae (Chlorella sp.) paste biomass: Drying characteristics, energy requirement and mathematical modeling. Bioresource Technology Reports, 11:100467. https://doi.org/10.1016/j.biteb.2020.100467

Behera, B. and Balasubramanian, P. (2021). Experimental and modelling studies of convective and microwave drying kinetics for microalgae. Bioresource Technology, 340:125721. https://doi.org/10.1016/j.biortech.2021.125721

Benseddik, A., Azzi, A., Zidoune, M. N. and Allaf, K. (2018). Mathematical empirical models of thin-layer airflow drying kinetics of pumpkin layer. Engineering in Agriculture, Environment and Food, 11:220-231.

Biswas, R., Hossain, M. A. and Zzaman, W. (2022). Thin Layer Modelling of Drying Kinetics, Rehydration Kinetics and Color Changes of Osmotic Pre-treated Pineapple (*Ananas comosus*) Layers During Drying: Development of a Mechanistic Model for Mass Transfer. Innovative Food Science and Emerging Technologies, https://doi.org/10.1016/j.ifset.2022.103094

BSN (2008). SNI 01-2907-2008: Biji Kopi. Badan Standarisasi Nasional, 1-16.

Chauhan, P. S., Kumar, A., Nuntadusit, C. and Banout, J. (2018). Thermal modeling and drying kinetics of bitter gourd flakes drying in modified greenhouse dryer. Renewable Energy, 118:799-813.

Dasore, A., Konijeti, R., Tarun, P. N. V. and Puppala, N. (2020). A novel empirical model for drying of root vegetables in thin-layers. International Journal of Scientific and Technology Research, 9:2639-2642.

Deeto, S., Thepa, S., Monyakul, V. and Songprakorp, R. (2018). The experimental new hybrid solar dryer and hot water storage system of thin layer coffee bean dehumidification. Renewable Energy, 115:954-968.

Franca, A. S. and Oliveira, L. S. (2019). Coffee. In *Integrated Processing Technologies for Food and Agricultural By-Products* (pp. 413-438). Elsevier Inc. https://doi.org/10.1016/B978-0-12-814138-0.00017-4

Fu, B. A., Chen, M. Q. and Li, Q. H. (2019). Heat transfer characteristics and drying kinetics of hematite thin layer during hot air convection. Thermochimica Acta, 682. https://doi.org/10.1016/j.tca.2019.178405

Gaikwad, P. S., Sunil, C. K., Negi, A. and Pare, A. (2022). Effect of microwave assisted hot-air drying temperatures on drying kinetics of dried black gram papad (Indian snack food). Applied Food Research, 2:100144.

Gautz, L. D., Smith, V. E. and Bittenbender, H. C. (2008). Measuring Coffee Bean Moisture Content. In *Engineer's Notebook* (pp. 2-4).

Huang, W., Zhang, Y., Qiu, H., Huang, J., Chen, J., Gao, L., Omran, M. and Chen, G. (2022). Drying characteristics of ammonium polyvanadate under microwave heating based on a thin-layer drying kinetics fitting model. Journal of Materials Research and Technology, 19:1497-1509.

Kulapichitr, F., Borompichaichartkul, C., Fang, M., Suppavorasatit, I. and Cadwallader, K. R. (2022). Effect of post-harvest drying process on chlorogenic acids, antioxidant activities and CIE-Lab color of Thai Arabica green coffee beans. Food Chemistry, 366:130504.

Kumar, A., Kandasamy, P., Chakraborty, I. and Hangshing, L. (2022). Analysis of energy consumption, heat and mass transfer, drying kinetics and effective moisture diffusivity during foam-mat drying of mango in a convective hot-air dryer. Biosystems Engineering, 219:85-102.

Manrique, R., Vásquez, D., Chejne, F. and Pinzón, A. (2020). Energy analysis of a proposed hybrid solar–biomass coffee bean drying system. Energy, 202:1-8.

Mugodo, K. and Workneh, T. S. (2021). The kinetics of thin-layer drying and modelling for mango layers and the influence of differing hot-air drying methods on quality. Heliyon, *7*:e07182.

Raaf, A., Putra, T. W., Mulana, F., Syamsuddin, Y. and Supardan, M. D. (2022). Investigation of kinetics of amla (Emblica officinalis) fruit drying process. South African Journal of Chemical Engineering, 41:10-16.

Sadaka, S. (2022). Impact of grain layer thickness on rough rice drying kinetics parameters. Case Studies in Thermal Engineering, 35:102026.

Sastro, S. J., Yuwana, Y. and Silvia, E. (2014). YSD UNIB 12 Solar Dryer Performance for Robusta Caffee Drying. Jurnal Agroindustri, 4:78-85.

Setyani, S., Subeki, S. and Grace, H. A. (2018). Evaluation of Defect Value and Flavour Robusta Coffee (Coffea canephora L.) Pro- duced by Small and Medium Industri Sector of Coffee in Tanggamus District. Jurnal Teknologi & Industri Hasil Pertanian, 23:103.

Shreelavaniya, R., Kamaraj, S., Subramanian, S., Pangayarselvi, R., Murali, S.and Bharani, A. (2021). Experimental investigations on drying kinetics, modeling and quality analysis of small cardamom (Elettaria cardamomum) dried in solar-biomass hybrid dryer. Solar Energy, 227:635-644.

Simha, P., Mathew, M. and Ganesapillai, M. (2016). Empirical modeling of drying kinetics and microwave assisted extraction of bioactive compounds from Adathoda vasica and Cymbopogon citratus. Alexandria Engineering Journal, 55:141-150.

Strocchi, G., Rubiolo, P., Cordero, C., Bicchi, C. and Liberto, E. (2022). Acrylamide in coffee: What is known and what still needs to be explored. A review. Food Chemistry, 393:133406.

Suherman, S., Widuri, H., Patricia, S., Susanto, E. E. and Sutrisna, R. J. (2020). Energy analysis of a hybrid solar dryer for drying coffee beans. International Journal of Renewable Energy Development, 9:131-139.

Susanti, D. Y., Sediawan, W. B., Fahrurrozi, M. and Hidayat, M. (2021). Foam-mat drying in the encapsulation of red sorghum extract: Effects of xanthan gum addition on foam properties and drying kinetics. Journal of the Saudi Society of Agricultural Sciences, 20:270-279.

Sustain Coffee. (2018). Coffee production in the face of climate change: Indonesia. Retried from https://www.sustaincoffee.org/assets/resources/Indonesia_CountryProfile_Climate_Coffee_6-11.pdf

USDA. (2022). Coffee: World Markets and Trade. In *Coffee: World Markets and Trade* (Issue June). Retried from http://apps.fas.usda.gov/psdonline/circulars/coffee.pdf

Younis, M., Abdelkarim, D. and Zein El-Abdein, A. (2018). Kinetics and mathematical modeling of infrared thin-layer drying of garlic layers. Saudi Journal of Biological Sciences, 25: 332-338.

Yuwana, Y., Silvia, E. and Sidebang, B. (2020). Observed performances of the hybrid solar-biomass dryer for fish drying. IOP Conference Series: Earth and Environmental Science, 583(1). https://doi.org/10.1088/1755-1315/583/1/012032

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