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Mathematical modeling of drying behavior of coconut grate in a modified screw mixed dryer

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Abstract. The research aimed to examine the drying behavior of coconut grate in an oil bath pilot-scale modified screw mixed dryer using scientific mathematical models. Various drying temperatures of 80, 85, 90, 95 and 100 °C were used to investigate it using a recognized mathematical model of drying. Exploratory information of moisture ratio, temperature and relative humidity attained from various dryer conditions were fitted to the different experimental drying models. The drying model performances were contrasted based on their correlation coefficient (R^2) between the observed moisture ratios. The result of the research showed that Wang and Singh's model demonstrated the best fit model among the modified screw mixed dryer.

1. Introduction

The largest coconut plantation in the world is located in Indonesia with an area of 3.88 million hectares in which 97% is a people's plantation producing 3.2 million tons of copra. Nevertheless, the export of coconut oil to traditional markets of the USA and EU may be inhibited by the issue of high aflatoxin content in copra and coconut oil processed from copra raw materials [1]. A rapid coconut drying model ought to be constructed to attain a dry white coconut as a raw material for aflatoxin-free coconut oil.

Food properties are changed during the process of drying. The changes include discoloring, aroma loss, textural changes, nutritive value, and there are also changes in physical appearance and shape. Higher drying temperature lessens the drying time; however, it may result in higher energy consumption, heat damage to the surface, and poor product quality. Conversely, lower drying temperatures may enhance the product quality but decrease the drying rate and lengthen the drying period [2]. The absence of heating generates the clear color of pure coconut oil because the hydrolysis and oxidation undergone by the components of carbohydrates, proteins, and fats occurring during heating affect the color of oil [3]. The mathematical models used to describe the drying curve are presented in table 1.

Mathematical models of forced convection solar drying Cuminum cyminum applying the methods of mixed and indirect drying were presented by Zomorodian and Moradi [4]. A non-linear regression analysis technique was used to determine the pertinent coefficients for each model by studying eleven different mathematical models. The best model was selected by considering the high pertinent coefficients. The results showed that the diffusion model with $R2$ = 0.995, $\chi2$ = 0.0023 and RMSE = 0.0199 in mixed mode and the Midilli model with $R2$ = 0.995 $\chi2$ = 0.023 and RMSE = 0.0225 in indirect mode were the best.

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Table 1. Mathematical models of drying curve.

No.	Model Name	Analytical expression	Reference
1	Page	$MR = \exp(-kt^y)$	[5]
2	Handerson and Pabis	$MR = a \exp(-kt)$	[6]
3	Wang and Singh	$MR = 1 + at + Bt^2$	[7]
4	Modified Page	$MR = \exp(-(kt)^y)$	[8]
5	Lewis	$MR = \exp(-kt)$	[9]
6	Logarithmic	$MR = a \exp(-kt) + c$	[10]

The research on drying model was conducted by Kaleta et al. [11], who investigated the drying behavior of apples in a fluidized bed dryer. There were three new types of drying models developed and compared with the accuracy of sixteen models derived from literature. The accuracy of the models was measured based on the correlation coefficient (R^2), root means square error (RMSE), and reduced chi-square (χ^2). In the last part of this study, the proposed model was considered the most suitable model with the value of $R^2 > 0.9977$, RMSE = 0.0094–0.0167, and $\chi^2 = 0.0001–0.0002$.

The research on mathematical modeling of drying was conducted by Kumar et al. [12] on thin layer hot-air drying carrot Pomace. The carrot pomace was dried at the average effective diffusivity values which range from 2.74×10^{-9} to 4.64×10^{-9} m2/sec and the activation energy value that was 23.05 KJ/mole. It was performed at the temperature of 60, 65, 70 and 75 degrees Celsius and carried out at 0.7 m/sec air velocity. The result of the experiment showed that the effective diffusivity increases in line with the increase of drying temperature, while the drying time of the carrot Pomace decrease.

The impacts of drying temperatures of 70, 80, 90 and 100°C by fluidized bed drying technique on dried coconut residue quality change regarding oil content and whiteness value was investigated by Assawarachan [13]. To determine the suitable drying empirical model, four empirical models including Newton, Henderson and Pabis, Page and Midilli et al. were studied. The study concluded that the *Page* model has the highest coefficient of determination (R^2), the least chi (X^2) and the lowest root mean square error. It means that short drying time requires higher drying temperature. The model has shown an excellent fit to predict the drying behavior of the coconut residue. The result of the research showed that based on the valuation of the quality, oil contents of dried coconut residue samples were higher in comparison with that of the fresh residue. Whereas dried coconut residue has the same range of whiteness values as that of fresh residue.

This study focused on the effects of temperature on the drying characteristics and drying time to undertake pilot-scale oil bath mixed drying by selecting a proper mathematical model of mixed drying which describes the drying kinetics of coconut grate.

2. Materials and methods

2.1. Materials

The coconut used in this study was obtained from a local market in Bantul, Yogyakarta, Indonesia. The coconut was broken into pieces and the meat was separated from the shell, washed and cleaned. It was then sliced to remove the tesla and grated by using a grating machine.

2.2. Experimental set-up and procedure

The sample of 3 kg coconut was dried in a pilot-scale mixing dryer. The experiments were performed at drying temperatures of 80, 85, 90, 95 and 100°C, and at a constant mixing velocity of 90 rpm. The coconut residue was dried to reach 0.002 from the initial 1,3 g_{water}/g_{dry} matter moisture contents. The samples were taken periodically in a 10 minutes interval during the drying process. They were subsequently measured and recorded to determine the moisture contents and fit drying models. The drying models adapted for the mixed drying grated coconut were Wang and Singh, Handerson and Pabis and Page models. They were used to obtain experimental drying data at different temperatures.

The non-linear regression was used to determine each constant of the tested models. The coefficient of determination (R^2) was used to evaluate the effectiveness of the model fit. The higher the R^2 the better the model fit [13], [14].

3. Results and Discussion

3.1. Drying process behavior

The initial moisture content (*Mi*) and equilibrium moisture content (*Me*) of coconut residue in the experiment were average 1.3 and 0.002 g_{water}/g_{dry} matter. The time required to dry coconut residue during fixed drying from the initial moisture contents of 1.3 to the final moisture content of 0.001 g_{water}/g_{dry} matter was 140, 120, 110, 110 and 100 minutes at the temperature of 80, 85, 90, 95 and 100°C respectively. As expected, the moisture ratio (*MR*) was rapidly decreasing from the beginning as illustrated in Figure 1. The figure shows the drying curves of coconut residue using mixed dryer at different temperatures under a constant mixing velocity of 90 rpm. The moisture ratio of coconut residue reduced exponentially as the drying time increased. Temperatures had a significant effect on drying. The drying time decreased as drying temperature increased because the increase of the pressure of water vapor within the coconut residue increased moisture removal.

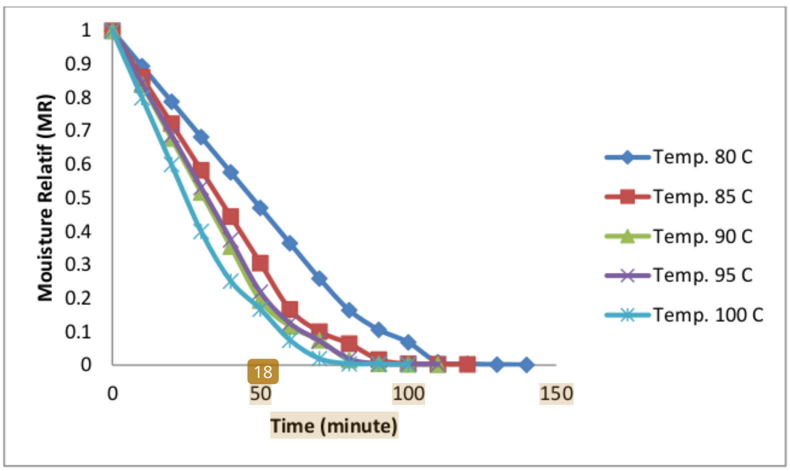

Figure 1. Effect of temperature on moisture ratio of coconut grate residue in the mixed dryer

There was no constant rate drying period in the drying curve of coconut residue during mixed drying. It was found only in the falling rate period. The moisture ratio was found diminished dramatically in the early stage of drying, and eventually changed a bit when it close to the desirable moisture content of around 0,039 g_{water}/g_{dry} matter. It showed that the higher drying temperature, the faster process to dry the sample to the final moisture content of around 0.039 g_{water}/g_{dry} matter. By using the highest level of drying temperature of 100°C, it resulted in the highest drying rate of coconut grate.

3.2. Modeling of Drying Kinetics.

To determine the suitable mathematical modeling that best describes the mixed drying of coconut grate, the non-linear regression analysis was used. Three empirical models were fitted to the drying curve to select the best model to describe it (Table 2). The average moisture content data were observed in g_{water}/g_{dry} matter during mixed drying at various different temperatures.

Table 2. Regression coefficients mixed drying models for coconut grate during mixed drying

Drying Models	Drying temperature	Empirical Drying Model Constants	R^2
Wang and Singh	80	b = -0.0145, c = 4.898x10^{-5}	0.9944
MR = 1+ bt + ct^2	85	b = -0.0191, c = 8.652x10^{-5}	0.9951
	90	b = -0.0215, c = 1.110x10^{-4}	0.9960
	95	b = -0.0211, c = 1.066x10^{-4}	0.9961
	100	b = -0.0240, c = 1.4122x10^{-4}	0.9984
Handerson and Pabis	80	k = 0.0528, a = 0.221	0.8874
MR = a e^{-kt}	85	k = 0.059, a = 0.288	0.9395
	90	k = 0.0698, a = 0.511	0.9435
	95	k = 0.0646, a= 0.298	0.9433
	100	k = 0.0732, a == 0.313	0.9534
Modified Page	80	a = 4.898E-05, b= -1.451E-02, c = 1.043	0.9798
MR = exp(at^2+bt+c)	85	a = 3.844E-04, b = 9.068E-03, c = -0.0785	0.9767
	90	a = 5.124E-04, b = 1.858E-02, c = 9.898	0.9832
	95	a = 3.783E-04, b = 1.918E-02, c = - 2.266	0.9686
	100	a = 4.202E-04, b = 2.695E-02, c = - 2.388	0.9736

The model with the highest value of R^2 was the best model used to describe the mixed drying of agriculture product during mixed drying (Figure 2). The parameters of empirical mathematical model (k, a, b and c) and statistical analysis results were applied to the models by considering air temperatures as presented in Table 2. The table shows that the values of R greater than 0.99 are in Wang and Singh model indicating a good fitting. It means that Wang and Singh's model was the most appropriate model of the three models to predict the moisture contents because it provided the highest value of R^2. Different from the previous studies conducted by some researchers arguing that *Page* model was suitable for describing drying curve in many agricultural materials in laboratory scale, this study found that Wang and Singh's model was the most suitable model in describing the mixed drying behavior of coconut grate in pilot scale.

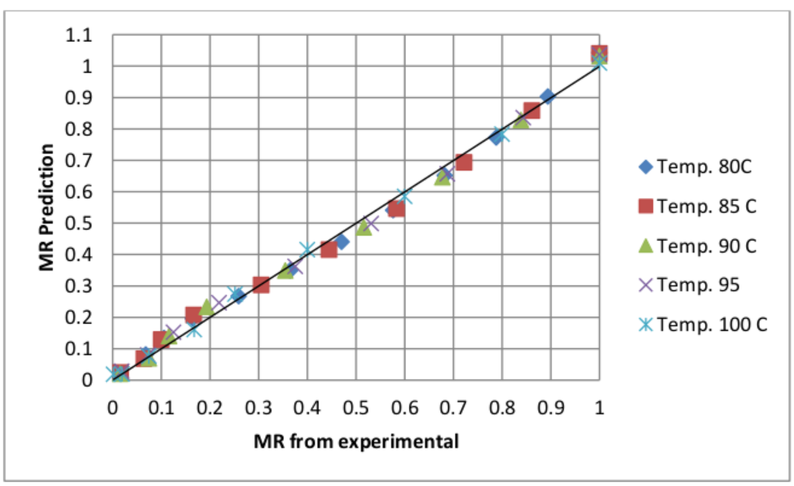

Figure 2. Experimentally determined and predicted moisture ratio of coconut grate during mixed drying

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4. Conclusion.

The effects of the air temperatures on drying characteristics of coconut grate during mixed drying process at different air temperature levels were investigated in the pilot scale. Mathematical modeling for predicting the changes in the moisture contents of coconut residue was successfully developed. The time required to dry coconut grate from initial moisture content of 1,3 to 0.002 g_{water}/g_{dry} was 140, 120, 110, 110 and 100 minutes at the temperature of 80, 85, 90, 95 and 100 °C, respectively. According to these results, the Wang and Singh model was the most suitable model for the description of drying characteristics of coconut grate related to time.

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