Simultaneous Heat and Mass Transfer Analysis on the Drying Process of Coconut Palm Sugar Using Air-oven Dryer

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ABSTRACT

Heat and mass transfer occurred simultaneously during the drying process. Therefore, the drying rate of coconut palm sugar was evaluated by analyzing heat and mass transfer simultaneously using the Runge-Kutta method. In this study, three different temperatures and three various drying loads were carried out to develop a prediction model of moisture content by determining the constant drying rate value. The result showed that the drying rate decreased significantly at the drying temperature of 80ºC according to the drying load, ranging from 1.36 to 0.32 h^{-1}. However, the load of the dryer only causes a slight decrease in drying rate at 60ºC. Furthermore, the developed model based on the simultaneous heat and mass transfer analysis can predict the moisture content of the sample effectively, with the value of correlation coefficient (R^2) over 0.97.

Keywords: *coconut palm sugar, Runge-Kutta method, drying rate*

1. INTRODUCTION

Palm species such as *Cocos nucifera, Arenga pinnata,* and *Borassus flabellifer*, produce higher sugar yields than sugarcane [1]. In Asia, palm sugar has been used as a sweetener for thousand years [2]. Nowadays it gains popularity as consumers try to replace refined sugars with healthier alternatives such as coconut palm sugar. It contains less fructose and has lower glycemic index [3]. Coconut palm sugar is the product of thickening coconut sap in powder form. The sap is heated and evaporated until it becomes thick and crystallizes. The color of sugar varies from light to dark brown [3, 4].

Drying reduces moisture content up to the condition where microorganisms cannot grow, hence it preserved food products for a longer period [5]. Food products have microscopic capillaries which cause a combination of transfer mechanisms to take place simultaneously during heating process between product and air. Mostly the mechanisms are conduction and convection. The convective heat transfer coefficient, h, is an essential parameter in determining drying rate as the temperature difference between product and air depends on this [6].

Determining convective heat transfer coefficient is necessary to evaluate heat transfer model. The value of h is influenced by some factors such as physical properties of fluid, thermal fluid velocity, temperature difference between product and drying medium, as well as characteristics of physical system [7]. Lack of proper knowledge on h value of food products made scientists assume constant value of convective heat transfer coefficient for their analysis and mathematical model which causes inaccurate results [8-10].

Drying rate depends on the rate of two simultaneous processes taking place in drying, which are heat transfer from surrounding environment to evaporate surface moisture and internal transfer moisture to the surface of food material and its evaporation due to the first process [11]. Optimization of drying is necessary to make the process efficient. A lot of numerical modeling has been developed to analyze heat and mass transfer in porous material [12]. The studies such as Feng [13] investigated both transfers during microwave drying, Maran et al. examined prediction of mass transfer

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during papaya drying [14], and Ortiz-Jerez studied heat transfer mechanisms in conductive hydrodrying of pumpkin [15]. There was Grajeda-Gonzalez et al [16] studied corn grain drying modeling by Runge-Kutta method, but to the best of author's knowledge, there has not been a study on analysing heat and mass transfer of coconut palm sugar drying using Runge-Kutta method. The objectives of this study were to simultaneously determine convective heat transfer coefficient and drying rate of coconut palm sugar drying using Runge-Kutta method.

2. METHOD

2.1. Materials

Coconut palm sugar was obtained from local home industry in Kulon Progo regency, Yogyakarta.

2.2. Air-oven dryer

Air oven dryer has principle of blowing air through a heater to dry up coconut palm sap. It consists of 10 shelves as shown in **Figure 1.** It used Liquefied Petroleum Gas (LPG) as a heating source. The air in the dryer was exhaled by the blower through the heater so the water vapor pressure passed across heater would drop. The air then blew and infiltrated the drying chamber through the air holes before moving through the material on each shelf. The water vapor of the material would move into the air because the water vapor pressure of the material was higher than the water vapor pressure of the air. Periodically, the dryer vent was opened to let a circulation between the air in the drying chamber and outside.

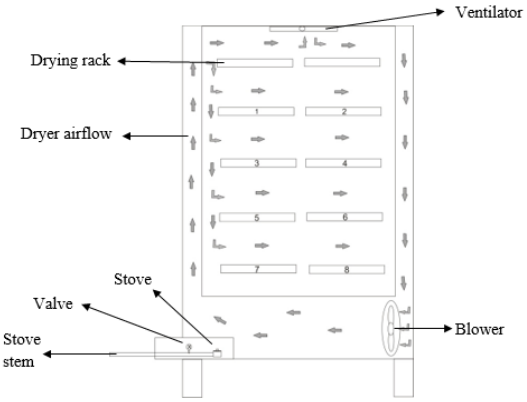

Figure 1 Front view of air oven dryer

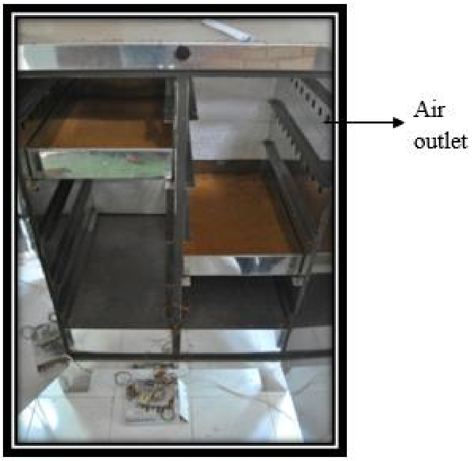

Figure 2 Air oven dryer

2.3. Parameters

Parameters observed were sample temperature, drying air temperature, and changes in the moisture content of the sample every 10 minutes. Three different drying temperatures of 60ºC, 70ºC, and 80ºC were applied in this study and there were three variations of coconut palm sugar drying load, namely 5 kg, 10 kg, and 15 kg. At a drying load of 5 kg, rack 1 and rack 6 were used as drying racks. The 10 kg drying load used 4 shelves of rack 1, rack 4, rack 5, and rack 8. The drying load of 15 kg used 6 shelves which were rack 1, rack 2, rack 3, rack 4, rack 5, rack 8.

2.4. Determination of convective heat transfer coefficient and decrease rate of moisture content

Moisture content of coconut palm sugar was obtained by using thermogravimetric method. In the drying process, heat and mass transfer occur simultaneously therefore the analysis should be also carried out simultaneously with the fourth order Runge-Kutta method as it is the easiest method and has a fairly high level of accuracy. Excel program was involved to run Runge-Kutta method. Changes in temperature and moisture content were taken into account in this method, both shown by Equation (1) and Equation (2).

$$f1 = \frac{\partial \theta}{\partial t} = \frac{1}{\rho_g (C_g + C_w M)} \left[h_a (T - \theta) + h_{fg} \frac{\partial M}{\partial t} \rho_g \right] \tag{1}$$

$$\boldsymbol{f2} = \frac{\partial M}{\partial t} = -\boldsymbol{k}(\boldsymbol{M} - \boldsymbol{M_e}) \tag{2}$$

where T is drying chamber temperature (ºC), θ is coconut palm sugar temperature (ºC), M is moisture content, M_e is equilibrium moisture content, h_a is convective heat transfer coefficient (J/m^{3}sºC), ρ_g is sample density, C_g is specific heat of sample (J/kgºC), C_w is specific heat of water (J/kgºC), hfg is heat of water desorption from free water surface (J/kg)

Equation (1) and Equation (2) were put into fourth-order Runge-Kutta equation to became

$$k1 = \frac{1}{\rho_g\,(C_g + C_w M_0)}\left[h_a(T - \theta) + h_{fg}(-k(M_0 - M_e))\rho_g\right]\Delta t \tag{3}$$

$$k2 = \frac{1}{\rho_g\,(C_g + C_w(M_0 + \frac{l1}{2}))}\left[h_a\left(T - (\theta + \frac{k1}{2}\right) + h_{fg}(-k\left((M_0 + \frac{l1}{2}) - M_e\right))\rho_g\right]\Delta t \tag{4}$$

$$k3 = \frac{1}{\rho_g\,(C_g + C_w(M_0 + \frac{l2}{2}))}\left[h_a + h_{fg}\left(-k\left((M_0 + \frac{l2}{2}) - M_e\right)\right)\rho_g\right]\Delta t \tag{5}$$

$$k4 = \frac{1}{\rho_g\,(C_g + C_w(M_0 + l3))}\left[h_a + h_{fg}(-k((M_0 + l3) - M_e))\rho_g\right]\Delta t \tag{6}$$

$$l1 = -k(M_0 - M_e)\Delta t \tag{7}$$

$$l2 = -k((M_0 + \frac{l1}{2}) - M_e)\Delta t \tag{8}$$

$$l3 = -k((M_0 + \frac{l2}{2}) - M_e)\Delta t \tag{9}$$

$$l4 = -k((M_0 + l3) - M_e)\Delta t \tag{10}$$

$$\Delta T = \frac{1}{6}(k1 + 2k2 + 2k3 + k4) \tag{11}$$

$$T_1 = T_0 + \Delta T \tag{12}$$

$$\Delta M = \frac{1}{6}(l1 + 2l2 + 2l3 + l4) \tag{13}$$

$$M_1 = M_0 + \Delta M \tag{14}$$

Equation (3) to Equation (6) was used to predict temperature at drying chamber at certain time shown by Equation (11). Equation (7) to Equation (10) was applied in determining moisture content of sample at specific time as shown in Equation (14). Based on those data, convective heat transfer coefficient and drying rate constant were determined by inputting the numbers which would generate a model similar to the observed data.

2.5. *Statistical analysis*

SPSS one-way analysis of variance (ANOVA) was used to compare the mean values at $P<0.05$.

3. RESULTS AND DISCUSSION

Heat transfer and mass transfer occurred during drying which affected each other, therefore it is necessary to determine heat transfer coefficient simultaneously. Figure 3 showed changes of sample temperatures and moisture contents during drying process, as well as the results of both predictions generated by Runge-Kutta method. It indicated a similar trend in various drying loads and drying temperatures. As the drying temperature increased, sample temperatures decreased. The increase in the temperature of sample during the process was due to convective heat transfer from the air into the sample.

Meanwhile, the moisture content of the sample tended to decrease over time as there was a difference in the vapor pressure of the environment with the sample, hence the water in the samples came out and evaporated. In Figure 3 (c) to (e), samples dried at higher chamber temperatures needed a shorter time to dry as the difference between water vapor pressure in drying chamber and samples was bigger. Increased drying temperatures rise the amount of water removed, thus reducing the time required to take out the moisture from the sample [17]. Based on Figure 3, the predictive model generated from Runge-Kutta model also looked well-fitted in general for various drying loads and drying temperatures.

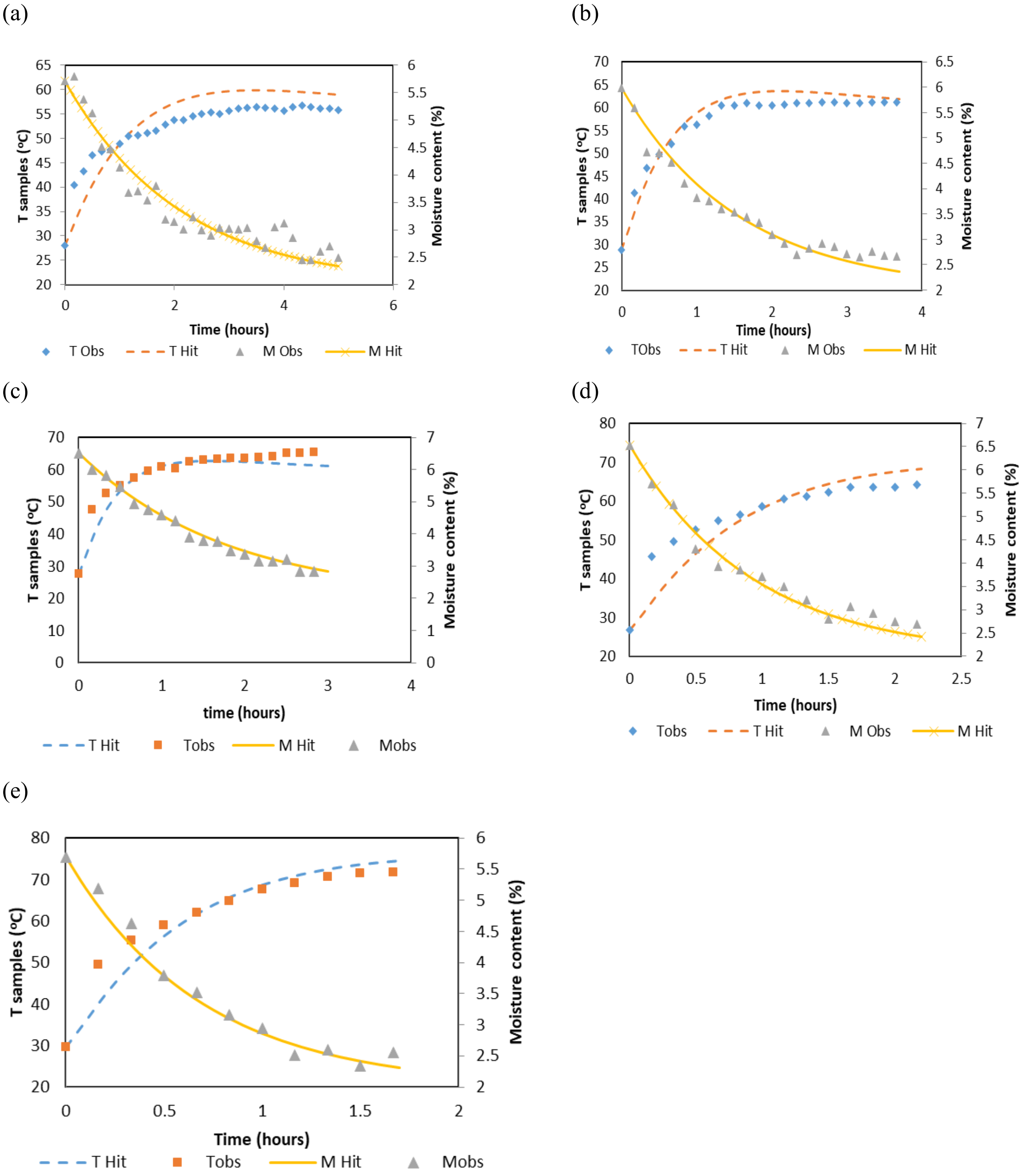

Figure 3. Changes in temperature and moisture content of the samples during drying at (a) drying load of 15 kg at 60ºC (b) drying load of 10 kg at 60ºC (c) drying load of 5 kg at 60ºC (d) drying load of 5 kg at 70ºC (e) drying load of 5 kg at 80ºC

Table 1 showed that rack 1 has the highest value of h in various drying loads and temperatures. Based on statistical analysis, h value on each rack was significantly different. It might be due to the location of rack 1 which was the closest to be exposed to hot air in the drying chamber, hence the velocity of drying air of rack 1 was higher than other racks. It has similar result to study reported by Ateeque et. al where heat transfer coefficient of material surface facing inlet was higher than material surface facing outlet [18]. Moreover, the value of h in this study was observed to vary ranging from 12.89 to 903.99 J/m^2 ºC s at different drying loads and temperatures. The overall h values were bigger at higher temperatures. It is in accordance with Tripathy et. al [19] report which stated higher temperatures difference enhanced heat transfer, thus h value is bigger at higher temperatures. At higher temperature, water vapor around outer surface product had thinner insulation, which created the least resistance to heat transfer [20].

Table 1. Convective heat transfer coefficient on each rack at various drying load and temperature

Drying load	Rack	h (J/m^2 ^{o}C s)		
		60	70	80
5 kg	Rack1	903.99^{p1}	281.12^{r2}	$601.40^{s1,2}$
	Rack6	135.95^{q3}	130.47^{r3}	148.19^{s3}
10 kg	Rack1	$450.10^{b4,5}$	113.59^{d4}	901.31^{e5}
	Rack4	28.61^{a6}	45.59^{c6}	196.51^{f7}
	Rack5	54.40^{a8}	119.80^{d8}	229.44^{f9}
	Rack8	16.52^{a10}	17.58^{c10}	112.64^{f11}
15 kg	Rack1	106.90^{g12}	295.87^{i13}	281.19^{o13}
	Rack2	68.55^{g14}	$133.79^{j14,15}$	193.57^{mn15}
	Rack3	85.81^{g16}	$148.66^{j16,17}$	248.41^{n17}
	Rack4	27.06^{g18}	60.45^{h19}	$41.01^{k18,19}$
	Rack5	103.32^{g20}	141.06^{j20}	139.70^{lm20}
	Rack8	12.89^{g21}	$26.88^{h21,22}$	80.05^{kl22}

The data are presented in means

The different superscripts denote the significantly different ($P \leqslant 0.05$)

Table 2. Drying rate on each shelf in various drying load and temperature

Drying load	Rack	k (/hour)		
		60^{o}C	70^{o}C	80^{o}C
5 kg	Rack1	0.9071^{t1}	0.7251^{s1}	1.3636^{r1}
	Rack6	0.5238^{t2}	0.4163^{s2}	1.1856^{r3}
10 kg	Rack1	0.6542^{pq4}	0.78540^{n4}	1.31110^{k5}
	Rack4	0.6622^{pq6}	0.40300^{o7}	0.85057^{l8}
	Rack5	0.8922^{q9}	0.52627^{no90}	0.99953^{l0}
	Rack8	0.4924^{p10}	0.51670^{no10}	0.62953^{m11}
15 kg	Rack1	0.49757^{ij12}	0.53720^{e12}	1.24843^{a13}
	Rack2	0.36830^{jh14}	0.47723^{efg15}	0.82370^{b16}
	Rack3	0.53697^{i17}	0.51830^{ef17}	0.87777^{b18}
	Rack4	0.36873^{jh19}	0.41760^{g19}	0.71313^{d20}
	Rack5	0.34257^{h21}	0.44213^{fg22}	0.66563^{d23}
	Rack8	0.31697^{h24}	0.39850^{g24}	0.50680^{c25}

The data are presented in means

The different superscripts denote the significantly different ($P \leqslant 0.05$)

Table 1 also showed the homogeneity test of heat distribution in drying chamber and convective heat transfer coefficient. The results were the more heavy the drying load, made the heat distribution was uneven, especially at higher drying temperatures. However, on the drying temperature of 60^{o}C, the heat distribution on all racks was even as shown by statistical number which was not significantly different. An even heat distribution was better process because the granulated sugar would dry at the same time. Uneven heat distribution would reduce the quality of the product as the product was not completely dry. The number of convective heat transfer coefficient affected drying rate of coconut palm sugar.

Table 2 showed the rate of decrease in moisture content which is called the drying rate. The drying rate from various drying loads and drying temperatures ranged from 0.32 to 1.36 h^{-1}. Drying temperature of 80^{o}C had the highest drying rate among drying load groups. This related to smaller water vapor pressure in the drying chamber as drying temperature increased, thus resulting in greater vapor pressure difference between samples and drying chamber. This caused the water within the samples to evaporate faster. Similar results were also reported by Seremet et. al [21], Moreira [22], Rahman and Kumar [23].

Drying rate value of each rack indicated same trend with convective heat transfer coefficient value, which rack 1 had the higher number than other racks. Moreover, it could be seen that the greater the drying loat, the lower the rate of drying on all racks. It is because the greater the drying load, the greater the water vapor that must be evaporated. The homogeneity test as also shown on Table 2 was carried out to determine the uniformity level of drying rate between each rack in one drying process and the uniformity of drying rate at various temperatures on each rack.

Table 3. R-squared test

Temperature (^{o}C)	Drying load (kg)	R^2	
		Temperature of samples	Moisture content of samples
60	5 kg	0.9914	0.9946
	10 kg	0.9917	0.9823

Table 3 showed the validation test of model to predict temperature and moisture content at specific time of coconut palm sugar under the condition of drying temperature 60^{o}C and drying load 5 kg and 10 kg. It illustrated that R^2 values were ranging from 0.98 to 0.99, or close to 1. This indicated that the model can be used to obtain moisture content and temperatures of coconut palm sugar at specific time.

4. CONCLUSION

Drying is a complicated process involving simultaneous heat and mass transfer. Convective heat transfer coefficient (h) of coconut palm sugar at various drying loads (5, 10, 15 kg) and drying temperatures (60,70, 80°C) were ranging from 12.89 to 903.99 J/m^2 °C s. The overall h values were bigger at higher temperatures. h value was used to determine drying rate (k) of coconut palm sugar. The results were 0.32 to 1.36/hour. Drying temperature of 80°C had the highest drying rate. Based on validation test with R-squared on condition of 60°C drying temperature and drying load of 5 and 10 kg, the model could be used to investigate the drying of similar products, or in the design and optimization of the drying

AUTHORS' CONTRIBUTIONS

Rizayu Wulandari performed the experiments (50%). Sri Rahayoe supervised and designed the whole experiments (25%). Hanim Zuhrotul Amanah evaluated the experiments (20%) and Hilda Maya Sintia Dewi was involved in writing the manuscript (5%).

REFERENCES

[1] M. Ishak, S. Sapuan, Z. Leman, M. Rahman, U. Anwar, and J. Siregar, Sugar palm (arenga pinnata): Its fibres, polymers and composites, in: J Carbohydrate Polymers, vol. 91, 2013, pp. 699-710, DOI: https://doi.org/10.1016/j.carbpol.2012.07.073

[2] R. H. P. Low, A. S. Baba, and F. Aboulfazli, Effects of different levels of refined cane sugar and unrefined coconut palm sugar on the survivability of lactobacillus acidophilus in probiotic ice cream and its sensory and antioxidant properties, in: J Food Science Technology Research, vol. 21, 2015, pp. 857-862, DOI: https://doi.org/10.3136/fstr.21.857

[3] J. Wrage, S. Burmester, J. Kuballa, and S. Rohn, Coconut sugar (cocos nucifera l.): Production process, chemical characterization, and sensory properties, in: LWT, vol. 112, 2019, p. 108227, DOI: https://doi.org/10.1016/j.lwt.2019.05.125

[4] H. Aripin, N. Hiron, E. Priatna, N. Busaeri, A. Andang, and S. Sabchevski, Automated temperature control with adjusting outlet valve of fuel in the process of cooking palm sugar, in IOP Conference Series: Materials Science and Engineering, IOP Publishing, Bristol, UK,2018, vol. 336, no. 1, pp. 012-018. DOI: 10.1088/1757-899X/336/1/012018

[5] A. S. Mujumdar and C. L. Law, Drying technology: Trends and applications in postharvest processing, in: J Food Bioprocess Technology, vol. 3, 2010, pp. 843-852, DOI: 10.1007/s11947-010-0353-1

[6] M. Krokida, N. Zogzas, and Z. Maroulis, Heat transfer coefficient in food processing: Compilation of literature data, in: International Journal of Food Properties, vol. 5, 2002, pp. 435-450, DOI: https://doi.org/10.1081/JFP-120005796

[7] R. P. Singh and D. R. Heldman, Introduction to food engineering: Gulf Professional Publishing, 2001.

[8] J. Guzman, A. Lauterbach, and R. Jordan, Method for determining overall performances of solar kilns, 1987,

[9] R. Goyal and G. Tiwari, Heat and mass transfer relations for crop drying, in: Drying Technology, vol. 16, 1998, pp. 1741-1754,

[10] N. Mehrdadi, T. Nasrabadi, H. Hoveydi, and S. JOSHI, Aplication of solar energy for drying of sludge from pharmaceutical industrial waste water and probable reuse, 2007,

[11] A. S. Mujumdar, Handbook of industrial drying: CRC press, 2006.

[12] T. Defraeye, B. Blocken, and J. Carmeliet, Analysis of convective heat and mass transfer coefficients for convective drying of a porous flat plate by conjugate modelling, in: International Journal of Heat Mass Transfer, vol. 55, 2012, pp. 112-124, DOI: https://doi.org/10.1016/j.ijheatmasstransfer.2011.08.047

[13] H. Feng, Y. Yin, and J. Tang, Microwave drying of food and agricultural materials: Basics and heat and mass transfer modeling, in: Food Engineering Reviews, vol. 4, 2012, pp. 89-106, DOI: 10.1007/s12393-012-9048-x

[14] J. P. Maran, V. Sivakumar, K. Thirugnanasambandham, and R. Sridhar, Artificial neural network and response surface methodology modeling in mass transfer parameters predictions during osmotic dehydration of carica papaya l, in: Alexandria Engineering Journal, vol. 52, 2013, pp. 507-516, DOI: https://doi.org/10.1016/j.aej.2013.06.007

[15] M. Ortiz-Jerez and C. Ochoa-Martínez, Heat transfer mechanisms in conductive hydro-drying of pumpkin (cucurbita maxima) pieces, in: Drying Technology, vol. 33, 2015, pp. 965-972, DOI: https://doi.org/10.1080/07373937.2015.1009538

[16] U. F. Grajeda-González, H. Flores-Breceda, J. Aranda-Ruiz, H. R.-F. Vidales-Contreras, and A. I. Luna-Maldonado, Modeling of corn grain drying by runge-kutta method, in: Journal of Experimental Biology, vol. 4, 2016, p. 5, DOI: 10.18006/2016.4(5).462.466

[17] R. Jabeen, T. Aijaz, and K. Gul, Drying kinetics of potato using a self-designed cabinet dryer, in: J Cogent Food Agriculture, vol. 1, 2015, pp. 1-5, DOI: https://doi.org/10.1080/23311932.2015.1036485

[18] M. Ateeque, R. K. Mishra, V. Chandramohan, and P. Talukdar, Numerical modeling of convective drying of food with spatially dependent transfer coefficient in a turbulent flow field, in: International Journal of Thermal Sciences, vol. 78, 2014, pp. 145-157, DOI: http://dx.doi.org/10.1016/j.ijthermalsci.2013.12.003

[19] P. Tripathy, S. Abhishek, and P. Bhadoria, Determination of convective heat transfer coefficient and specific energy consumption of potato using an ingenious self tracking solar dryer, in: Journal of Food Measurement Characterization, vol. 8, 2014, pp. 36-45, DOI: 10.1007/s11694-013-9163-2

[20] K. Neethu, A. Sharma, H. A. Pushpadass, F. M. E. Emerald, and M. Manjunatha, Prediction of convective heat transfer coefficient during deep-fat frying of pantoa using neurocomputing approaches, in: Journal of Innovative Food Science Emerging Technologies, vol. 34, 2016, pp. 275-284, DOI: https://doi.org/10.1016/j.ifset.2016.02.012

[21] L. Seremet, E. Botez, O.-V. Nistor, D. G. Andronoiu, and G.-D. Mocanu, Effect of different drying methods on moisture ratio and rehydration of pumpkin slices, in: Food chemistry, vol. 195, 2016, pp. 104-109, DOI: https://doi.org/10.1016/j.foodchem.2015.03.125

[22] R. G. Moreira, Impingement drying of foods using hot air and superheated steam, in: Journal of Food Engineering, vol. 49, 2001, pp. 291-295, DOI: https://doi.org/10.1016/S0260-8774(00)00225-9

[23] N. Rahman, S. J. E. C. Kumar, and Management, Evaluation of convective heat transfer coefficient during drying of shrinking bodies, vol. 47, 2006, pp. 2591-2601,