Semi empirical modelling for thin sliced potato drying under active-mode indirect solar dryer

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Abstract. This paper aims to select the best semi-empirical model for thinly sliced potato drying under active mode indirect solar dryer with variations of the exhaust air velocities. The exhaust air velocities to remove the vaporized moisture inside the drying chamber were set at 0.2m/s, 0.4m/s, 0.6m/s, and 0.8m/s. The solar intensity, temperature and relative humidity were measured. The Sigmaplot software was used to select the best thin layer drying model for sliced potatoes drying under indirect solar dryer assisted with a solar accumulator and exhaust fan. From the result, drying at 0.2m/s shows a significant drying performance with reduced mass percentages at 69%. The lowest the exhaust air velocity, the better reduction of the mass percentages and the higher the evaporation rate. Consequently, a Rational four (4) parameter was selected as the best of all the drying models, according to r^2, RSME, and x^2. This study gives a useful understanding of the significant effect of the variations of the exhaust air velocities on the drying performance.

1 Introduction

Solar energy is one of the most promising forms of alternative energy. The indirect solar dryer can optimize the solar energy to dry range of agriculture and marine products, such as fruits, fish, and seaweed. Indirect solar dryers are classified into two categories. The first is in active mode, while the second one is in passive mode indirect solar dryer. The active mode indirect solar dryer uses a fan or blower to circulate warm air around the drying chamber, whereas the passive mode indirect solar dryer does not use any additional fan or blower. The passive solar dryer, also known as a natural circulation solar energy dryer, relies on the natural movement of warm air. The active mode of the indirect solar dryer was proven to increase the quality of the final dried products quality. It has a faster drying rate than the passive mode [1]. Active circulation of the warm air inside the drying chamber can help to improve heat transmission through the product inside the drying chamber [2]. The effect of variation of the exhaust air velocity on evaporation rate is explored experimentally in this study.

2 Literature Review

2.1 Solar Drying Process

Solar drying is a method of preservation is widely practiced by farmers to preserve fresh harvested agricultural produces up to a safe moisture content limit. The drying process can minimize storage volume, avoiding waste and microbiological development and providing a longer shelf life for food products [3]. During the drying process, moisture from the inside of the products diffused up to the surface of the product before being evaporated to the surrounding chamber [4]. During the drying process, the airflow and latent heat can raise the vapor pressure over the fresh products that we want to dry before vaporized moisture is exhausted to the environment [5]. The equilibrium moisture content and the drying constant is higher when the drying temperature increase [6]. Drying fresh foods products up to 10% to 20% moisture content can prevent the growth of the bacteria, yeast, mould, and enzyme. The solar dryer is an effective drying method that can maintain the color, taste, and mould count of the final dried products. It is a simple drying system with minimum cost of maintenance for long-term usage.

2.2 The Advantages of the Indirect Solar Dryer (Active Mode)

The common practice of active mode indirect solar dryer is blowing the warm air passing through the product placed onto the drying trays during the drying process [6]. The active mode indirect solar dryer has a significant effect on the reduction of the drying time compared to the traditional drying method with a reduction of drying time at 42.85% [7]. The final food products were considered as clean and had better quality compared to the open sun drying method [1]. The drying time was found to be shorter when drying a variety of range of food products at different air flow rates during

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drying. Furthermore, drying food products at proper drying conditions can provide a longer shelf life of the dried food products. Drying with a solar dryer also provides an efficient energy saving for drying food products [8]. The different percentage of performance for both passive and active modes of indirect solar dryers is 10% [9]. An active mode indirect solar dryer can shorten drying time by up to 60%. It can be equipped with various additional equipment such as a fan or blower, heat exchangers and parameters setting.

2.3 The Material Composition of Potatoes

The material used for this study is potatoes which consist of 63% to 83% of initial moisture content with specific heat and density at 675 kg/m^3 and 3660±447.4 $\text{J}^{\text{kg-1K-1}}$ [10], [11]. Figure 1 shows the configurations setting for data monitoring. The K-Type thermocouple use to measure the temperature, the digital hygrometer uses to measure the relative humidity, the pyranometer data logger use to record the solar radiation and anemometer use to measure the air velocity.

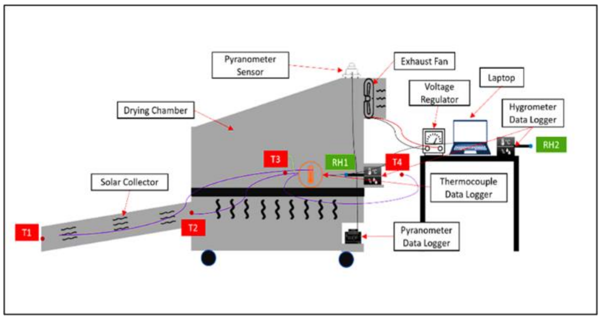


Fig. 1. The configuration setting for data monitoring

3 Materials Preparation

The Potato (Solanum tuberosum) was selected for this study. The fresh potato was bought from. the nearest market in Kota Kinabalu, Sabah, and checked for bruises, spots, and other damages. The fresh potatoes were then cleaned and washed to remove any dirt. The potatoes' skin was peeled and sliced into thin slices at 1.5 mm each of size 2.5 cm × 2.5 cm. Before drying, the hot water blanching treatment was done to remove starch content. The blanched process will remove the starch content that caused blackening at the surface areas of the sliced thin potatoes after the drying process. Hot water blanching treatment of more than 70oC temperature + 2.0 min blanching duration results in optimal potato slice recovery, shrinkage percentage, rehydration ratio, lowering sugar, sucrose, and total phenol [12]. The method of blanched started with soaking the thin sliced potatoes in the boiled hot water for a few minutes. The thin sliced potato was then rinsed and put aside to drying mesh to drain excess water. The thin sliced potato was then sliced into a square mold to create a uniform warm air distribution throughout the drying chamber within the samples at a different set of exhaust air velocities. The initial weight of the thin sliced potatoes before and after drying was recorded for the experiment. The acquired data were plotted using Microsoft Excel for Windows 10 to plot drying curves, drying rate curves, and moisture ratio curves.

3.1 Method of Experimental

The evaluation factors used for this study are the measurement of the drying air temperatures, ambient (surrounding) air temperature, drying chamber relative humidity, ambient (surrounding) relative humidity, moisture content, solar radiation, and exhaust air velocity. Before drying, the mass (g) and thickness (mm) of the thin sliced potatoes were measured using the digital scale and digital vernier calliper. The samples then were then placed onto the drying wire mesh following the set of grids from B_3, B_2, B_1, C_3, C_2, C_1, D_3, D_2 and D_1. The drying tray is placed at the center of the drying chamber for best indication of drying performance. The exhaust air velocity was set at 0.2 m/s, and then the same procedures were repeated for 0.4 m/s, 0.6 m/s and 0.8 m/s. The drying experiment was run from 9.00 am to 6.00 pm for straight 9 hours of drying time for four consecutive days with different exhaust fan speeds. The moisture ratio was calculated from Equation 1 before the dried samples for each drying condition sealed by a vacuum sealer before storage at room temperature [8].

$$\text{MR} = \frac{M - M_e}{m_0 - m_e} \tag{1}$$

or

$$\text{MR} = \frac{M}{m_0} \tag{2}$$

Where M_e is the Equilibrium moisture content, M_o as the Initial moisture content, M as the moisture content of materials. The moisture content can be calculated using equation (5). The average drying rate was analysed following below equation [6]:

$$\text{D} = \frac{M_w Q}{t_d - A_d} \tag{3}$$

D as the average evaporation rate, t_d as the drying time in hours (h) and A_d as the drying area (m^2). The Evaporation Rate equation as following [6]:

$$\dot{m}_{ev} = \frac{m_i - m_f}{t} \tag{4}$$

$\dot{m}_{ev}$ as the evaporation rate (g/hr), m_i as the mass before drying (g), m_f as mass after drying (g) and t as the drying time (hr)

3.2 Moisture Content Analysis

The AOAC traditional method of moisture content analysis (the oven method) is used to determine the initial moisture content of the fresh potatoes. The sample of fresh potato weighed 2 to 5 grams. The measured mass of the sample was then placed onto the petri dish and measured for a second time with petri dish weight before being placed in the oven for three (3) hours straight at 103°C oven temperature. The final moisture content was measured after samples in the petri dish dried. The sample continued to dry in the oven for another one (1) hour and the mass after drying was recorded. The procedure was repeated until the recorded value of mass was constant. (Faculty of Food Science and Nutrition, 2019). The value of moisture content was calculated by following the equation below:

$$\textbf{Moisture Content}\ (\%) = \frac{\boldsymbol{m_i - m_f}}{\boldsymbol{m_i - m_c}}\ \boldsymbol{x\ 100} \tag{5}$$

Where m_i as the initial mass of crucible and sample, m_f as the final mass of crucible and sample and m_c as the mass of crucible. The moisture content of the sample can be calculated using two method including dry basis moisture content (d_b)and wet basis moisture content (w_b). The equation as below (Fudholi et al., 2011):

$$w_b = \frac{w(t) - d}{w} \tag{6}$$

and

$$d_b = \frac{w(t) - d}{d} \tag{7}$$

Where w_b is wet basis, d_b is dry basis, w(t) is mass of sample at any time (t), w is mass of wet material and d is mass of dry material [8]. Equation (8) is for the calculation of Percentage of Mass Reduction & Thickness [12]:

$$\boldsymbol{Shrinkage} = \frac{\boldsymbol{Initial\ Volume\ - Final\ Colume}}{\boldsymbol{Initial\ Volume}}\ \boldsymbol{x\ 100\%} \tag{8}$$

For an analysis of the thin layer drying model of the sample, there are various semi-empirical drying models applicable for drying agricultural and marine produces. The primary criteria for the best-fit drying model can be determined by the value of the determination of coefficient (r^2), root mean square error (RMSE) and reduced-chi square (x^2). The higher the R^2 and the lowest value of RMSE and x^2 indicates the best fit of the drying model [13]:

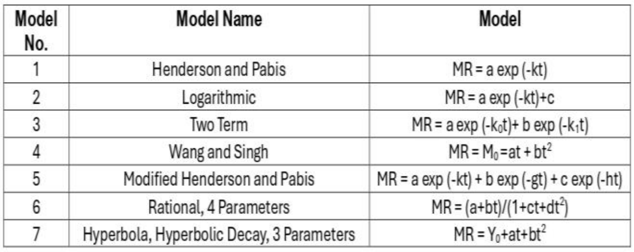
$$\boldsymbol{r^2 = 1 - \frac{SS_{res}}{SS_{tot}}} \tag{9}$$

and

$$x^2 = \sum \frac{(0 - E)^2}{E} \tag{10}$$

Where, the SS_{res} is residual sum of square, SS_{tot} is total of sum of square, O is observed value and E as expected value. As shown in Table 1.1, those listed five (5) drying kinetic models were considered for thin sliced potatoes drying.

Table 1. The thin layer drying kinetic model consider to thin sliced potatoes drying [13]



Model No.	Model Name	Model
1	Henderson and Pabis	MR = a exp (-kt)
2	Logarithmic	MR = a exp (-kt)+c
3	Two Term	MR = a exp (-k_0t)+ b exp (-k_1t)
4	Wang and Singh	MR = M_0=at + bt^2
5	Modified Henderson and Pabis	MR = a exp (-kt) + b exp (-gt) + c exp (-ht)
6	Rational, 4 Parameters	MR = (a+bt)/(1+ct+dt^2)
7	Hyperbola, Hyperbolic Decay, 3 Parameters	MR = Y_0+at+bt^2

3.3 Drying Kinetic Model

During drying, the sample moisture content will gradually decrease over time. The moisture diffused from the inner side towards the surface of the sample during the falling rate period triggered the moisture removal, which reduce mass of the samples. This condition causes the mass transfer of the samples to the surrounding of the drying chamber due to moisture evaporation [13].As listed in Table 1, there are various thin layer drying models, including Henderson and Pabis, Logarithmic, Two Term, Wang and Singh and Modified Henderson and Pabis that can be used to select best drying model to fit the experimental data.

4 Result and Discussion

The data monitoring was performed from 9:00 am until 6:00 pm, during which the experimental location received the maximum solar radiation. Figure 2 shows the recorded value of the mass reduction of the sample (%) against the drying time (hour) at variations of exhaust air velocities. As the drying proceeded, the recorded sample weight was gradually decreased due to loss of moisture. The graph, as shown below, indicates the dependency of the mass reduction on drying temperature and drying time. The curve line indicates a steady decrease in the mass of the samples for all drying conditions. From the analysis of the reduction of mass (%) during the drying process, it was found that drying the thin sliced potatoes at 0.2, 0.4 m/s, 0.6 m/s and 0.8 m/s bring a significant reduction of the percentage of the mass of the samples at 81%, 80%, 80% and 79%. The amount of moisture removed during the drying process was reflected by the initial mass of the sample. The higher the sample mass (g), the higher of the amount moisture removed.

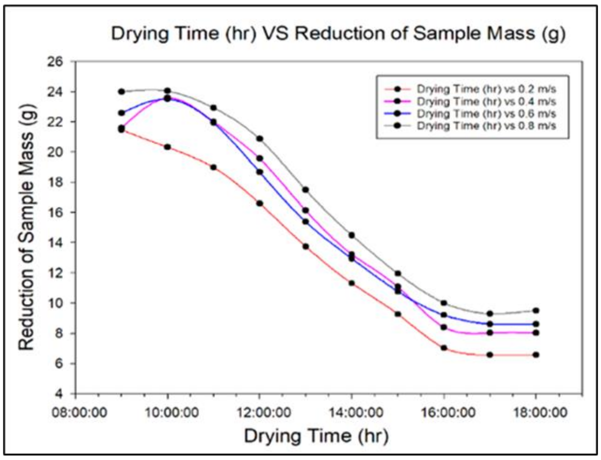


Fig. 2. The reduction of mass of the samples (%) against drying time (hr)

Figure 3 shows that the highest average evaporation rate (g/hr) is 6.08 g/hr at 0.2 m/s exhaust air velocity at 10.00 am. The evaporation rate is closely related to the value of the solar intensity and drying temperature. The intensity of the solar radiation started to increase from 9.00 am to 2.00 pm and began to decline at 4.00 pm. During the drying process, the activation of the kinetic energy is significant to the amount of diffused moisture from the inside up to the surface of the sample. The higher the activated kinetic energy, the higher the amount of moisture diffused from the sample. The statistical analysis result shows a significant relationship between the evaporation rate with the drying temperature and velocity of the air. The lower the air velocity, the higher the evaporation rate. Nevertheless, the opposite result was obtained for an experimental study of the effect of the drying temperature on the drying velocity during the drying process [6]. The drying condition for this study was slightly different from the previous research because we focus on the feasibility study of the performance of the dryer without any additional artificial heater which we solely used a solar accumulator to replace the air heater to supply heat to the drying chamber.

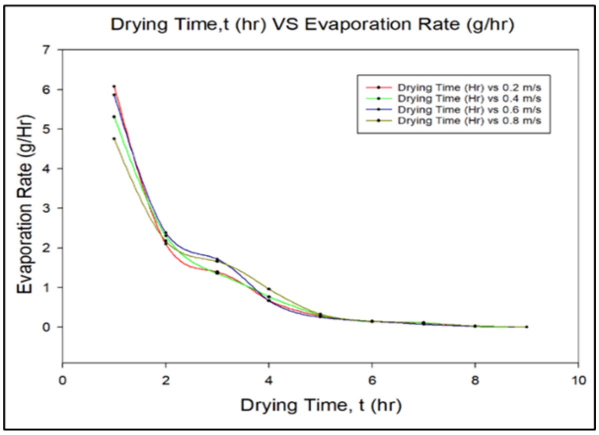


Fig. 3. The evaporation rate (g/hr) against the drying temperatures (^{o}C)

As shown in the curves line for the evaporation rate at 0.2 m/s, the evaporation rates show steady state drying conditions compared to drying at 0.4 m/s, 0.6m/s and 0.8 m/s. As drying proceeded at lower exhaust air velocity, the evaporation rate (g/hr) is steadily declining until the sample was fully dried. The fresh potato has a higher initial moisture content, the evaporation rate is higher at the first hour of drying. A higher drying air temperature can accelerate the kinetic energy of the moisture content of the samples. At higher air temperatures, the molecules of surrounding air inside the drying chamber are expanded, which accelerates the air potential to absorbs water vapor diffused from the wet product. At constant air velocity, the curves line shows a steady state condition which indicates a saturated evaporation rate. The moisture content accelerated diffused from inner to outer surfaces of the thin slices potato before being evaporated to surrounding of the drying chamber then exhausted to outdoor environment. At higher exhaust air velocity, a large amount of air mass flow rate was created surrounding the drying chamber. The warm air exhausted faster from the drying chamber to the outdoor environment at higher exhaust air velocity than drying at lower exhaust air velocity.

The mass of the samples decreased over time since the water content evaporated during drying process. The graph of the drying curve over time as in Figure 4 shows the curve line of the moisture ratio versus drying time at 0.2 m/s, 0.4 m/s, 0.6 m/s, and 0.8 m/s. The lower the exhaust air velocity, the higher the drying constant. At higher air mass flowrate, the amount of air passing through the drying chamber increases. More amounts of air passing through the drying trays, the easier the water vapor is transported from the surfaces of samples to the surrounding of the drying chamber before being exhausted to the outside environment. Nevertheless, it was found that the drying temperatures showed a less significant effect at higher velocities. The higher the air velocity, the lower the temperature. In a study of the thin layer figs drawing, air speeds of more than 2 m/s can be neglected because they have no discernible impact on the drying rate. The air temperature is more significant to the drying kinetic [6].

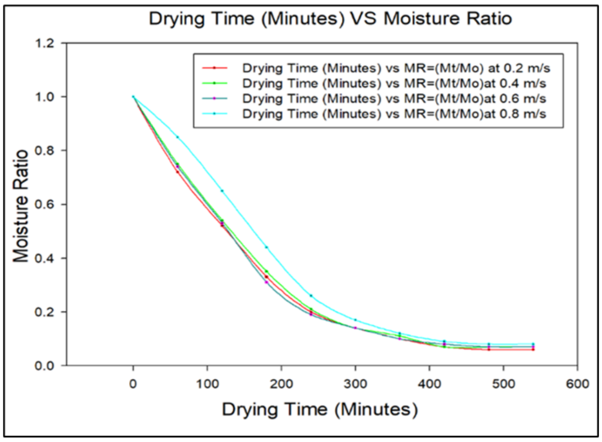


Fig. 4. The moisture ratio against the drying time

As shown in the curves line for the evaporation rate at 0.2 m/s, the evaporation rates show steady state drying conditions compared to when drying at 0.4 m/s, 0.6m/s and 0.8 m/s. As drying proceeded at lower exhaust air velocity, the evaporation rate (g/hr) is steadily declining until the sample was fully dried. The fresh potato has a higher initial moisture content, the evaporation rate is higher at the first hour of drying. A higher drying air temperature can accelerate the kinetic energy of the moisture content of the samples. At higher air temperatures, the molecules of surrounding air inside the drying chamber are expanded, which accelerates the air potential to absorbs water vapor diffused from the wet product. At constant air velocity, the curves line shows a steady state condition which indicates a saturated evaporation rate. The moisture content accelerated diffused from inner to outer surfaces of the thin slices potato before being evaporated to surrounding of the drying chamber then exhausted to outdoor environment. At higher exhaust air velocity, a large amount of air mass flow rate was created surrounding of the drying chamber. The warm air exhausted faster from the drying chamber to the outdoor environment at higher exhaust air velocity than to drying at lower exhaust air velocity.

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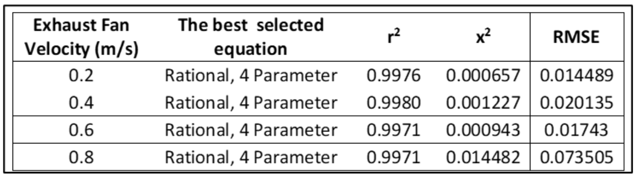
4.1 Drying Efficiency

The percentage difference before and after drying of the sample of thin sliced potato shows that, at lower exhaust fan velocity at 0.2 m/s, the percentage of mass reduction and thickness reduction is higher compared to higher exhaust air velocity at 0.4 m/s, 0.6m/s and 0.8 m/s. At all drying conditions, the reduction of the mass of the fresh thin sliced potatoes is more than 60%.

4.2 Semi Empirical Model (Thin Layer Drying Model)

The result obtained for the moisture ratio for this study was fitted in the selected thin layer drying models are represented in Table 1. The two other general equations were also considered for analysis of the curve fitting of experimental data to the thin layer drying models including, Rational 4 Parameters and Hyperbolic Decay 3 parameters. Table 2 shows the result of curve fitting analysis using the sigma plot software. The best model was selected based on statistical parameters, the lowest value of RMSE and chi square (x^2) and highest r^2 (Nag, S. and Dash, 2016). The best equation fit in the experimental data for thin sliced potatoes drying at variation of exhaust fan velocities at 0.2 m/s, 0.4 m/s, 0.6 m/s and 0.8 m/s grounds of the highest r^2 and lowest RMSE and x^2 was found to be Rational 4 Parameters when drying at 0.2 m/s, 0.4 m/s and 0.6 m/s and Logarithmic drying model when drying at 0.8m/s. A similar basis was used for mathematical modelling of thin layer drying model for elephant apple.

Table 2. The result of best selected equation for thin layer drying model of thin sliced potato



Exhaust Fan Velocity (m/s)	The best selected equation	r^2	x^2	RMSE
0.2	Rational, 4 Parameter	0.9976	0.000657	0.014489
0.4	Rational, 4 Parameter	0.9980	0.001227	0.020135
0.6	Rational, 4 Parameter	0.9971	0.000943	0.01743
0.8	Rational, 4 Parameter	0.9971	0.014482	0.073505

The drying temperatures will influence the heat transfer and moisture diffusivity during the drying process. Increasing the drying temperature can contribute to higher moisture diffusivity and heat transfer. The moisture diffusivity is an indicator of moisture removal from the wet sample. The diffusion mechanism will accelerate the moisture migration from the sample's interior to the surface before uptake into the drying chamber surrounding air. The equilibrium moisture content for each drying material varied inversely with time. In this study, it was found that drying at lower variation of exhaust air velocities can attribute to the higher mass transfer rates at elevated drying temperatures compared to drying at the higher variation of air velocities. As in Figure 4, the moisture ratio data versus drying time was plotted accordingly. From the graph observation, the moisture ratio will decrease concerning drying time.

5 Conclusion

This study evaluate the significant effects of the exhaust air velocity variations on the drying performance and the best thin-layer drying models for drying the thin-slice potatoes drying under active mode indirect solar dryer. The increasing drying temperature and lower air velocity can be attribute to a higher evaporation rate and reduction of the mass of the sample at the elevated drying time. At all drying conditions, the initial evaporation rate is significantly high, but it tends to decrease as the drying proceeded. It is concluded that, drying the thin sliced potatoes at lower velocity at 0.2 m/s using the indirect solar dryer assisted with the solar accumulator under free environment control shows significant reduction of the mass of the samples (g) and higher evaporation rate compared to drying at 0.4 m/s, 0.6 m/s and 0.8 m/s. The result obtained for the selection of the best drying model for thin sliced potatoes drying using the indirect solar dryer assisted with solar accumulator and exhaust fan shows that the highest r^2 and lowest RMSE and x^2 was found to be Rational 4 Parameters when drying at 0.2 m/s, 0.4 m/s and 0.6 m/s and 0.8m/s.

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