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Original Article

Drying characteristics and optimization of time-temperature combination of intermittently dried sweetened jackfruit (*Artocarpus heterophyllus*) pulp

Julious B. Cerna[1*], Jose F. Tarrega IV[2] and Ivy C. Emnace[2]

ABSTRACT

Dehydrated jackfruit pulp processing is an emerging industry in Leyte, Philippines, that still relies on traditional drying methods, resulting in slow production and inefficient energy use. This study investigated the impact of intermittent drying strategies on the drying kinetics and cost efficiency of jackfruit pulp dehydration to improve the processing method of drying jackfruit pulp. A 3×3 factorial experimental design was employed, incorporating three drying temperatures (60°C, 70°C, and 80°C) and three drying-to-tempering period combinations (30:480min, 60:480min, and 90:480min). A control treatment employing a continuous drying treatment at 60°C was also conducted. Experimental results indicated that the Page model is sufficient to describe the drying kinetics of intermittently dried jackfruit pulp. Continuous drying at 60°C achieved only 27% moisture content (wet basis) after 480mins (8h)—substantially higher than the recommended final moisture content of 3%–20% for dehydrated fruits. In contrast, samples subjected to intermittent drying with tempering phases required only 60 to 171mins to reach comparable moisture levels, corresponding to a 64.4% to 87.5% reduction in the overall drying time. The findings demonstrated that a drying schedule consisting of a 30min drying period at 80°C, repeated for two cycles, was most effective for producing sweetened dehydrated jackfruit pulp suitable for storage. This protocol produced a final product with a safe moisture level of 14.3% (wet basis). Each drying run consumed 0.41kg of LPG and 2.01kWh of electricity, resulting in a production cost of PhP171 per kilogram of dried fruit.

Keywords: Intermittent drying, Tempering, Dehydrated jackfruit, Optimization

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[1]Department of Food Science and Chemistry, College of Science and Mathematics, University of the Philippines Mindanao, Mintal, Tugbok District, Davao City, Philippines
[2]Department of Food Science and Technology, Faculty of Agriculture and Food Science, Visayas State University, Baybay City, Leyte

*Corresponding Author. Address: Department of Food Science and Chemistry, College of Science and Mathematics, University of the Philippines Mindanao, Mintal, Tugbok District, Davao City, Philippines; Email: jbcerna@up.edu.ph

INTRODUCTION

In a bid to have healthier and more natural food, consumers have been encouraged to increase their daily intake of fruits and vegetables that are well recognized as low fat suppliers of vitamins, minerals, and fiber (Liu, 2013). However, the water content of most fruits and vegetables is higher than 80% (Shah et al., 2022), which limits their shelf-life and makes them more susceptible to storage and transport problems. Vegetables and fruits can be made more acceptable to consumers by drying (Abonyi et al., 2002). In addition, there is a global market for dehydrated fruits and vegetables (Shams et al., 2024; Testa et al., 2023), which increases the importance of drying for most countries worldwide (Funebo & Ohlsson, 1998).

Jackfruit (*Artocarpus heterophyllus* Lam.), specifically the EVIARC Sweet varieties, is intensively propagated in Leyte, Philippines. This is being processed and commercialized at the Department of Food Science and Technology (DFST), Visayas State University (VSU) into a dehydrated product. The technology was then adopted by local food processors in Mahaplag, Baybay City, and Ormoc City, Leyte (Ngoho et al., 2025). The current drying process, using a food dehydrator, takes 8h for a 10kg load of sweetened pulp to reach a moisture content of 27% (wet basis) prior to sweating. This results in higher production costs, lower production output, and lower product shelf life due to high final moisture content. In the process of drying, heat is required to evaporate moisture from the product and a flow of air is needed to carry away the evaporated moisture, making drying a high energy consuming operation (Jokiniemi et al., 2011). Due to the increasing demands and higher prices of electricity and fuel (Unar et al., 2025), alternative methods for processing and cutting the length of drying time has become very important.

Several drying techniques have been proposed in order to rationalize the use of energy, and to reduce other problems during the drying process, such as cracking, fissure, loss of germination power and vigor of grains and seeds, non-enzymatic browning of fruits and vegetables (Guiné, 2018). These techniques include freeze-drying, vacuum drying, osmotic dehydration (Calín-Sánchez et al., 2020), refractance window drying (Nansereko et al., 2021), and intermittent drying (Barbosa de Lima et al., 2016). Advanced drying technologies like freeze, vacuum, spray, and refractance window dryers are too expensive for micro, small, and medium enterprises (MSMEs) due to high investment costs (Boroze et al., 2014). Improving traditional drying methods with intermittent techniques offers a more affordable alternative. Intermittent drying is a process that alternates drying periods with rest or relaxation periods. The product is subjected to the action of hot air in a drying chamber at regular time intervals, i.e., heat is supplied discontinuously. In the rest period (non-drying, tempering), the product goes through part of the system which does not get heated air, allowing homogenization of moisture and cooling (Dong et al., 2009). Each rest period between two intermittent drying periods is called a 'pass'.

The aim of determining the duration and number of cycles (or tempering) in the intermittent drying process is to minimize costs (energy) and produce a good quality final product (Kowalski & Pawłowski, 2011). Several studies have focused on optimizing dehydrated jackfruit pulp processing, such as Nansereko et al. (2022), who utilized freeze, oven, solar, and refractance window dryers; Tamanna et al. (2023), who employed freeze, cabinet, and vacuum dryers; and Kaushal and Sharma (2014), who investigated osmo-convective drying. However, these studies exclusively examined continuous drying techniques. Recent studies on intermittent drying applied to fruits were conducted by Pereira et al. (2025) on oven-dried melon, Polat et al. (2024) on infrared-assisted dried persimmon, Borah et al. (2023) on microwave-assisted dried persimmon, and Shekar and Ramapure (2023) on guava. These studies focused on thin slices of materials subjected to abrupt heating; thus, they required shorter drying times and tempering periods that lasted from seconds to hours. This means that the tempering period is process specific and purely experimental.

During peak season, reducing the bulk moisture content to a safe level using intermittent drying, could improve the overall efficiency of any industry that processes seasonal fruits. Hence, this study aimed to determine the optimal time-temperature combination for intermittent drying specifically for jackfruit pulp processing, with a focus on reducing energy consumption and achieving faster drying times without incurring additional investment costs.

MATERIALS AND METHODS

Dehydration of Jackfruit Pulp

The production of dehydrated jackfruit pulp was based on the established procedure of the Department of Food Science and Technology, Visayas State University, Baybay City, Leyte. This included cleaning, depulping, addition of other ingredients, cooking, addition of preservatives, plumping, drying, and packaging (Figure 1). Jackfruit of the EVIARC Sweet 1 variety was bought from the City Agriculture Office, Baybay City, Leyte. Other ingredients such as sugar, sodium metabisulfite, sodium benzoate, and citric acid were procured in Cebu City. The ripe jackfruit was washed and sanitized with a 15-ppm chlorine solution. The fruit was then split and depulped. The pulp was weighed and sugar and water added at a ratio of 1:2:1. The pulp was then boiled for 3 to 5mins per kg of pulp. After cooking, the product was allowed to cool to 50°C. After the right temperature was achieved, preservatives like Sodium metabisulfite, Sodium benzoate, and Citric acid were added at 0.1%, 0.1%, and 0.3%, respectively. After a thorough mixing, the mixture was plumped for 12 hours, after which the pulp was drained.

The pre-treated jackfruit pulp samples were subjected to intermittent drying under controlled conditions, utilizing three distinct drying temperatures (60°C, 70°C, and 80°C) and three corresponding drying period-to-tempering time schedules (30:480min, 60:480min, and 90:480min), arranged in a 3×3 factorial experimental design as detailed in Table 1. For instance, after each designated drying interval, samples underwent a 480mins (8h) tempering phase before resuming the drying process. This drying–tempering cycle was repeated until the target moisture content of ≤ 10% (wet basis) was reached. The tempering was done inside a plastic container under ambient conditions with temperatures ranging from 24°C to 32°C and relative humidity of 77% to 87%. The average loading density of the samples was maintained at 2kg/m². Drying operations were conducted using a laboratory-scale cabinet dryer heated using LPG and housed at the Department of Food Science and Technology, Visayas State University, Visca, Baybay City, Leyte. The average airflow rate of the system was 41.3m³/min and was measured using RS-PRO rotary vane digital anemometer (Model: RS 90). The dryer was equipped with an onboard Proportional-Integral-Derivative temperature controller attached to an RTK thermocouple. The total energy consumption associated with the drying process was quantified according to Equation 1. The electrical consumption for the blower was measured using a digital single-phase kWh meter.

$$Q = \frac{\frac{m_f h_v}{3600} + Q_e}{t} \qquad (1)$$

Where:

Q = energy consumption of the dryer (kW)
m_f = mass of consumed LPG (kg)
h_v = heating value of LPG (kJ/kg)
Q_e = electricity load of the blower (kWh)
t = drying time (hour)

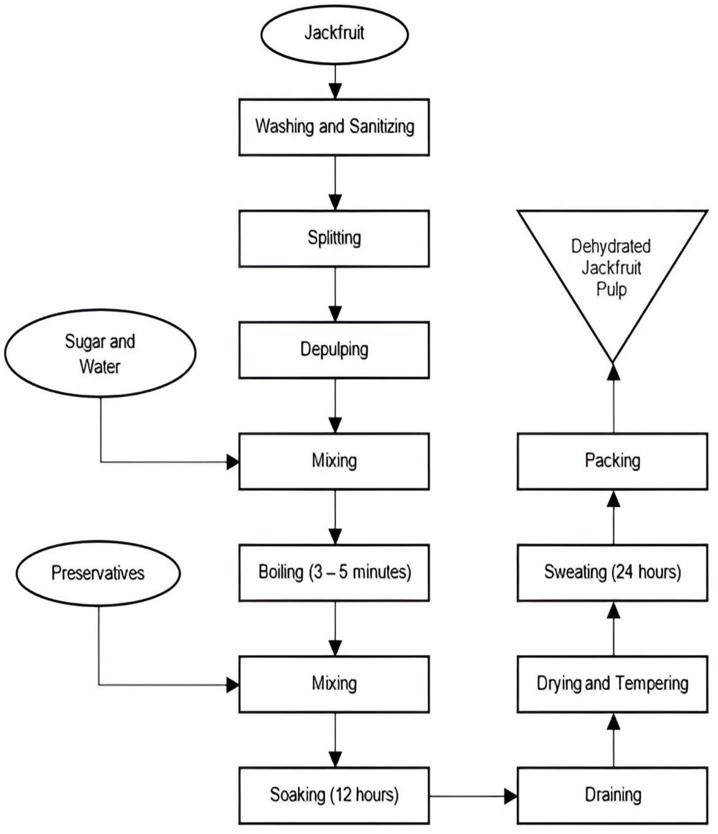

Figure 1. Process flow of producing dehydrated jackfruit pulp.

Table 1. Treatment combinations in intermittent drying of dehydrated jackfruit

Treatment	Variables	
	Time (mins)	Temperature (ºC)
1	30	60
2	60	60
3	90	60
4	30	70
5	60	70
6	90	70
7	30	80
8	60	80
9	90	80

tempering time is 480mins

Predicting the Drying Behavior

The moisture content (MC) was determined using the oven-drying method following the AOAC (2019) protocol. The sample was weighed, using a Kern analytical balance (model, before drying (W_i) and after drying (W_f), and the moisture content was calculated using the following equation below (Equation 2). The drying model used in this study was limited to the Newton (Equation 3) and Page (Equation 4) models (Simpson et al., 2017). Using the moisture ratio (MR), the regression constant for the Newton Model was determined using equation 7.

$$MC(\%) = \frac{W_i - W_f}{W_f} \times 100 \quad (2)$$

$$MR(t) = \frac{M(t) - EMC}{M_i - EMC} = exp(-k_N t) \quad (3)$$

$$MR(t) = \frac{M(t) - EMC}{M_i - EMC} = exp(-k_P t^n) \quad (4)$$

$$M(t) = \frac{m_p(t) - m_{dm}}{m_{dm}} \quad (5)$$

$$m_N = \frac{\sum x_N y_N}{\sum {x_N}^2} \quad (6)$$

$$k_N = -\frac{1}{m_N} \quad (7)$$

$$x_N = t \quad (8)$$

$$y_N = ln(MR) \quad (9)$$

For the Page model, the constants of regression were determined using equations 11 and 13.

$$m_P = \frac{\sum(x_P - \bar{x}_P)(y_P - \bar{y}_P)}{\sum(x_P - \bar{x}_P)^2} \quad (10)$$

$$N_P = -\frac{1}{m_P} \quad (11)$$

$$b_P = \bar{y}_P - m_P\bar{x}_P \quad (12)$$

$$k_P = exp(b_P) \quad (13)$$

$$x_P = ln(t) \quad (14)$$

$$y_P = ln[-ln(MR)] \quad (15)$$

The coefficient of determination (R^2) and root mean square error (RMSE) were used to determine the appropriate drying model and were calculated using equations 16 and 17, respectively:

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(\bar{y} - \hat{y}_i)^2} \quad (16)$$

$$RMSE = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{N}} \quad (17)$$

The tempering cycle (N_T) was based on the best fit model, the Page model, and determined using equation 19:

$$t_d = \left[-\frac{ln(MR_d)}{k_P}\right]^{\frac{1}{n}} \quad (18)$$

$$N_T \geq \frac{t_d}{t_D} \quad (19)$$

Where:

MR = moisture ratio
M(t) = any moisture content (dry basis)
EMC = equilibrium moisture content
t = drying time (min)
t_d = total drying time (min)
t_D = intermittent drying time (min)
$m_p(t)$ = mass of pulp at any time of drying (grams)
m_{dm} = dry matter of the pulp (grams)
y_i = actual MR at any time, t

Optimization and Data Analysis

The computed total drying time and the actual electrical and fuel consumption were subjected to response surface regression following a second-degree polynomial model (Equation 20). The data were analysed using STATISTICA Version 10 software. The optimum drying time and temperature were determined by superimposing the contour plots of the total drying time, fuel consumption, and electrical consumption.

$$\gamma = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} a_{ii} x_i^2 + \sum_{i=1}^{k} \cdot \sum_{j=1}^{k} a_{ij} x_i x_j + \varepsilon \qquad (20)$$

Where:

γ = response obtained
a_0 = constant
a_i = linear effect of the input factor
a_{ij} = linear interaction between the factors
a_{ii} = the quadratic effect of the factor
ε = random error

RESULTS

Behavior of the Drying Process

The initial moisture content of plumped jackfruit pulp was 54.85%. When continuously dried at 60°C for 8h, the pulp reached an equilibrium moisture content (EMC) of 26.58%, which is higher than the moisture content of most dehydrated fruit products (3.5% to 18.28%, Afolabi, 2014) except for plum (28% - 30%, Agricultural Marketing Service, 2019). In contrast, intermittently dried sweetened jackfruit pulp exhibits a lower EMC, ranging from 5.50% to 8.72% (Table 2). The variation in EMC among dehydrated jackfruit pulp is strongly associated with drying temperature and time, whether linear or quadratic effect, with a 99% predictability rate (Table 3). To improve the model predictability, a quadratic model was tested and it was found that it only improved the predictability by 0.53%. Thus, a linear relationship between EMC, drying time, and temperature is sufficient. The negative coefficients for drying time and temperature indicated that increasing both drying parameters would result in a lower equilibrium moisture content (Figure 2). This means that for every 16min increase in drying time or 11°C increase in drying temperature, the equilibrium moisture content would decrease by 1%.

The behavior of moisture removal during the drying process is shown in Figure 3. The first falling rate (FFR) happened within the first 170mins of continuous drying. The average rate of moisture removal during the first falling rate period is 0.0159g/100g-min (Table 4). After reaching a critical moisture of 58.76% (dry basis), the second-falling rate (SFR) of drying took over. On the average, the second-falling rate had an average moisture reduction of 0.005g/100g-min. The models predicting the rates of moisture removal for FFR and SFR are shown in equations 21 and 22.

$$\frac{dM}{dt} = -(0.0159MC_{db} - 0.8054) \qquad 58.76 \le MC_{db} \le MC_i \qquad (21)$$

$$\frac{dM}{dt} = -(0.0050MC_{db} - 0.1667) \quad EMC < MC_{db} \le 58.76 \qquad (22)$$

Table 2. Initial moisture content and equilibrium moisture content of plumped and drained jackfruit pulp at different drying conditions

Intermittent Drying Schedule (min)	Drying Temperature (°C)	Initial Moisture Content (%)[a]	Equilibrium Moisture Content (%)[a]
30	60	54.82	8.72
60	60	54.89	7.39
90	60	54.89	6.55
30	70	54.85	7.76
60	70	54.89	6.85
90	70	54.84	5.93
30	80	54.88	7.13
60	80	54.81	6.15
90	80	54.80	5.50
Continuous	60	54.85	26.58

a – moisture content is in wet basis, tempering time is 480mins

Table 3. Summary of the regression analysis for the equilibrium moisture content of intermittently dried jackfruit pulp at different drying conditions

Effects	Regression Coefficient	
	Linear	Quadratic
Intercept	15.1446**	18.5212**
(1) Drying Time (L)	-0.0631**	-0.0807**
Drying Time (Q)	---	0.0002**
(2) Drying Temp (L)	-0.0912**	-0.1763**
Drying Temp (Q)	---	0.0006**
1L by 2L	0.0005**	0.0005**
R-sqr	0.9905	0.9958

Note: (*) Significant at 5% probability, (**) Significant at 1% probability, ns – not significant

Table 4. Summary of the parameter estimates of the behavior of the First-Falling Rate and Second-Falling Rate of continuous drying of jackfruit pulp

Effects	Regression Coefficient	
	FFR	SFR
Intercept	-0.8054**	-0.1667**
MCdb	0.0159**	0.0050**
R-sqr	0.9762	0.9686

Note: (**) Significant at 1% probability

The instantaneous change in moisture content was modeled using Newton and Page models. The efficacy of the drying models was evaluated using the Coefficient of Determination (R^2) and Root Mean Square Error (RMSE). Regression analysis showed that the Page model consistently displayed better prediction on the changes of moisture content of the jackfruit pulp during the drying process (Table 5). Newton's model has lower R^2 values ranging from 0.9506 to 0.9897, while the Page model has higher values ranging from 0.9761 to 0.9989. Conversely, Newton's model has higher RMSE, ranging from 0.0224 to 7.3456, while the Page model has lower errors, ranging from 0.0170 to 0.6917.

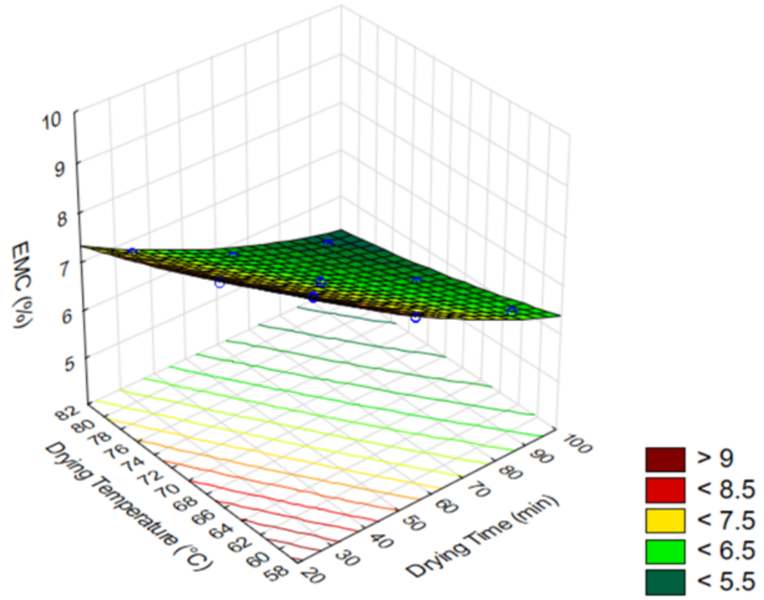

Figure 2. Surface plot of the EMC (dry basis) as affected by the intermittent drying time and temperature

Table 5. Summary of the Coefficient of Determination and Root Mean Square Error of Newton and Page models describing the drying kinetics of intermittently dried jackfruit pulp.

Intermittent Drying Schedule (min)	Drying Temperature (°C)	Newton's Model		Page Model	
		R^2	RMSE	R^2	RMSE
30	60	0.9506	0.1134	0.9887	0.0340
60	60	0.9631	0.1126	0.9870	0.0225
90	60	0.9747	0.0466	0.9916	0.0170
30	70	0.9569	0.1065	0.9866	0.0359
60	70	0.9751	0.1022	0.9870	0.0284
90	70	0.9904	0.0224	0.9889	0.0171
30	80	0.9561	0.1431	0.9943	0.0230
60	80	0.9731	0.0979	0.9817	0.0284
90	80	0.9695	0.0318	0.9761	0.0205
Continuous	60	0.9897	7.3456	0.9989	0.6917

The poor predictability and high RMSE of Newton's model for the continuous drying process are shown in Figure 4(a). Most of the inefficiencies in prediction happened at the early stage of the continuous drying process. The Page model did not have any problem predicting the early stage of the drying process. Consistently, from continuous drying (Figure 4[a]) to intermittent drying (Figures 4[b] to 4[d]), the prediction curves of moisture contents using the Page model accurately track the actual points.

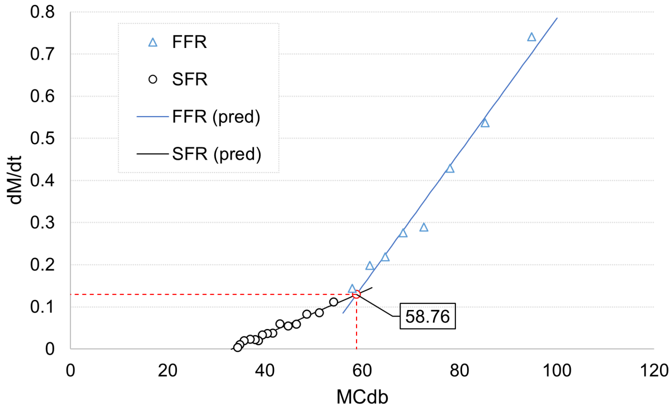

Figure 3. Behavior of the moisture removal from jackfruit pulp under continuous drying condition

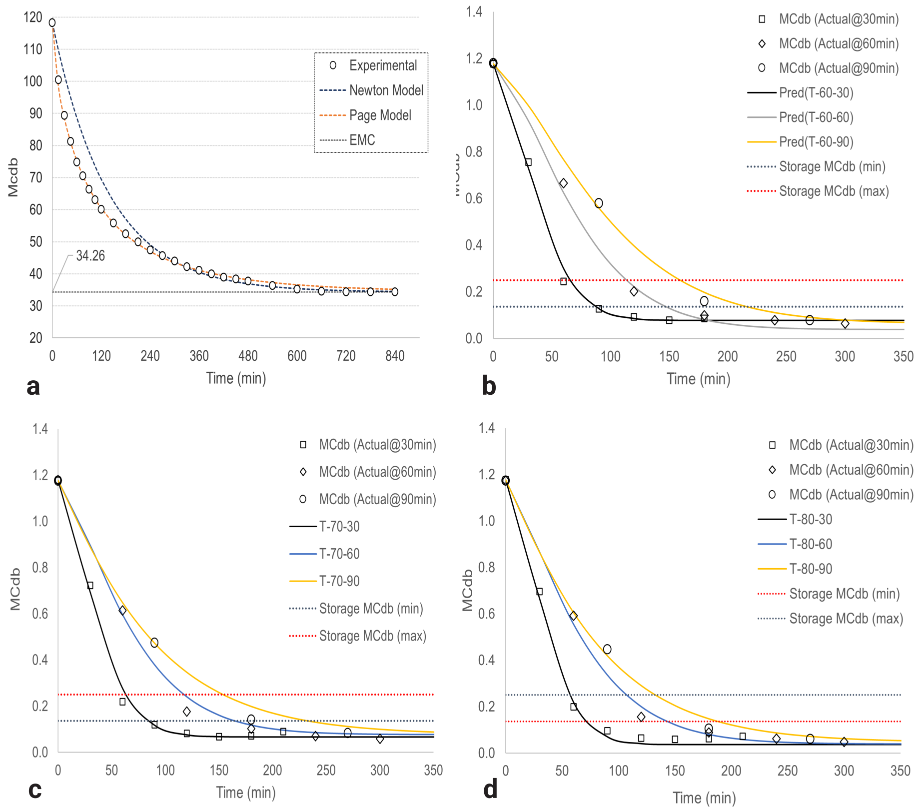

Figure 4. Drying behavior of sweetened jackfruit pulp using Page Model for (a) Continuous drying, (b) intermittent drying at 60°C, (c) intermittent drying at 70°C, and (d) intermittent drying at 80°C

The drying constants n and k for the Page model are presented in Table 6. The parameter k ranged from 0.0017 to 0.0071, while the n values spanned from 1.1042 to 1.6172. The variation in both k and n was more accurately described by second-degree polynomial model of drying time and temperature, which yielded coefficients of determination (R^2) of 92.99% and 98.39%, respectively. In comparison, simpler linear models accounted for only 77.18% and 92.45% of the variation in k and n, respectively, indicating the use of the second-degree polynomial model is appropriate due to greater predictive capability (Table 7).

Table 6. Summary of parameter estimates for the Page model at different drying temperatures and intermittent drying time

Intermittent Drying Schedule (min)	Drying Temperature (°C)	n	k	R^2
30	60	1.6096	0.0022	0.9887
60	60	1.4544	0.0017	0.9870
90	60	1.3874	0.0016	0.9916
30	70	1.5339	0.0031	0.9866
60	70	1.3461	0.0030	0.9870
90	70	1.1042	0.0071	0.9889
30	80	1.6172	0.0024	0.9943
60	80	1.3084	0.0037	0.9817
90	80	1.1331	0.0068	0.9761
Continuous	60	0.6993	0.0410	0.9989

Table 7. Summary of parameter estimates for the regression constants of Page model

Effects	n		k	
	Linear	Quadratic	Linear	Quadratic
Intercept	1.2855**	5.6490**	0.0104**	-0.0481*
(1) Drying Time (L)	0.0095**	0.0061**	-0.0003^{ns}	-0.0004*
Drying Time (Q)	---	0.0000^{ns}	---	0.0000^{ns}
(2) Drying Temp (L)	0.0069^{ns}	-0.1170*	-0.0001^{ns}	0.0017*
Drying Temp (Q)	---	0.0009*	---	0.0000^{ns}
1L by 2L	-0.0002^{ns}	-0.0002*	0.0000^{ns}	0.0000^{ns}
R-sqr	0.9245	0.9839	0.7718	0.9299

The variations of n and k with respect to the changes of drying time and temperature are shown in Figures 5 and 6. The regression constant, n, is negatively affected by the drying time, drying temperature, and their interaction. The constant, k, is negatively affected by the drying time and positively affected by the drying temperature. This means that the value of k increases with temperature but decreases with drying time, only if the drying temperature is relatively low, otherwise it would increase with drying time (Figure 6).

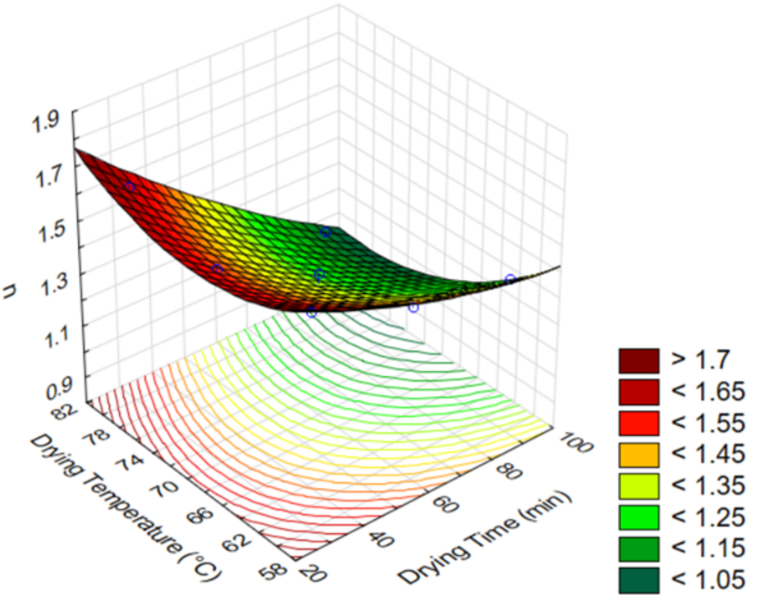

Figure 5. Surface plot of the constant n as affected by the intermittent drying time and temperature

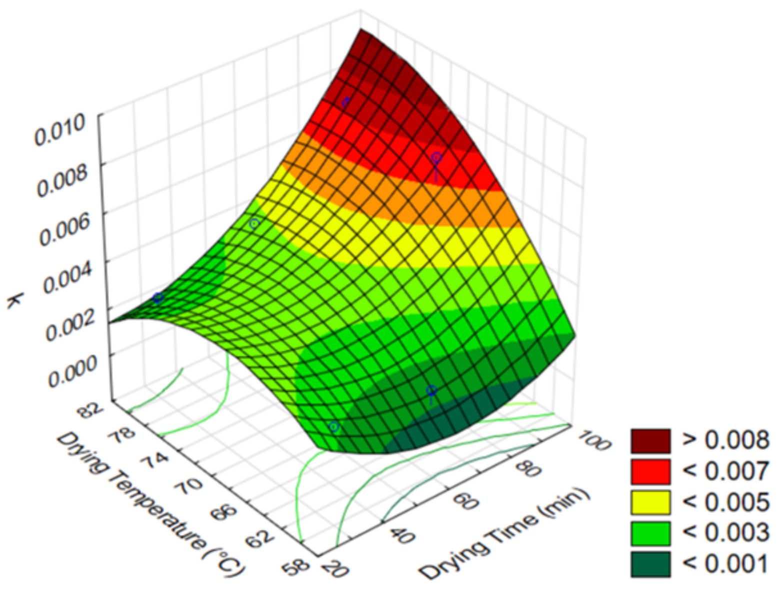

Figure 6. Surface plot of the constant k as affected by the intermittent drying time and temperature

Performance Evaluation of Intermittent Drying

Table 8 summarizes the performance parameters of intermittently dried jackfruit pulp. The average drying time to reach the lower limit of moisture content for storing dehydrated fruits at 10-11% (wet basis) ranges from 60.72 to 171.41mins. The estimated total drying time for intermittently dried jackfruit is positively affected by the length of the intermittent drying time, both linear and quadratic (Table 9). Figure 7 showed the total drying time was increasing at a decreasing order. The overall predictability of the estimation of the drying time per run is 98.33%.

Table 8. Summary of the performance parameter of intermittently dried jackfruit pulp

Intermittent Drying Schedule (min)	Drying Temperature (°C)	Total Drying Time (min)	Fuel Consumption (kg/run)	Electrical Consumption (kWh/run)
30	60	72.87	0.42	2.02
60	60	131.60	1.05	3.53
90	60	171.41	1.69	4.91
30	70	69.35	0.46	1.88
60	70	128.33	1.06	3.64
90	70	165.89	1.55	4.32
30	80	60.72	0.40	1.98
60	80	122.09	1.04	3.23
90	80	148.40	1.50	3.95
Continuous	60	480-600*	3.69	13.92

* - based on the existing drying method

Table 9. Summary of the parameter estimates of the performance parameter of intermittently dried jackfruit pulp

Effects	Total Drying Time (min)	Fuel Consumption (kg)	Electrical Consumption (kWh)
Intercept	-164.54^{ns}	-0.8834^{ns}	-2.3196^{ns}
(1) Drying Time (L)	3.8790**	0.0362**	0.1323**
Drying Time (Q)	-0.0140**	-0.0001^{ns}	-0.0003**
(2) Drying Temp (L)	4.4760^{ns}	0.0116^{ns}	0.0388^{ns}
Drying Temp (Q)	-0.0330^{ns}	0.0000^{ns}	-0.0001^{ns}
1L by 2L	-0.0090^{ns}	-0.0001^{ns}	-0.0008**
R-sqr	0.9833	0.9479	0.9804

Note: (*) Significant at 5% probability, (**) Significant at 1% probability, ns – not significant

The LPG requirement per drying run of jackfruit pulp ranged from 0.40kg to 1.69kg for intermittent drying and 3.69kg for continuous drying (Table 8). The fuel consumption is solely dictated by the length of each drying period at 99% confidence (Table 9). Longer drying periods after every tempering process required more fuel for drying. Parameter estimates predicted that every 1min increase in drying time required an additional fuel consumption of 36g of LPG. The coefficient of determination of fuel consumption is 94.79%.

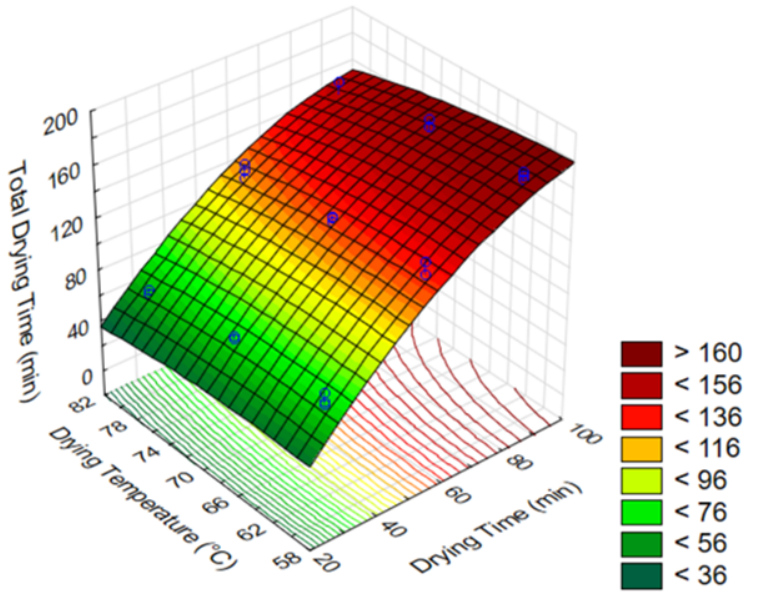

Figure 7. Surface plot of the estimated total drying time as affected by the intermittent drying time and temperature

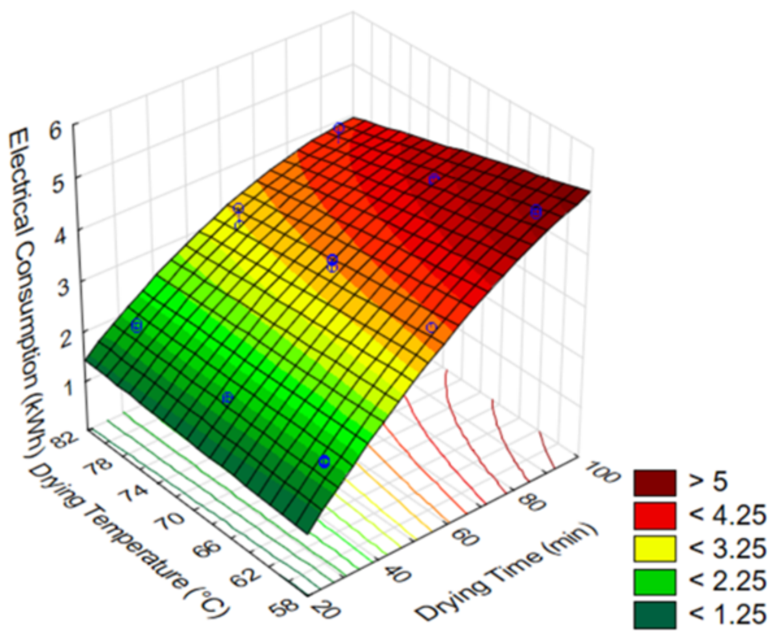

Figure 8. Surface plot of the electrical consumption as affected by the intermittent drying time and temperature

The electrical consumption of the dryer ranged from 1.88kWh/run to 3.95kWh/run for intermittent drying while 13.92kWh/run was used for continuous drying at 60°C (Table 8). Regression analysis revealed that the electrical consumption was significantly affected by the duration of drying, both linear and quadratic, and its interaction with drying temperature (Table 9). The electrical consumption increased with decreasing order as reflected by the positive linear and negative quadratic effects of drying time. Negative interactions of both variables showed that longer drying time at lower drying temperatures consumed more electricity (Figure 9).

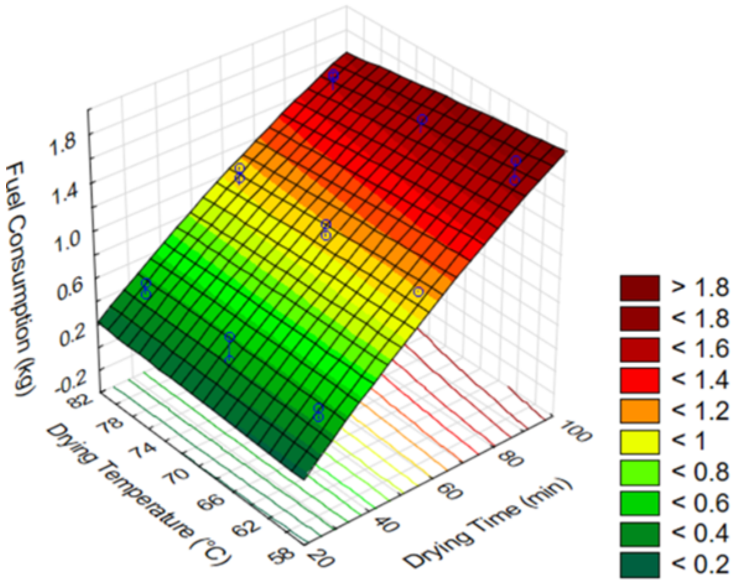

Figure 9. Surface plot of the fuel consumption as affected by the intermittent drying time and temperature

Optimum Combination of Intermittent Drying Time and Temperature

By superimposing the contour plots of total drying time per run (≤ 80min/run), fuel consumption (≤ 0.65kg/run), and electrical consumption (≤ 1.85kWh/run), the optimum region for intermittent drying of jackfruit pulp was revealed. This region ranged from 66°C to 80°C drying temperature and 30 to 35mins of intermittent drying (Figure 10). Desirability profiling pinpointed the optimum point at a drying time of 30mins and drying temperature of 80°C (Figure 11).

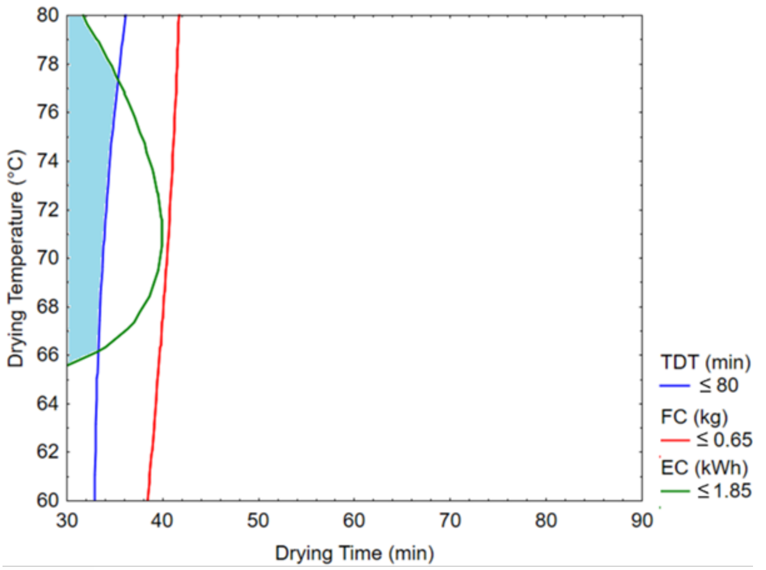

Figure 10. Super-imposed contour plots of the total drying time, fuel consumption, and electrical consumption.

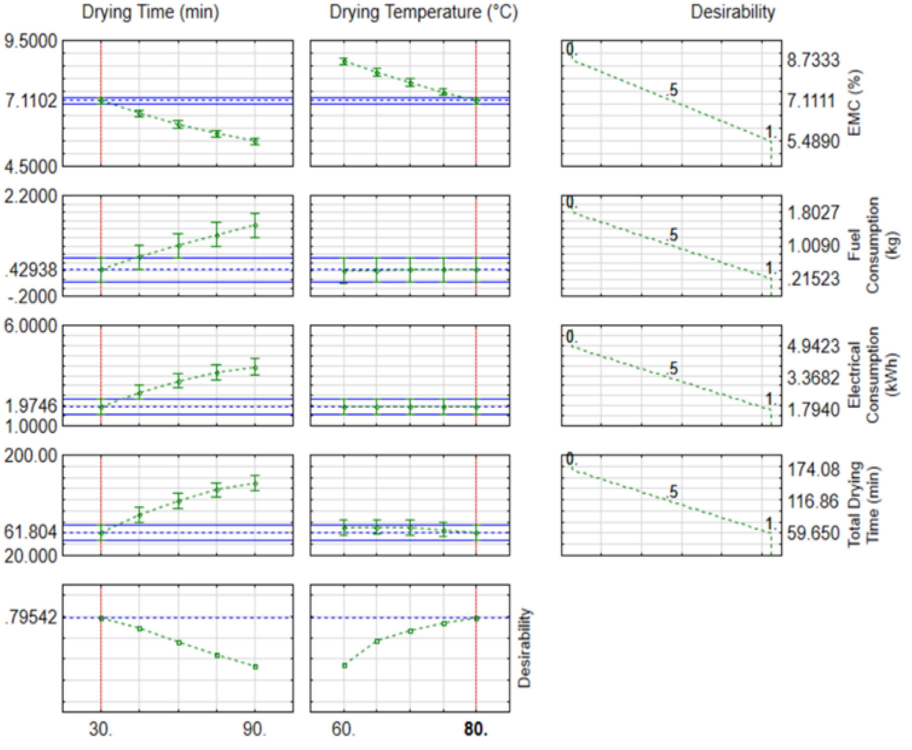

Figure 11. Desirability profile of the different performance parameters for drying

DISCUSSION

Behavior of the Drying Process

The reduction of equilibrium moisture content with drying time and temperature is due to the increasing vapor pressure difference of water in the drying air and food with increasing drying temperature. Based on the Clausius-Clapeyron equation, the logarithm of the vapor pressure of a food product at a constant moisture content is linearly related to the inverse of the absolute temperature (Labuza, 1977). The impact of drying time on the equilibrium moisture content should not be significant, especially for the continuous drying process (Pereira et al., 2020). However, during intermittent drying, the effect on EMC can be attributed to the relaxation process of moisture inside the product during the tempering period (Dong et al., 2009). The relaxation normalizes the moisture gradient within the product, as well as its surface moisture, thereby removing more water when the next cycle of drying takes place (Pereira et al., 2020).

The rate of moisture removal from complex products is categorized into initializing period, constant rate period, first falling rate period, second falling rate period (Heldman et al., 2018), and equilibrium stage (Brooker et al., 1974). Most foods display only the falling rate and equilibrium periods as the constant rate period removes the unbound water at the surface of the food (Heldman et al., 2018). The plumped jackfruit pulp was drained before being dried and its surface moisture was a high concentration sugar solution; thus, the presence of unbound surface moisture that contributed to the constant rate period was negligible.

The presence of FFR and SFR in the rate of moisture removal suggested that Newton's model is not sufficient in describing the drying kinetics of dehydrated jackfruit pulp as it usually overestimated the first falling rate period (Inyang et al., 2018) as shown in Figure 4a. The use of Page model in describing the moisture removal during the process is backed by its high coefficients of determination and low RMSE. Although there are more advanced and non-linearizable models for drying, their advantage over the Page model is small. For instance, results of the thin layer drying kinetics for pineapple showed that the Page model is only 0.3% to 0.9% lower than the model with the highest coefficient of determination (Olanipekun et al., 2014). Another study on the thin layer drying characteristics of star fruit showed that the Page model has an R^2 value that is only 0.03% lower than the best fit model (Doloi, 2013). On the other hand, the Page model was found to be the best fit model in drying a number of products, for example purslane (Kashaninejad & Tabil, 2004), carrots (Doymaz, 2007), Amelie mango (Dissa et al., 2008), and pineapple (Ramallo & Mascheroni, 2012).

The drying constants k and n of the Page model help to effectively predict the instantaneous moisture content of the pulp during the drying process, usually found to have anomalous diffusion rates during long drying operations, which cannot be explained by Fick's Law (Simpson et al., 2017). Although n is purely empirical, it is simple and more flexible. Usually, the value of n is within 1.06 to 2.05 (Simal et al., 2004). During the intermittent drying process, all n values fall within the specified limits. In contrast, for continuous drying, the n value is significantly lower than the lower limit.

The value of n decreases with intermittent drying time and increases with temperature. The higher n is, the higher the rate of moisture removal, as shown in equation 23; thus, reinforcing the relationship between n and temperature. The effect of temperature is associated with the energy needed to vaporize water during drying and the differential vapor pressure that excites water to facilitate diffusion more efficiently (Luikov, 1975). Increasing values of n with increasing convective drying temperature were also observed during the thin layer drying of Kent mango (Ampah et al., 2022), Amelie mango (Dissa et al., 2008), and gooseberry (Methakhup et al., 2004). However, n decreases with temperature for the vacuum drying process of gooseberry (Methakhup et al., 2004). In addition, n also showed independence from drying temperature in cases of beans, potato, and peas (Senadeera et al., 2003).

$$\frac{dM}{dt} = -knt^{n-1} \times exp(-kt^n) \qquad (23)$$

The constant k in the Page model is an empirical parameter, in contrast to the k in Fick's law, which incorporates the geometric characteristics of the material. In practice, the Page model's k serves as a fitting parameter to capture the influence of operational variables, such as drying temperature, on the overall moisture removal kinetics (Simal et al., 2004). Empirical data have demonstrated that k exhibits a direct relationship with both the drying temperature and the duration of high-temperature intermittent drying. This trend aligns with findings for various agricultural products, including green peas (Simal et al., 2004), fluidized bed dried vegetables (Senadeera et al., 2003), and grapes (Azzouz et al., 2002), where elevated drying temperatures consistently yield higher k values, indicating enhanced drying rates.

Performance Evaluation of Intermittent Drying

Longer drying time per run means higher cost of labor, fuel, and electricity. The total drying time per run is positively influenced by the length of intermittent drying alone (Table 9). According to Inyang et al. (2018), temperature has a significant effect on the drying rate as it influences the vapor pressure deficit between the food and air. However, for intermittently dried jackfruit, the impact of temperature on the drying is minimal. This can be attributed to the relaxation of moisture during tempering which allows the diffusion of moisture from the core of the product to its surface, resetting the property of the product back to a faster water diffusion state (Pereira et al., 2020), making the drying process relatively faster. In addition, shorter intermittent drying means maintaining a high moisture removal rater as tempering makes it possible that there is a lot of surface and near surface moisture in the product. Conversely, longer drying time means removing water from deep within the product making the diffusion slower (Heldman et al., 2018); thus, lengthening the drying process.

Fuel and electrical energy consumption are quantitatively correlated with both drying time and process temperature due to the fundamental thermodynamic relationship between energy input and moisture removal. Prolonged drying duration results in increased cumulative energy demand. For intermittent drying, the specific fuel consumption is approximately 36.2g of LPG per minute, corresponding to a total consumption range of 0.42 to 1.69kg per drying cycle.

These values represent a reduction of 54.2% to 89.16% in fuel usage compared to continuous drying operations, attributable to improved thermal efficiency during intermittent cycles. The electrical demand of the blower is governed by the total pressure head and mass flow rate of air delivered (Heldman et al., 2018) with consumption increasing nonlinearly with drying time. This is partly due to the reduction in air density and moisture content in the drying air over time, which diminishes the blower's load requirements as the drying process progresses. The overall reduction of electrical consumption ranges from 64.73% to 86.49%. It is important to note that the dryer used in this study used partially recirculated air.

Drying temperatures, of 60°C to 80°C, did not significantly affect the fuel consumption. The fuel consumption per run is more or less the same within a 20°C drying temperature difference. The effect of drying temperature may have been lumped with the intermittent drying time to the total drying time. Supposedly, higher temperature needs more heat; thus, requires more fuel. However, the total variation of fuel consumption within the range of this study is only 240g. On the other hand, the drying time brought a total of 2.17kg of fuel consumption variation. The negative interaction of temperature and intermittent drying time on the electrical consumption of the blower can be attributed to the improved vapor pressure gradient at higher drying temperatures (Luikov, 1975); thus, improving the drying process and reducing the total drying time.

Optimum Combination of Intermittent Drying Time and Temperature

The optimum drying condition for intermittently dried sweetened jackfruit pulp involved a high drying temperature and a shorter drying period. This aligns with Shekar and Ramapure (2023), who found that guava chips dried best at 70°C with an intermittent drying ratio of 0.25, resulting in a reduced drying time. Higher drying air temperatures supply more energy, while shorter drying periods per cycle help sustain the fastest drying rate (FFR) for amorphous materials (Belhamri, 2003) . In addition, FFR decreases with time (Heldman et al., 2018), maintaining shorter drying phases ensures efficient drying.

The optimum drying condition was determined to be two drying cycles, each lasting 30mins at 80°C, for a total of 60mins. This is based on a 2kg/m^2 density load. After drying, the average moisture content of the jackfruit was 12.2% (wet basis), which increased to 14.3% (wet basis) following the sweating process. The increase in moisture content can be attributed to the adsorption process when food material with low water activity is exposed to air with relatively higher relative humidity (Labuza, 1977). The final moisture content of the product was still within the optimal range for gummy fruit leather at 12% to 20% (Diamante et al., 2014). The energy consumption for this optimum process, including preheating, was 0.41kg/run of LPG and 2.01kWh/run of electricity. The direct material, energy, and labor costs for the optimum process resulted in a cost of 170.92 pesos (2.89 USD) per kilogram of dried product. Although market analysis has to be conducted, this cost is only 11.4% of the price compared to the existing dehydrated jackfruit pulp sold by the Baybay Women's Association at 75 pesos per 50g pack (25.38 USD/kg).

CONCLUSION

In conclusion, the Page model is sufficient to describe the moisture removal of both continuously and intermittently dried sweetened jackfruit pulp. The critical moisture content of plumped jackfruit is 58.76% (dry basis). The equilibrium moisture content of the dried jackfruit pulp is negatively affected by the drying temperature and intermittent drying time. The theoretical total drying time and the energy needed for drying are positively dictated by the length of intermittent drying. Shorter intermittent drying cycles have shorter total drying time and lower energy consumption. The optimum drying temperature and intermittent drying time are 80°C and 30mins. The fuel and electrical energy savings compared to continuous drying are 89.16% and 86.49%, respectively. The dehydrated sweetened jackfruit pulp dried using the optimum process has 14.3% moisture content (wet basis) and at a cost of Php170.92 per kilogram (2.89 USD).

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Author Contributions

JFT conducted the experiment of the study as his thesis manuscript. ICE served as the thesis adviser. JBC also served as the thesis adviser, introduced the idea of the study, analyzed the data, and prepare the final draft of this journal article.

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Availability of Data and Materials

Data and materials generated or analyzed during this study are included in this article and its supplementary files, and/or available from the corresponding author upon request.

Ethical Considerations

No human and animals were used in this study.

Competing Interest

The authors declare no competing interests.

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