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Influence of two-stage drying methods on the physical properties and drying characteristics of sweet potato slices

Antal, T.

University of Nyíregyháza, Institute of Engineering and Agricultural Sciences, Department of Vehicle and Agricultural Engineering, Kótaji Str. 9-11., H-4400 Nyíregyháza, Hungary

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Abstract

The effects of single-stage freeze-drying, two-stage mid-infrared assisted freeze-drying and vacuum pre-drying and freeze finish-drying on the operational time, energy uptake, color and hardness properties of sweet potatoes were investigated. Prior to the drying procedure, the samples were unpretreated and pretreated in citric acid solution. Drying curves of sweet potato were determined for mid-infrared and vacuum pre-drying at different drying temperatures (40, 50 and 60°C). The combination of mid-infrared and freeze-drying showed the largest reduction in both drying time (52%) and specific energy consumption (52%) compared to single-stage freeze-drying. Four different empirical thin-layer drying models were compared based on their coefficient of determination and root mean square error to estimate the drying curves. The results showed that the Polynomial and Henderson-Pabis models were the most appropriate to describe the drying of sweet potato slices. The total color difference and hardness values of sweet potato degraded while increasing the pre-drying temperature. The citric acid pretreatment enhanced the texture and color of dried sweet potato.

1. Introduction

Sweet potato (*Ipomoea batatas* L.) is an important crop product in Europe. Sweet potatoes contribute greatly to the human diet by providing at least 90% of daily dietary needs. The plant is rich in β-carotene, anthocyanin, polyphenols, vitamins A and C, dietary fiber, starch, potassium ions, iron, calcium and mineral content (Lin *et al*., 2005; Doymaz, 2012; Ruttarattanamongkol *et al*., 2016). Raw sweet potatoes have a relatively high water content and are highly sensitive to spoilage of microbes, and enzymatic browning so the pretreatment and dehydration procedure is vital (Xiao *et al*., 2009).

Soaking in water solution (blanching and citric acid) inactivates the enzyme activities and improves product acceptability (Doymaz, 2007). To preserve the quality of sweet potatoes, various pretreatment methods ($NaHSO_3$, $CaCl_2$, ascorbic acid) have been investigated (Ahmed *et al*., 2010a, de Souza *et al*., 2021).

Dehydration is a heat treatment that prolongs the shelf-life of the dried material by reducing water content, inhibiting enzymatic degradation, and limiting microbial activity. Dying affects the quality of foods, i.e. chemical, physical, and microstructural properties, and therefore different drying methods have been developed for drying foods (Lewicki, 2006). Dried sweet potatoes are an excellent base for baked goods such as cakes, pancakes, flatbreads, biscuits, cookies, noodles, chips and bread (Van Hal, 2000).

Freeze-drying (FD) usually helps to maintain better quality when drying plant materials. However, the running cost of lyophilization is significantly higher than that of hot air, vacuum and infrared drying (Jia *et al*., 2019). Despite the high costs and drying time required for lyophilization, this treatment results in minor alterations in texture, color and bioactive components (Nawirska *et al*., 2009). Therefore, drying techniques should be designed to minimize the energy costs of the drying process.

Infrared drying (IR) has been studied as an alternative to reduce the drying time and improve the quality of dried foods. The rapid heating of food materials by infrared radiation increases the rate of water delivery to the surface, resulting in an increase in the drying rates (Onwude *et al*., 2018). The use of IR technique as pre-drying in combination with freeze-drying can eliminate most of the disadvantages (operational time) associated with FD. The use of mid-

*Corresponding author.
Email: *antal.tamas@nye.hu*

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wavelength infrared rays is recommended for uniform energy distribution on the material surface (Bazyma *et al*., 2006).

Vacuum drying (VD) is suitable for processing heat-sensitive foods, which can improve the quality characteristics of dehydrated final products compared to hot-air drying (Lee and Zuo, 2013).

There have been some reports on the drying characteristics of sweet potatoes (Lin *et al*., 2005; Xiao *et al*., 2009; Orikasa *et al*., 2010; Olawale and Omole, 2012; Doymaz, 2012; Saini *et al*., 2012; Yan *et al*., 2013; Zhu and Jiang, 2014; Sebben *et al*., 2017; Onwude *et al*., 2018; Onwude *et al*., 2019a). There is little information available in the literature on the effect of the so-called hybrid drying on the drying characteristics and quality of sweet potatoes.

One of the most important aspects in the development of drying methods is the modelling of drying processes. The modelling principle of drying kinetics is based on the use of mathematical models that are able to adequately characterize a given system and the operation and optimization of dryers (Akpinar and Bicer, 2008; Fernando and Amarasinghe, 2016). Existing mathematical models widely used, that is suitable for describing simultaneous heat and mass transfer on foods, such as thin-layer drying models, namely Newton, Page, modified Page, Henderson and Pabis, modified Henderson and Pabis, Logarithmic, Wang and Singh, Two-term, Two-term exponential, Linear, Midilli, Verma, Thompson, Sigmoid models. (Ertekin and Yaldiz, 2004; Lahsasni *et al*., 2004; Figiel, 2009; Guiné *et al*., 2019). The thin-layer drying kinetics are usually given by empirical and semi-empirical relationships (Olawale and Omole, 2012). Little data are available on modelling the two-stage drying characteristics of sweet potato slices using semi-empirical drying equations.

The color characteristics are important quality factors of dehydrated foods as they influence consumer acceptability. The color parameters of foods depend on both bioactive compounds and the physical characteristics of the substance (Zielinska and Markowski, 2012). Color characteristics of the final products should closely resemble the color parameters of the raw plant material (Moreira *et al.,* 2008).

The texture is the result of complex interactions between food components at microstructural and higher structural levels. Modifications in mechanical characteristics are related to the textural attributes of the food. Hence, it is important to determine the texture of the dried products (Guiné and Barroca, 2012).

The main aim of this study was to determine the effects of single and two-stage drying techniques on the drying characteristics and quality of sweet potatoes. For this purpose, the drying of white-fleshed sweet potato was conducted using different drying temperatures (40, 50 and 60°C) and the effects on the quality of the sweet potato were evaluated. In this study, the combination of vacuum drying and freeze-drying (VD-FD), infrared drying and freeze-drying (MIR-FD) and single freeze-drying (FD) with and without citric acid pretreatment were used to determine the physical characteristics of the sweet potato slices.

2. Material and methods

2.1 Materials

Raw sweet potatoes (color of flesh: white) were bought from a local Hungarian producer. The samples were stored in a refrigerator (model Husqvarna QRT4650X, Electrolux LTD, Jászberény, Hungary) at 5±1°C until they were used. The samples were washed with tap water, and peeled with a hand peeler. The samples were sliced by hand with stainless steel knives to a thickness of 3 mm.

The white-fleshed sweet potato slice was subjected to two different pretreatment conditions (1) immersed in 3% citric acid solution at room temperature for 10 mins (Mosneaguta *et al.,* 2012) and (2) no pretreatment (control). After soaking, the samples were blotted with tissue paper to remove excess solution.

2.2 Moisture content

The water content was determined by drying the materials in a drying oven (model LP302, LaborMIM, Budapest, Hungary) at 105°C for 24 hrs until the weight stabilized. The samples were weighed by a digital balance (limit of measurement: 500 g, sensitivity of ±0.1 g, model JKH-500, Jadever Co., New Taipei, Taiwan), and final results were recorded by the wet and dry base.

The moisture content of the samples (M_t) or dry basis was determined as the mass of the samples at a specific time (m_0) to the final mass of the sweet potato sample after dehydration (m_d) as expressed in equation (1):

$$M_t = \frac{m_0 - m_d}{m_d} \quad (1)$$

The water content of the drying sample at time *t* can be transformed to be dimensionless moisture ratio (MR) (2):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

The moisture ratio (MR) was simplified to M_t/M_o

instead of $(M_t-M_e)/(M_0-M_e)$ since M_e is relatively small as compared with M_0 – for all drying techniques (Antal and Kerekes, 2016).

The average initial moisture content of the samples was found to be 77.4±0.1% (wet basis) or 3.42±0.05 kg water kg dry matter^{-1} (dry basis). Experiments were carried out using three different drying methods, *viz*. VD -FD, MIR-FD and FD, until the water content of the final product reached 3.4-8.1% (wet basis).

2.3 Drying experiments

The experiments were performed at drying temperatures of 40, 50 and 60°C. The mass of the sweet potato slice was weighed by digital scale (model JKH-500) and 50±0.5 g mass of the sample was utilized in each experiment. The sample was evenly loaded onto the drying tray in a single layer.

The lab-scale vacuum dryer (model Kambic VS-50C, Kambic Lab. Eq., Semic, Slovenia), infrared dryer (model Precisa HA60, Precisa Instruments AG, Dietikon, Switzerland) and freeze dryer (model Armfield FT-33, Armfield Ltd, Ringwood, England) were used in this research.

2.3.1 Vacuum drying

A lab-scale vacuum dryer operated at 5 kPa was used during the drying process. The drying temperatures (40-60°C) were measured using T-type thermocouples. To measure the weight of the sweet potatoes during drying, the tray containing the sample was removed from the drier, weighed on the digital balance and then returned to the chamber. The mass measurement was repeated every hour. The digital balance is placed close to the vacuum dryer.

2.3.2 Mid-infrared drying

The drier consists of a box-type drying chamber, a quartz glass infrared emitter (wavelength of 2.4-3 µm, power of 410 W), a drying tray (110 mm × 110 mm) and a load cell (limit of measurement: 100 g, a precision of ±0.001 g). The sample weight was automatically recorded every 1 min. The distance between the infrared emitter and the sample tray was kept constant at 150 mm. The IR intensity is 3-5 kW m^{-2}, which corresponds to a drying temperature of 40-60°C.

2.3.3 Freeze-drying

A lab-scale freeze-dryer was set at a chamber pressure of 30-40 Pa. The temperature of the heating plate and condenser chamber were 20 and -45°C. During drying the material temperature was registered by a thermocouple (type T) placed on the slice and connected to a data logger. The weight of the sample was automatically recorded every 1 min using a balance (model PAB-01, Emalog Ltd., Budapest, Hungary), which was installed in the dryer chamber.

2.3.4. Hybrid or two-stage drying

The drying air temperature (40, 50 and 60°C) and pre-drying time were set in the first stage (VD pre-drying and MIR pre-drying) in the two-stage drying experiment. The first drying stage was followed by the second stage (so-called post-drying: FD). Details of each experiment are shown in Tables 1-2.

The dried sweet potato slices were stored in polyethylene bags at low temperatures (5±1°C) in the refrigerator (model Husqvarna QRT4650X) prior to analysis.

2.4 Evaluation of thin-layer drying of sweet potato

Drying data was expressed as moisture ratio (MR) versus drying time (t). The progress of dehydration in one layer of slices is known as thin-layer dewatering. Moisture ratio (MR) was calculated from the moisture loss profile of dried sweet potatoes and fitted to four empirical models used to characterize thin-layer drying. (Table 3).

The coefficient of determination (R^2) was used to fit the suitability of the drying model while the accuracy of fits was evaluated by root mean square error (RMSE). The criterion is that the higher the R^2 values and the lower the RMSE values, the better is the goodness of fit.

These statistical parameters can be calculated as (3, 4):

$$R^2 = \frac{residual\ sum\ of\ squares}{corrected\ total\ sum\ of\ squares} \tag{3}$$

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (MR_{\exp_i} - MR_{pre_i})^2} \tag{4}$$

where $MR_{exp,i}$ stands for the experimental moisture ratio found in any measurement, $MR_{pre,i}$ is the predicted moisture ratio for this measurement and N is the total number of observations.

2.5 Measuring of specific energy consumption

Measuring the amount of energy uptake is an important step in determining the energy efficiency of a given drying method and comparing it with the results of other drying techniques. Specific energy consumption (SEC) during dehydration was expressed in MJ kg^{-1} of water removed. The required energy for drying 1 kg of fresh sweet potato slice was computed by the following equation (5):

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Table 1. Experimental detail of single and two-stage drying with pretreatment.

Experiment no.	Drying methods	Drying temperature T [°C]	Pre-drying time t [min]	$MR_{residue}$ [-]	Post-drying time t [min]	MR_{final} [-]	Final moisture content (in dry basis) [kg water kg dm^{-1}]
1	VD-FD	40	120	0.584	900	0.0181	0.0619
2	VD-FD	40	180	0.41	780	0.0181	0.0619
3	MIR-FD	40	3	0.842	840	0.0207	0.0707
4	MIR-FD	40	5	0.661	720	0.0155	0.053
5	VD-FD	50	120	0.532	900	0.0103	0.0353
6	VD-FD	50	180	0.366	780	0.0258	0.0884
7	MIR-FD	50	3	0.799	780	0.0181	0.0619
8	MIR-FD	50	5	0.573	660	0.0103	0.0353
9	VD-FD	60	120	0.492	840	0.0129	0.0442
10	VD-FD	60	180	0.306	720	0.0232	0.0796
11	MIR-FD	60	3	0.724	720	0.0258	0.0884
12	MIR-FD	60	5	0.461	600	0.0207	0.0707
13	FD	-	-	-	1260	0.0258	0.0884

FD: freeze-drying, MIR-FD: mid-infrared-assisted freeze-drying, VD-FD: vacuum pre- and freeze finish drying.

Table 2. Experimental detail of single and two-stages drying without pretreatment.

Experiment no.	Drying methods	Drying temperature T [°C]	Pre-drying time t [min]	$MR_{residue}$ [-]	Post-drying time t [min]	MR_{final} [-]	Final moisture content (in dry basis) [kg water kg dm^{-1}]
1	VD-FD	40	120	0.591	900	0.0232	0.0796
2	VD-FD	40	180	0.422	780	0.0258	0.0884
3	MIR-FD	40	3	0.829	840	0.0155	0.0530
4	MIR-FD	40	5	0.659	720	0.0207	0.0707
5	VD-FD	50	120	0.521	900	0.0103	0.0353
6	VD-FD	50	180	0.345	780	0.0258	0.0884
7	MIR-FD	50	3	0.784	780	0.0207	0.0707
8	MIR-FD	50	5	0.561	660	0.0181	0.0619
9	VD-FD	60	120	0.481	840	0.0207	0.0707
10	VD-FD	60	180	0.294	720	0.0258	0.0884
11	MIR-FD	60	3	0.711	720	0.0129	0.0442
12	MIR-FD	60	5	0.423	600	0.0207	0.0707
13	FD	-	-	-	1260	0.0232	0.0796

FD: freeze-drying, MIR-FD: mid-infrared-assisted freeze-drying, VD-FD: vacuum pre- and freeze finish drying.

Table 3. Thin-layer mathematical models given by various authors for the drying curves.

Model no.	Model name	Model equation	References
1	Third-degree polynomial	$MR = a \cdot t^3 + b \cdot t^2 + c \cdot t$	Antal *et al.* (2011)
2	Page	$MR = \exp(-k \cdot t^n)$	Page (1949)
3	Newton	$MR = \exp(-k \cdot t)$	O'Callaghan *et al.* (1971)
4	Henderson and Pabis	$MR = a \cdot \exp(-k \cdot t)$	Henderson and Pabis (1961)

$$SEC = \frac{E \times 3{,}6}{m_0 - m_f} \quad (5)$$

where m_o is the initial mass of the sample and m_f is the final mass of the sample.

The electrical energy consumption (E, kWh) during dehydration was measured by an ammeter (model EKM 265, Conrad Electronic GmbH, Hirschau, Germany).

2.6 Hardness

The texture is most accurately determined by mechanical testing (Chong *et al.*, 2014). The texture of dehydrated white-fleshed sweet potato products was measured by a compression test using CT3-4500 texture analyzer (Brookfield Engineering Laboratories, Middleboro, USA). The following setting parameters were used: 4.5 kg force load cell, 2 mm s^{-1} test speed, 20 mm travel distance and 4 mm diameter of the cylindrical

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probe. The maximum depth of penetration was 3 mm and the trigger force was 10 g. A dried sweet potato sample was placed on a rotary base table with a 115 mm diameter while compressing the sweet potato samples. The maximum compression force of the sample was used to describe the material texture in terms of firmness. The results of the penetrometer measurements are reported in Newton (N).

2.7 Color

Taking into account consumer preferences and the property of the fresh material, the method of drying must be chosen so as to: compared to the fresh material, the appearance of the finished product has changed only slightly. The color of dried white-fleshed sweet potato slices was measured with a ColorLite sph900 colorimeter (ColorLite GmbH, Katlenburg-Lindau, Germany). A spectrophotometer for a standard illuminant D65, observers 10 and 8 diaphragm was used to characterize color parameters of sweet potato. The powder obtained by grinding in a laboratory milling machine (model QC-124, Kapacitív Ltd, Budapest, Hungary) was used for color estimation of the dried material. The colorimeter is supplied with a special adapter. MA38 adapter converts the scanning spot from 3.5 to 38 mm. This device can be used to measure powdered products. The color values were expressed as L^* (whiteness/darkness), a^* (redness/greenness), and b^* (yellowness/blueness). The change in sweet potato color, which is referred to as the total color difference (ΔE), was calculated according to the following equation (6):

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \quad (6)$$

Fresh sweet potato slices were used as a reference and the higher ΔE indicates a greater color change compared to the control material.

2.8 Data analysis

Each experimental conditions were performed in triplicate for each sample and the average of the water content at each value was used for preparing the drying curves. A significant difference between drying methods was determined by a one-way ANOVA Tukey test ($P < 0.05$, $P < 0.01$). Data were processed on IBM SPSS Statistics version 20.0 (IBM Inc., Armonk, NY, USA) for Windows software.

3. Results and discussion

3.1 Drying characteristics of sweet potato

The final moisture content values of sweet potato (in MR and dry basis) slices produced by single and two-stage drying were indicated in Tables 1 and 2, respectively. The drying curves for the three different methods dried (VD-FD, MIR-FD and FD) pretreated sweet potato at 40, 50, and 60°C are shown in Figure 1. The operational time varies among the single and two-stage drying methods, the FD, VD-FD and MIR-FD need 1260, 900-1020 and 605-843 mins to finish the dehydration procedures, respectively. This study revealed that the freeze-drying time-consuming processing technique in contrast to MIR-FD and VD-FD. It was found that the drying rate decreased continuously throughout the drying process until the final moisture content (0.0353-0.0884 kg water kg dry matter^{-1} d.b.).

In Figure 1, it can be observed that the drying progress of freeze-drying consists of three stages. First, the drying rate is slow and then becomes constant (second), and finally, the drying rate slows down (third). Our finding is consistent with the results of a previous study (Tang and Pikal, 2004). Both constant and falling drying rate periods were observed at far-infrared freeze-drying (Lin *et al.*, 2005).

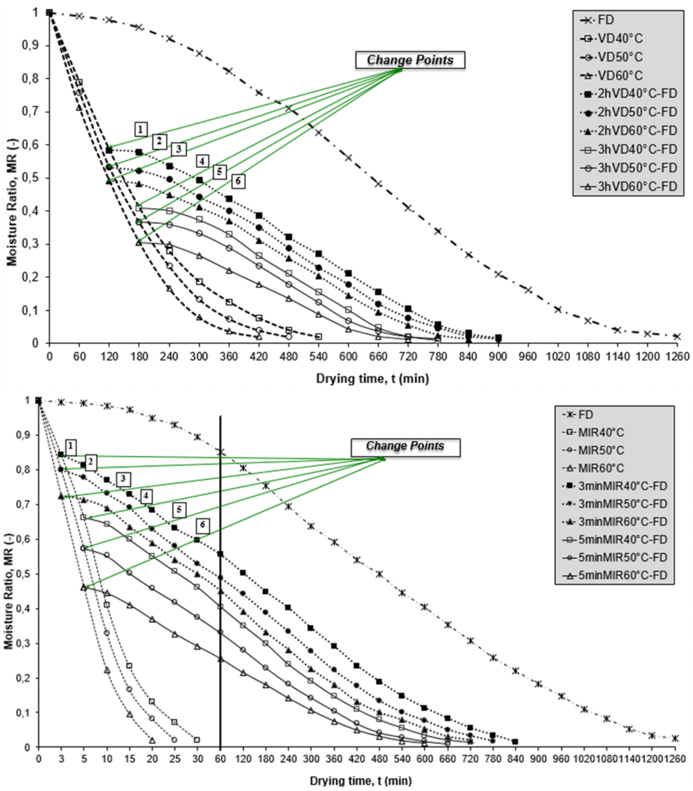

Figure 1. Effect of single and two-stage drying methods on drying time for pretreated sweet potato slices.

It is illustrated in Figure 2, that the drying time to reach the final water content (0.0353-0.0884 kg water kg dry matter^{-1} d. b.) was 605-843, 900-1020 and 1260 mins for unpretreated MIR-FD, VD-FD and FD samples, respectively. It was also observed that pretreated sweet potato slices dried in the same amount of drying time as untreated slices.

The connection points (points 1-6) of the hybrid drying methods (VD-FD and MIR-FD) are shown in

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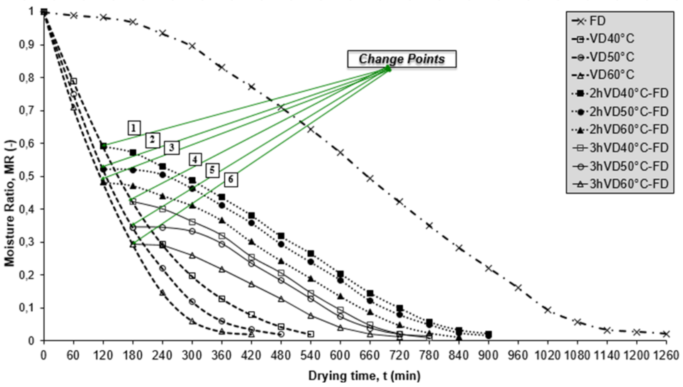
Figures 1-2. The dimensionless moisture content values of citric acid pretreated and untreated sweet potatoes at the junction ($MR_{residue}$) are given in Tables 1-2.



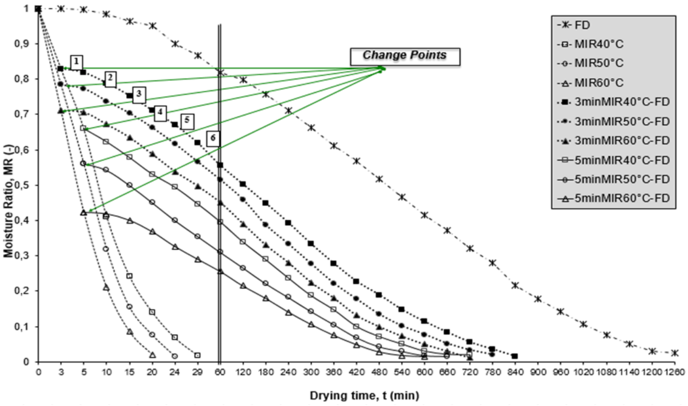


Figure 2. Effect of single and two-stage drying methods on drying time for unpretreated sweet potato slices.

Table 4 shows the significant effect of single and two-stage drying methods on drying time (P<0.01). A comparison using a one-way analysis of variance (ANOVA) is shown in Table 4.

The drying temperature range used for pre-drying is similar to a previous study (Fan *et al*., 2015). In the case of vacuum pre-drying (VD-), it was found that the water transfer increased and the drying time decreased, compared to single-stage FD. The vacuum pre-drying was performed in constant and falling rate drying periods.

An increase in drying temperature at pre-drying resulted in a decline in the operational time at hybrid drying, thus raising the drying rate. This increase in drying rate is because of the raised heat transfer potential between the drying air and the sweet potato, which favors the removal of moisture from the samples (Zhu and Jiang, 2014). The drying temperature had an outstanding effect on the reduction of the moisture ratio. Falade and Solademi (2010) reported that the higher air temperature (from 50 to 80°C) resulted in a higher drying rate, and consequently shorter drying time.

At the same pre-drying temperature, the drying rate of mid-infrared pre-drying (MIR-) was higher than that of vacuum pre-drying, resulting in a shorter operational time. The MIR drying has a higher drying rate, than the vacuum drying method, and is applicable as a pre-drying technique before lyophilization. Our results agree with the Onwude *et al*. (2019a) experimental results, that the drying kinetics were significantly affected by drying temperature and MIR intensity at sweet potato drying.

The moisture evaporation from samples under MIR pre-drying occurs more rapidly with mid-infrared heating. The drying curve of mid-infrared shows that drying of sweet potato slices happens in a constant and falling-rate period. According to Thao and Noomhorm (2011), the shorter drying time in infrared drying could be explained by the penetration of radiation into the sample offered more uniform heating, reduced moisture gradient during heating as well as drying period or caused water molecules to vibrate, at that state, less energy was needed to transport of water vapor out of the foods.

The combination of 60°C-5 min-MIR-FD presented the greatest reduction in drying time (51.98%) as compared to single-stage FD. Onwude *et al* (2019a) found that the intermittent infrared and convective-hot-air drying combination method has the most favorable effect on total drying time (113–120 mins) when drying a sweet potato. Freeze-drying with far-infrared radiation was found to be able to decrease the operational time of sweet potatoes (Lin *et al.,* 2005).

3.2 Fitting of drying curves

The drying data obtained from the trials were fitted by four thin-layer mathematical models mentioned in Table 3. The best mathematical model characterizing the drying curves of white-fleshed sweet potato was chosen as the one with the highest R^2 values and the lowest RMSE values. Tables 5 and 6 show the statistical regression results of the thin-layer models, including the drying model constants and the statistical criterions used to evaluate the goodness of fitting of drying curves, including R^2 and RSME.

Table 4. Analysis of variance for influence of single and two-stage drying techniques on drying time, SEC and quality meters.

Appellations	Drying time	Specific energy consumption [SEC]	Color [ΔE]	Hardness
Drying methods	31592.451*	25445.112*	962.881*	2853.342*
error	220.331	167.440	0.432	11.672
CV	2.499	3.932	0.942	0.694

*Significant difference (p<0.01)

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Table 5. Model constants and criteria for evaluating the goodness of fit of pretreated sweet potatoes at different drying methods.

Experiment no.	Drying methods	Drying temperature T [°C]	Pre-drying time t [min]	Drying models and model constants								Statistical criterions	
				Polynomials			Page		Newton	Henderson and Pabis		R^2	RMSE
				a	b	c	k	n	k	a	k		
1	VD-FD	40	120	0.0004	-0.0108	0.0413	-	-	-	-	-	0.9996	0.010052
							0.236	0.742	-	-	-	0.9585	0.185033
									0.289	-	-	0.9968	0.042196
										1.035	0.278	0.9974	0.041436
2	VD-FD	40	180	0.0008	-0.0224	0.1420	-	-	-	-	-	0.9995	0.010187
							0.233	0.966	-	-	-	0.9741	0.146389
									0.289	-	-	0.9968	0.042196
										1.035	0.278	0.9974	0.041436
3	MIR-FD	40	3	0.0001	-0.0035	-0.0143	-	-	-	-	-	0.9995	0.010134
							0.132	0.724	-	-	-	0.9483	0.221065
									0.185	-	-	0.9863	0.169900
										1.0121	0.191	0.9862	0.177454
4	MIR-FD	40	5	0.0002	-0.0055	-0.0001	-	-	-	-	-	0.9996	0.010007
							0.136	0.939	-	-	-	0.9719	0.166308
									0.185	-	-	0.9863	0.169900
										1.0121	0.191	0.9862	0.177454
5	VD-FD	50	120	0.0004	-0.0121	0.0534	-	-	-	-	-	0.9997	0.009910
							0.238	0.784	-	-	-	0.9631	0.146526
									0.293	-	-	0.9965	0.063481
										1.0132	0.314	0.9971	0.053614
6	VD-FD	50	180	0.0009	-0.0236	0.1508	-	-	-	-	-	0.9997	0.009919
							0.253	0.934	-	-	-	0.9769	0.151841
									0.293	-	-	0.9965	0.063481
										1.0132	0.314	0.9971	0.053414
7	MIR-FD	50	3	0.0001	-0.0036	-0.0190	-	-	-	-	-	0.9994	0.010503
							0.167	0.751	-	-	-	0.9478	0.197468
									0.284	-	-	0.9862	0.118121
										1.0026	0.269	0,9878	0.111004

FD: freeze-drying, MIR-FD: mid-infrared-assisted freeze-drying, VD-FD: vacuum pre- and freeze finish drying.

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Table 5 (Cont.). Model constants and criteria for evaluating the goodness of fit of pretreated sweet potatoes at different drying methods.

Experiment no.	Drying methods	Drying temperature T [°C]	Pre-drying time t [min]	Drying models and model constants								Statistical criterions	
				Polynomials			Page		Newton	Henderson and Pabis		R^2	RMSE
				a	b	c	k	n	k	a	k		
8	MIR-FD	50	5	0.0002	-0.0048	-0.0048	-	-	-	-	-	0.9996	0.010031
							0.183	0.948	-	-	-	0.9692	0.188201
									0.284	-	-	0.9862	0.118121
										1.0026	0.269	0.9878	0.111004
9	VD-FD	60	120	0.0005	-0.0130	0.0609	-	-	-	-	-	0.9998	0.009856
							0.262	0.833	-	-	-	0.9567	0.159538
									0.348	-	-	0.9968	0.061693
										0.986	0.342	0.997	0.060232
10	VD-FD	60	180	0.0008	-0.0198	0.1175	-	-	-	-	-	0.9992	0.011682
							0.278	0.996	-	-	-	0.9768	0.141166
									0.348	-	-	0.9968	0.061693
										0.986	0.342	0.997	0.060232
11	MIR-FD	60	3	0.0002	-0.0054	-0.0003	-	-	-	-	-	0.9994	0.011030
							0.234	0.902	-	-	-	0.9463	0.181994
									0.382	-	-	0.9886	0.096890
										1.028	0.366	0.9902	0.083336
12	MIR-FD	60	5	0.0001	-0.0038	-0.0065	-	-	-	-	-	0.9996	0.010002
							0.247	0.911	-	-	-	0.959	0.174823
									0.382	-	-	0.9886	0.096890
										1.028	0.366	0.9902	0.083336
13	FD	-	-	0.0002	-0.0085	0.0263	-	-	-	-	-	0.9998	0.009833
							0.066	1.048	-	-	-	0.9031	0.293073

FD: freeze-drying, MIR-FD: mid-infrared-assisted freeze-drying, VD-FD: vacuum pre- and freeze finish drying.

Table 6. Model constants and criterions for evaluating the goodness of fit of no pretreated sweet potatoes at different drying methods.

Experiment no.	Drying methods	Drying temperature T [°C]	Pre-drying time t [min]	Drying models and model constants								Statistical criterions	
				Polynomials			Page		Newton	Henderson and Pabis		R^2	RMSE
				a	b	c	k	n	k	a	k		
1	VD-FD	40	120	0.0004	-0.0106	0.0374	-	-	-	-	-	0.9998	0.007659
							0.239	0.751	-	-	-	0.9606	0.076146
									0.299	-	-	0.9952	0.037947
										0.995	0.27	0.9977	0.034352
2	VD-FD	40	180	0.0007	-0.018	0.0993	-	-	-	-	-	0.9997	0.009256
							0.242	0.977	-	-	-	0.9787	0.061632
									0.299	-	-	0.9952	0.037947
										0.995	0.27	0.9977	0.034352
3	MIR-FD	40	3	0.0002	-0.0051	0.0006	-	-	-	-	-	0.9996	0.009887
							0.127	0.911	-	-	-	0.9258	0.289206
									0.194	-	-	0.9888	0.174246
										0.986	0.188	0.989	0.17281
4	MIR-FD	40	5	0.0002	-0.0051	-0.0034	-	-	-	-	-	0.9997	0.009344
							0.133	0.987	-	-	-	0.972	0.253021
									0.194	-	-	0.9888	0.174246
										0.986	0.188	0.989	0.17281
5	VD-FD	50	120	0.0005	-0.0148	0.0792	-	-	-	-	-	0.9996	0.009784
							0.256	0.713	-	-	-	0.9555	0.094155
									0.337	-	-	0.9961	0.055384
										0.981	0.309	0.9972	0.048207
6	VD-FD	50	180	0.001	-0.0268	0.185	-	-	-	-	-	0.9993	0.011543
							0.265	0.925	-	-	-	0.9709	0.073213
									0.337	-	-	0.9961	0.055384
										0.981	0.309	0.9972	0.048207
7	MIR-FD	50	3	0.0002	-0.0061	0.0079	-	-	-	-	-	0.9996	0.009665
							0.152	0.806	-	-	-	0.9246	0.197462
									0.292	-	-	0.9877	0.116022
										0.991	0.283	0.9887	0.110116

FD: freeze-drying, MIR-FD: mid-infrared-assisted freeze-drying, VD-FD: vacuum pre- and freeze finish drying.

Table 6 (Cont.). Model constants and criterions for evaluating the goodness of fit of no pretreated sweet potatoes at different drying methods.

Experiment no.	Drying methods	Drying temperature T [°C]	Pre-drying time t [min]	Drying models and model constants								Statistical criterions	
				Polynomials			Page		Newton	Henderson and Pabis		R^2	RMSE
				a	b	c	k	n	k	a	k		
8	MIR-FD	50	5	0.0001	-0.0038	-0.0144	-	-	-	-	-	0.9995	0.010339
							0.175	0.932	-	-	-	0.9726	0.155435
									0.292	-	-	0.9877	0.116022
										0.991	0.283	0.9887	0.110116
9	VD-FD	60	120	0.0005	-0.0145	0.0725	-	-	-	-	-	0.9997	0.009683
							0.271	0.822	-	-	-	0.957	0.160472
									0.369	-	-	0.9949	0.068569
										0.977	0.355	0.9955	0.064618
10	VD-FD	60	180	0.0009	-0.0222	0.1371	-	-	-	-	-	0.9996	0.009743
							0.294	0.961	-	-	-	0.9775	0.099775
									0.369	-	-	0.9949	0.068569
										0.977	0.355	0.9955	0.064618
11	MIR-FD	60	3	0.0002	-0.0057	0.0046	-	-	-	-	-	0.9995	0.010778
							0.228	0.746	-	-	-	0.9161	0.265337
									0.403	-	-	0.9913	0.077145
										0.979	0.394	0.9921	0.076257
12	MIR-FD	60	5	0.0002	-0.0063	0.0215	-	-	-	-	-	0.9994	0.010843
							0.254	0.882	-	-	-	0.945	0.181873
									0.403	-	-	0.9913	0.077145
										0.979	0.394	0.9921	0.076257
13	FD	-	-	0.0003	-0.009	0.0319	-	-	-	-	-	0.9997	0.009688
							0.055	1.083	-	-	-	0.9117	0.282199

FD: freeze-drying, MIR-FD: mid-infrared-assisted freeze-drying, VD-FD: vacuum pre- and freeze finish drying.

The drying constant (k) of Henderson-Pabis and Newton models increased (VD-FD: from 0.278 to 0.342, MIR-FD: from 0.191 to 0.366 and VD-FD: from 0.289 to 0.348, MIR-FD: from 0.185 to 0.382) with increasing the pre-drying temperature at citric acid pretreatments (Table 5). The drying constant (k) of Henderson-Pabis and Newton models increased (VD-FD: from 0.270 to 0.355, MIR-FD: from 0.188 to 0.394 and VD-FD: from 0.299 to 0.369, MIR-FD: from 0.194 to 0.403) with increasing the pre-drying temperature at without pretreatments (Table 6).

The vacuum and mid-infrared pre-drying experimental data were used to simulate the drying curves of sweet potato slices using the Newton and Henderson-Pabis models. Two mathematical models, namely Page and third-degree polynomial were tested to fit the drying curve of the freeze-drying and post-drying sweet potato.

Thao and Noomhorm (2011) and Zhu and Jiang (2014) used Newton, Page, Henderson and Pabis thin-layer mathematical models for describing the drying behavior of sweet potatoes under hot air, infrared and fluidized bed drying. In a previous study, it was found that the modified Page equation best described the thin-layer hot-air drying of sweet potato slices (Diamante and Munro, 1991). Falade and Solademi (2010) found that the Page model is suitable for thin-layer drying of 5-15 mm thick slices of sweet potato at a drying temperature of 50-80°C. According to Lin et al (2005), the Page model described the far-infrared freeze-drying characteristics of sweet potatoes properly, since the coefficients of determination (R^2) were above 0.98.

All thin-layer drying models are suitable to describe the single and two-stage drying processes of sweet potato slices. This is because that the R^2 and RMSE values were generally greater and lower than 0.903 and 0.293073 in all the cases. According to Devi and Mani (2019), if the coefficients of determination (R^2) values of the empirical drying model are greater than 0.9, then the model is suitable for fitting.

Based on our results, the third-degree polynomial and Henderson-Pabis models were found to be the best thin-layer models for fitting the drying kinetic data of the sweet potato when considering the closeness of the maximum R^2 and minimum RMSE of the four models. The statistical parameter estimations of third-degree polynomial and Henderson-Pabis models showed that R^2 and RMSE values ranged from 0.9998 to 0.9862, and 0.007659 to 0.177454, respectively.

Similar to our results, Doymaz (2012) also found that the Henderson and Pabis model more accurately describes the drying curves of infrared-dried sweet potato slices than the Newton model.

The fitting procedure showed that the applied models could be used to predict the thin-layer drying behavior of sweet potatoes.

3.3 Energy uptake of drying processes

Figure 3 shows the specific energy consumption (SEC) of pre- and unpretreated sweet potato slices during single and two-stage drying operations at different drying temperatures. The FD-specific energy consumption - defined by the equation 5. - was the highest (SEC: 527.8 MJ kg_{water}^{-1}) among the three drying methods, whereas 60°C-5 min-MIR-FD energy uptake was the lowest (SEC: 254.3 MJ kg_{water}^{-1}). The high electricity cost of lyophilization is due to the high energy input required to achieve low temperature and low pressure, and heat transfer to the product for drying (Ciurzyńska and Lenart, 2011).

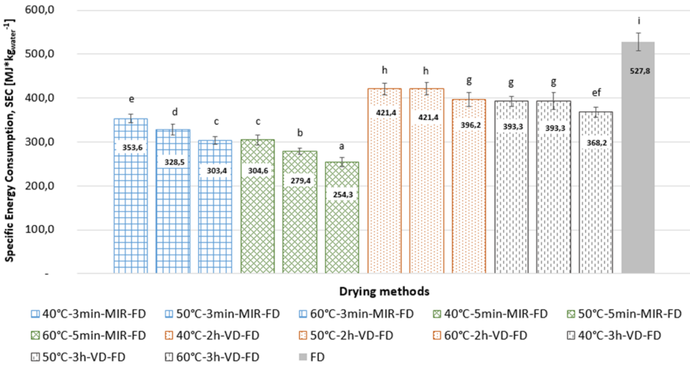

Figure 3. Influence of different drying techniques on SEC of sweet potato slices. Values are presented as mean±SD. Bars with different notations are statistically significantly different ($p<0.05$).

Consistent with previous studies, the SEC value for hybrid drying decreased significantly ($P<0.05$) with increasing pre-drying temperature (from 40°C to 60°C) and operational time (from 3 mins to 5 mins and from 2 hrs to 3 hrs). Energy consumption was reduced by far-infrared drying at higher temperatures (from 60 to 80°C), slower air velocities (from 0.8 to 0.6 m/s) and thinner steamed sweet potatoes (8 mm) (Lee *et al.,* 2017).

It was found that there is a significant difference ($P<0.05$) between the energy consumption of MIR-FD and VD-FD drying methods, with the exception of 40°C-3min-MIR-FD and 60°C-3h-VD-FD methods. The results show that MIR pre-drying has a more favorable effect on SEC than VD pre-drying.

These studies show that the use of infrared and vacuum drying as pre- or finish drying in combined drying has a beneficial effect on the energy uptake of drying during the drying of sweet potatoes. Onwude *et al*. (2019a) reported that the combined infrared and hot-

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air drying (SEC: 27.67–41.44 kWh kg^{-1}) resulted in 69.34–85.59% reduction in the SEC of convective hot-air drying. The energy consumption of microwave-freeze-drying (10027.33 kJ kg_{water}^{-1}) was about two times higher than that of microwave-vacuum drying methods (4259.33 kJ kg_{water}^{-1}) (Liu *et al*., 2012).

The mid-infrared freeze-drying (60°C-5 min-MIR-FD) presented the greatest reduction in specific energy consumption (51.82%) compared to single-stage freeze-drying. The specific energy consumption of the 60°C-3 h-VD-FD method is also noteworthy.

The results show that there is a direct correlation between the total operating time of the different drying methods and the SEC value.

Table 4 shows that specific energy consumption (SEC) was affected by different drying methods in sweet potato slices (P<0.01).

3.4 Effect of drying on surface hardening

The textural characteristic presented in this paper viz. hardness values of sweet potato changed during the drying procedures. Figures 4-5 illustrate the hardness values of white-fleshed sweet potatoes dried with single and two-stage drying and pretreated or unpretreated. The hardness of the raw sample is 1.651 N. This value was found to be higher than pretreated and pre-dried at 40-50°C and FD sweet potatoes, except for 40-50°C-5min-MIR-FD materials. For the unpretreated and dried samples, only freeze-dried, 40°C-3min-MIR-FD, 60°C-3min-MIR-FD and 40°C-2h-VD-FD sweet potatoes have lower hardness values compared to the raw sample. This is probably due to the combination of pre-treatment and freeze-drying.

It was found that the firmness values of pretreated sweet potato were affected by pre-drying time and pre-drying temperature except for 50°C-MIR-FD products (P<0.05). For the unpretreated sweet potato samples, it was observed that the texture was mainly influenced by the pre-drying time, with the pre-drying temperature only at 40-50°C (P<0.05). In general, the highest hardness was observed in VD-FD, followed by those in MIR-FD and FD, increasing slightly with an increase in pre-drying time and temperature. The significantly low hardness (P<0.05) of the lyophilized sweet potato slice is due to the crisp, porous, spongy structure and soft of the freeze-dried product (Pan *et al*., 2008; Setiady *et al*., 2009). The hardness of hybrid dried sweet potato slices is adequate if the difference in hardness of the lyophilized samples is as small as possible.

Figures 4-5 show that the firmness of products pretreated by citric acid is higher than that of the products unpretreated at 60°C. Our results are in contrast to the conclusion of Xiao *et al.* (2009). The firmness of the dried sweet potato bars underwent 0.2 and 0.4% citric acid solution before drying at a temperature of 60°C was lower than that of not pretreated samples (Xiao *et al*., 2009). The citric acid pretreatment is characterized by lower (P<0.05) product hardness in all drying modes at drying temperatures of 40 and 50°C, except for 5min-MIR-FD at 40°C. This is probably due to the fact that citric acid pretreatment can cause softening of structure and lead to low firmness of dried samples.

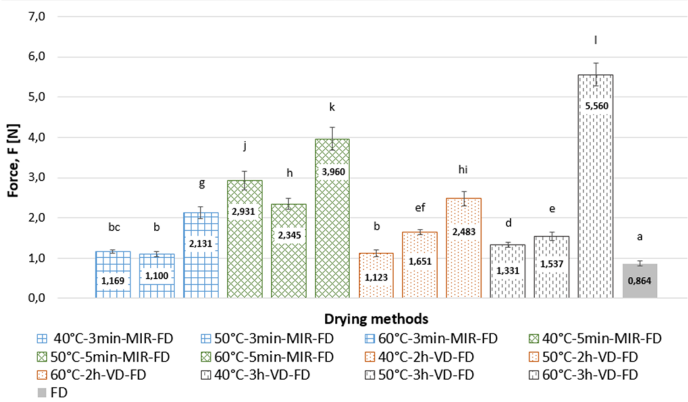

Figure 4. Effect of various drying methods on the texture of pretreated sweet potato slices. Values are presented as mean±SD. Bars with different notations are statistically significantly different (p<0.05).

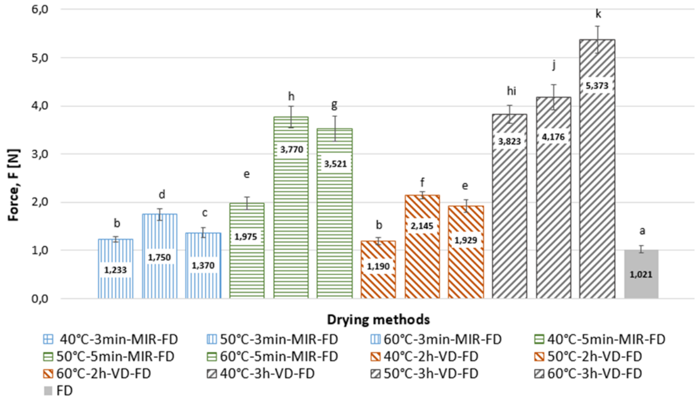

Figure 5. Effect of various drying methods on the texture of unpretreated sweet potato slices. Values are presented as mean±SD. Bars with different notations are statistically significantly different (p<0.05).

Agree with previous studies, we found that infrared and vacuum pre-drying have a good effect on the hardness of the product. Sweet potato granules undergoing microwave-freeze-drying processing own a maximum penetration force was 23.06 N, whereas microwave-vacuum drying treated samples show a higher penetration force (27.95 N) (Liu *et al*., 2012). Thao and Noomhorm (2011) found that the hardness of sweet potato starches was slightly lower by infrared drying than by tray drying, with no significant difference (P>0.05) between them.

The result suggested that both 40°C-2h-VD-FD and

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40-50°C-3min-MIR-FD methods can maintain the texture of sweet potatoes with citric acid pretreatment well and approached the value of the FD sample.

The reason for the high hardness of the samples pre-dried at 60°C is the high air temperature during drying (Jaisut *et al.*, 2009).

The results of data analysis of variance (ANOVA) in Table 4 show that the different drying methods have a significant effect on firmness of products, in the 1% probability level (P<0.01).

3.5 Effect of drying on color

Dehydration is a process that causes some alterations in the color of the food products. The different drying methods have a significant effect (P<0.01) on color retention of the dried product (Table 4).

Figures 6-7 show the color difference (ΔE) for the white-fleshed sweet potato after drying with different conditions and pretreated or unpretreated. A greater ΔE value presents a larger color difference from the reference (color parameters of raw white-fleshed sweet potato: L* = 96.22, a* = -1.71 and b* = 15.9). The total color difference (ΔE) of the powder significantly increased (P<0.05) with increasing pre-drying temperature for pretreated and unpretreated samples. It can be observed, especially in the samples pretreated with citric acid that the pre-drying temperature of 60°C resulted in very high ΔE values.

Ahmed *et al*. (2010b) reported that the ΔE values decreased with increasing drying temperatures (from 55 to 65°C) for sulphite-pretreated sweet potato flours. The sulphite pretreated samples had higher ΔE values than unpretreated sweet potato flours. The citric acid pretreated dried sweet potato powders were characterized by a significant reduction in ΔE values, compared with untreated dried ones. Singh *et al*. (2006) found that KMS -citric acid pretreatment has a beneficial effect on hot-air -dried sweet potato slices.

Shin *et al*. (2011) found that ΔE increased with increasing drying time at vacuum drying of sweet potatoes. This finding is consistent with our results for untreated sweet potatoes for VD-FD and MIR-FD (P<0.05). In contrast, the color difference of the samples pretreated with citric acid significantly decreased (P<0.05) with increasing pre-drying time in MIR-FD and VD-FD methods, except for 40°C-5min-MIR-FD and 40°C-3h-VD-FD products.

These studies show that two-stage drying has a good effect on the color difference of sweet potatoes. Yan *et al*. (2013) have reported that the difference in color among the microwave-vacuum-dried and freeze-dried sweet potato samples is small, but there is a significant difference (P<0.05) between them. Liu *et al.* (2012) indicated that the total color difference of the microwave freeze-dried (ΔE = 47.66) sweet potato was higher compared to the microwave-vacuum drying methods (ΔE = 44.09). Two-stage sequential infrared and hot-air dried sweet potato has better color change than that of simultaneous infrared and hot-air dried, and two-stage sequential hot-air and infrared dried ones (Onwude *et al.*, 2019b).

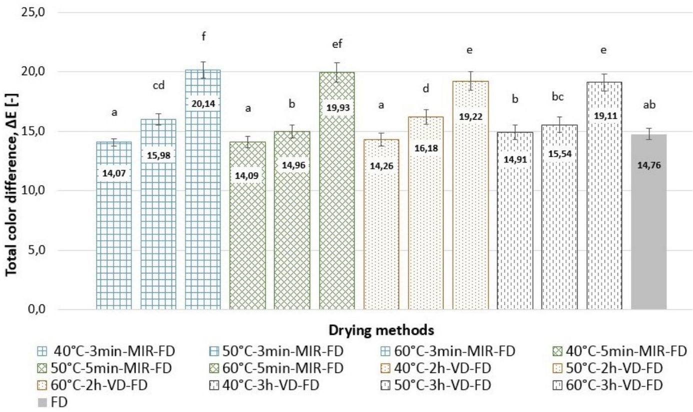

Figure 6. The effects of different drying conditions on the total color difference of pretreated sweet potato powder. Values are presented as mean±SD. Bars with different notations are statistically significantly different (p<0.05).

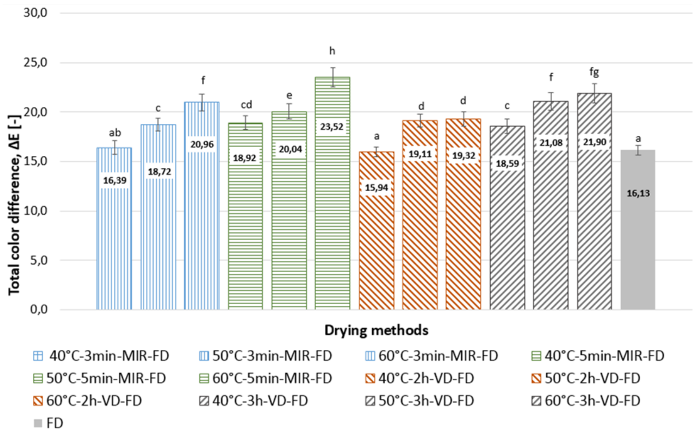

Figure 7. The effects of different drying conditions on the total color difference of unpretreated sweet potato powder. Values are presented as mean±SD. Bars with different notations are statistically significantly different (p<0.05).

There was no significant difference (P>0.05) between the color difference of the pretreated lyophilized sweet potato powders and the samples pretreated and dried by two-stage drying at 40°C. In addition, there was no significant difference (P>0.05) between unpretreated two-stage drying methods (pre-drying time: 3 min and 2 h) which dried at 40°C and unpretreated freeze-dried sweet potatoes. Ahmed *et al.* (2010a) reported that the freeze-dried sweet potato flours produced higher lightness (L* values) and lower redness (a* values) and yellowness (b* values) than those of dried with hot air, this is due to thermal exposure during this dehydration

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process. According to Wang *et al.* (2018), the color retention of freeze-dried apples can be attributed to low exposure to high temperatures and no enzymatic browning occurred. Our results also support the above findings, as the L* parameter value (97.42) of the FD sample pretreated with citric acid was found to be higher compared to L* values of the pretreated and hybrid dried sweet potato.

The result suggested that both 40°C-2h-VD-FD and 40°C-3min-MIR-FD methods can maintain the color of sweet potatoes well and had a more favorable value than lyophilized ones.

4. Conclusion

The effects of citric acid pretreatment and various drying methods on the drying characteristics, textural and color properties of white-fleshed sweet potato were investigated. The drying characteristics of sweet potatoes were determined using heated ambient air at temperatures from 40 to 60°C. The study shows that there is an inverse relationship between the drying temperature of pre-drying and drying time. Results showed that the four thin-layer models applied in this study were able to describe the drying kinetics of sweet potato slices. Statistical parameters such as R^2 and RMSE confirmed the adequacy of these mathematical models. Higher pre-drying time and pre-drying temperature significantly reduced the operational time and the specific energy consumption. The values of color and hardness degraded as the drying temperature was increased from 40°C to 60°C for mid-infrared and vacuum pre-drying. Single-stage freeze-drying decreased the hardness and increased the color difference compared to two-stage drying at a pre-drying temperature of 40°C. In general, freeze-drying gave the best quality product, but this technique was the most expensive among the three dehydration methods. Pretreatment by citric acid caused the textural and color properties of dried sweet potato to be significantly different from those of unpretreated samples. It is therefore recommended that citric acid pretreatment prior to two-stage drying should be conducted as a method for producing sweet potato. It must be concluded that vacuum pre-drying and freeze finish-drying (2h-VD-FD) at 40°C and mid-infrared freeze-drying (3min-MIR-FD) at 40°C adjustment were the best two options for sweet potato drying.

Conflict of interest

The author declare no conflict of interest.

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