EXPERIMENTAL INVESTIGATION OF THE DEHYDRATION KINETICS OF WHITE YAM (*DIOSCOREA ROTUNDATA*) USING A REFRACTANCE WINDOW™ DRYER

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ABSTRACT

The objective of this study is to investigate the dehydration characteristics of yams slices at different drying temperatures and for different thicknesses of yam slices. Yam slices 1.5, 3.0, and 4.5 mm thick were dehydrated in a laboratory-scale Refractance Window™ dryer at 65, 75, 85, and 95ºC. During the drying operations, moisture content data were recorded. The experimental moisture content data were fitted into empirical and semi-theoretical thin-layer drying models. For the process conditions studied, the drying data fitted all the thin-layer drying models considered in this report, with a correlation coefficient greater than 98%. However, the Haghi and Ghanadzadeh model gave a higher correlation than the other models implying that the model predicts the drying kinetics of yam better than other models. The data was also used to plot the drying curve and the drying rate curve. The drying times to dehydrate the yam slices to a moisture ratio of 0.11g-water/g-solid varied between 25 to 320 minutes. The drying times were observed to decrease as the temperature increased for a given slice size. Also, the drying times increased with slice size for a given temperature. This study was performed to facilitate the understanding of the dehydration characteristics of the Refractance Window™ (RW) drying operations for yam slices, with the intentions of designing, modelling, and operating a continuously operating RW dryer.

Keywords: Yams; Thin-Layer Drying Models; Drying Curves; Refractance Window™ Dryer

INTRODUCTION

Yams produce elongated large cylindrical-shaped tubers which are grown bi-annually in tropical regions of the world. Yams are from the plant species whose genus is *Dioscorea* (family *Dioscoreaceae*) and white yams, *Dioscorea rotundata*, are the most popular species especially in the dominant yam production zones in Africa (IITA, 2009). Raw yams constitute, 69.60 % water, 27.88 % carbohydrates, and 1.53 % protein; 100g of yam provides 118 kcal of energy (Cock, 1985; USDA, 2017).

Yam tubers, processed into powdered form, are used to prepare many cuisines around the world (Hudgens and Trillo, 2003). The powder preparation process involves washing, peeling, slicing, and dehydrating. The process is a labour-intensive process (Lancaster *et al.,* 1982), which may take about 3 to 5 days in regions where sun-drying is the dehydration method. Also, dirt and microorganisms may cause degradation of the quality of the dehydrated yams (Agoreyo et al., 2011). A fast-drying process producing a suitably dry final product can prevent the degradation of dehydrated yams (Maskan, 2000). There is, therefore, a need to find an alternative drying method to reduce significantly, the time taken to dry yam tubers.

The Refractance Window™ drying technique patented by Magoon (1986) and fully developed by MCD Technologies Inc., Tacoma, WA, USA, is increasingly being used in dehydrating food. Studies using a Refractance Window™ dryer conducted by Nindo and Tang, (2007) indicated that purees and juices prepared from fruits, vegetables, or herbs could be dehydrated to 10% within 3 -5 minutes. Akinola *et al.,* (2016) using a Refractance WindowT^{M} drying dryer, demonstrated that carrot slices, 3 mm thick, could be dried to a moisture content of less than 10% within 200 minutes. Akinola *et al.*, (2018) demonstrated that at 60ºC, a laboratory-scale Refractance Window™ dryer would dehydrate 3 mm-thick cucumber slices to a moisture content of less than 10% within 120 minutes. These times are considerably less than the 3 – 5 days taken for sun-drying of yams.

The article reports the dehydration characteristics of yam under varied conditions, using a laboratoryscale Refractance Window™ dryer. The dehydration characteristics determined are the drying curve and the drying rate curve, which are essential characteristics required in the design, modelling, operations of dryers, in this case, the Refractance Window^{TM} dryer.

METHODS AND MATERIALS

Drying Apparatus

The drying of yam slices was investigated using a laboratory-scale Refractance Window^{TM} dryer fabricated at the University of Lagos, Lagos, Nigeria. The apparatus is similar to those used by Akinola *et al.* (2018). The apparatus, presented in Figure 1, consists of a 1 cm thick stainless steel shallow water tub, 1.0 meter in length, 0.5 meters wide, and 75 mm deep. A 0.15 mm thick transparent polyethylene terephthalate (PET) Mylar plastic film covered the water tub.

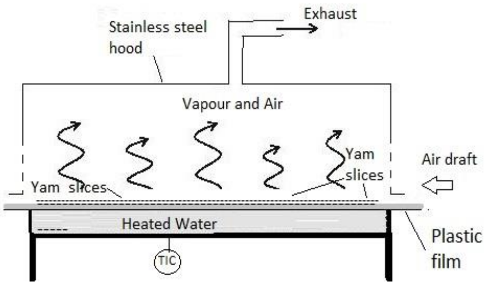

Fig. 1 A Schematic Diagram of a Refractance Window Dryer (Akinola *et al.*, 2018)

The water in the equipment was heated with a 2.5 kW heater which was controlled using a Bayite BTC201 Pre-Wired Digital Temperature Controller. The lower surface of the PET film was always in contact with the water, and the film was secured, with metal brackets. The moist air above the drying film was extracted using a suction fan in the hood above the dryer; this was to ensure that the moist air does not inhibit the drying process.

Sample Preparation and Experimental Procedure

White yam tubers bought from a local market were used, in this study. The yam tubers had lengths between 45 cm to 60 cm and maximum diameters between 11.3 and 16.4 cm; they had elongated cylindrical shapes with tapered ends. For experimentation, the yam tubers were cut, into 1.5, 3.0 and 4.5 mm thick slices, using a mechanical Mandolin slicer and then carefully cut into 2.54 cm squares with a sharp knife. Thin slices were used because they have higher drying rates than thicker slices (Azizi *et al.,* 2017). Also, the 1.5 to 4.5 mm yam slices size range used in this study is within the 1.0 - 6.0 mm slice sizes for most experiments done in the literature (Madamba *et al.,* 1996; Azizi et al., 2017).

Experiments were performed for each set of slice size, with water temperatures of 65°C, 75°C, 85°C, and 95°C in the Refractance Window^{TM} dryer. The high temperature of 95°C was selected to be slightly lower than the maximum possible operating temperature (100°C) for a Refractance Window^{TM} dryer. The low temperature of 65°C was selected to have a reasonable drying time. The 75°C and 85°C temperatures were selected to study the kinetics within the lower and upper boundaries.

The initial moisture content of yam slices was determined to be 65.98% wet basis, using an OHAUS moisture analyser (OHAUS Corporation, 2011). A dozen sets of experiments were performed, each for a combination of a temperature and a slice size. The drier was started and allowed to attain the desired temperature before loading of samples on the heated transparent polyethylene terephthalate (PET) Mylar plastic film. At 5-minute intervals, during the experiments, some yam slices were removed and their moisture content determined. All drying operations were performed 3 times.

Determining the Moisture Ratio

The moisture ratio at given drying period was determined using Equation 1(Akgun and Doymaz (2005); Doymaz (2004); Sharifian *et al.,* 2012).

$$MR = MC_t/MC_i \quad (1)$$

where

MC_t is the moisture content of the sample after drying for time t and

MC_i is the initial moisture content of the fresh sample, all in the unit of grams of water removed/grams of solids.

Thin-Layer Drying Models

The experimental data were fitted to 9 common empirical, and semi-theoretical thin-layer drying models used in the dehydration of roots, corms, bulbs, fruits and vegetables; these thin-layer models are presented in Table 1 (Ezeorah, 2018).

Table 1 Thin-Layer Drying Models Used in this Study (Akinola *et al.*, 2018)

No.	Model Names	Models
1.	Newton model	$MR = \exp(-kt)$
2.	Page model	$MR = \exp(-kt^n)$
3.	Modified Henderson and Pabis model	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
4.	Logarithmic model	$MR = a\exp(-kt) + c$
5.	Demir *et al.* model	$MR = a\exp(-kt)^n + b$
6.	Verma *et al.* model	$MR =$

Table 1 Thin-Layer Drying Models Used in this Study (Akinola *et al.*, 2018)

No.	Model Names	Models
		$a\exp(-kt) + (1-a)\exp(-gt)$
7.	Weibull model	$MR = a - b\exp(-k_0 t^n)$
8.	Peleg model	$MR = 1 - t/(a + bt)$
9.	Haghi & Ghanadzadeh	$MR = a\exp(-bt^c) + dt^2 + et + f$

Where

MR is the moisture ratio,

t is the drying time and,

a, b, c, d, e, f, k, k_0, and n are all constant determined by regression analysis.

RESULTS AND DISCUSSION

Experimental Environment

During the drying operations, the surface of the dryer was exposed to ambient conditions. The ambient conditions in the laboratory, over the several days of experimental work, were such that the temperature ranged from 29 to 31ºC, while the humidity varied between 53 to 62%.

Moisture Ratio and Drying Time Relationship

The thin layer drying model that best describes the relationship between moisture ratio and drying time, the drying kinetics, was determined by fitting the experimental drying data to the models presented in Table 1. The thin-layer drying model that best describes the drying kinetics of the yam slices is the one in which the following three criteria are satisfied. The criteria are the coefficient of determination (R^2), is to be closest to unity, the sum-of-square-error (SSE), and the root mean-square-error (RMSE) are closest to zero. The method of estimating R^2, SSE and RMSE are discussed extensively in literature (Ogunnaike, 2011; Johnson, 2017), and have been used in works on drying kinetics of agricultural food materials (Ertekin and Yaldiz, 2004; Kabiru *et al.*, 2013, Sanful et al., 2015; Akinola et al., 2016). The Matrix Laboratory software (MATLAB) was used to perform the statistical analysis.

The results of the statistical analysis for fitting the thin-layer drying models are presented in Tables 2, 3, 4, and 5.

For the 12 sets of experiments performed, all the 9 models were observed to fit the experimental data with a coefficient of variance R^2, better than 0.96. However, the Haghi and Ghanadzadeh (2005) thin-layer drying model was found to fit because it had an R^2 value closest to unity. The constants obtained for the Haghi and Ghanadzadeh model at different slice sizes and the drying temperature are presented in Table 6.

Validation of Selected Models

To corroborate that the Haghi and Ghanadzadeh (2005) thin-layer drying model best fits the drying kinetics, the relationship between the predicted (PMR) and experimental moisture ratio (EMR) values were determined. Table 7 shows that in all cases, the linear relationship had slopes close to unity and intercepts close to zero. Also, in all cases, the coefficient of variance (R^2), was better than 0.99 (Table 7). The implication is that there was no significant difference between moisture ratios determined by performing experiments and the predicted moisture ratios for the process conditions considered when modelling using the Haghi and Ghanadzadeh (2005) thin-layer drying model.

Table 2: Result Summary of the Statistical Curve Fitting Analysis at 65ºC For 1.5, 3.0 and 4.5 mm Yam Slices

Slice Thickness →		1.5 mm			3.0 mm			4.5 mm		
No.	**Model Name**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**
1	Haghi & Ghanadzadeh	0.998	0.002	0.016	0.999	0.001	0.016	1.000	0.001	0.007
2	Verma et al	0.997	0.003	0.019	0.997	0.003	0.021	0.998	0.003	0.014
3	Modified Henderson & Pabis	0.997	0.004	0.023	0.989	0.011	0.048	0.998	0.003	0.016
4	Page	0.995	0.005	0.021	0.997	0.003	0.018	0.999	0.001	0.008
5	Logarithmic	0.995	0.006	0.024	0.995	0.006	0.026	0.998	0.003	0.013
6	Demir et al	0.995	0.006	0.025	0.995	0.006	0.028	0.998	0.003	0.014
7	Peleg	0.994	0.006	0.024	0.986	0.015	0.041	0.998	0.002	0.011
8	Newton	0.994	0.007	0.024	0.994	0.007	0.026	0.990	0.012	0.027
9	Weibull	0.992	0.008	0.030	0.998	0.002	0.017	1.000	0.001	0.007

Table 3: Result Summary of the Statistical Curve Fitting Analysis at 75ºC For 1.5, 3.0 and 4.5 mm Yam Slices

Slice Thickness →		1.5 mm			3.0 mm			4.5 mm		
No.	**Model Name**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**
1	Haghi & Ghanadzadeh	1.000	0.000	0.005	0.998	0.002	0.016	0.999	0.001	0.009
2	Verma et al	1.000	0.000	0.004	0.995	0.006	0.023	0.997	0.003	0.017
3	Modified Henderson & Pabis	1.000	0.000	0.005	0.913	0.102	0.113	0.991	0.008	0.035
4	Page	0.999	0.001	0.009	0.994	0.007	0.024	0.996	0.004	0.019
5	Logarithmic	0.993	0.006	0.026	0.995	0.006	0.024	0.992	0.008	0.028
6	Demir et al	0.993	0.006	0.028	0.995	0.006	0.025	0.992	0.008	0.029
7	Peleg	1.000	0.000	0.005	0.993	0.008	0.026	0.997	0.003	0.016
8	Newton	0.969	0.026	0.051	0.994	0.007	0.023	0.978	0.021	0.042
9	Weibull	1.000	0.000	0.008	0.991	0.011	0.033	0.989	0.010	0.034

Table 4: Result Summary of the Statistical Curve Fitting Analysis at 85ºC For 1.5, 3.0 and 4.5 mm Yam Slices

Slice Thickness →		1.5 mm			3.0 mm			4.5 mm		
No.	**Model Name**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**
1	Haghi & Ghanadzadeh	1.000	0.000	0.010	0.998	0.002	0.019	0.999	0.001	0.016
2	Verma *et al*.	0.999	0.001	0.011	0.997	0.002	0.017	0.998	0.002	0.017
3	Modified Henderson & Pabis	0.999	0.001	0.015	0.998	0.002	0.019	0.998	0.002	0.018
4	Page	0.999	0.001	0.013	0.996	0.004	0.021	0.998	0.002	0.014
5	Logarithmic	0.994	0.004	0.029	0.990	0.009	0.033	0.998	0.002	0.015
6	Demir *et al.*	0.994	0.004	0.032	0.990	0.009	0.036	0.998	0.002	0.016
7	Peleg	0.999	0.001	0.011	0.994	0.005	0.024	0.995	0.006	0.025
8	Newton	0.976	0.018	0.050	0.982	0.016	0.040	0.998	0.002	0.016
9	Weibull	0.999	0.001	0.015	0.980	0.017	0.050	0.998	0.002	0.016

Table 5: Result Summary of the Statistical Curve Fitting Analysis at 95ºC For 1.5, 3.0 and 4.5 mm Yam Slices

Slice Thickness →		1.5 mm			3.0 mm			4.5 mm		
No.	**Model Name**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**	R^2	**SSE**	**RMSE**
1	Haghi & Ghanadzadeh	0.998	0.002	0.040	0.998	0.003	0.020	0.999	0.002	0.014
2	Verma et al	0.997	0.003	0.025	0.994	0.007	0.026	0.998	0.004	0.016
3	Modified Henderson & Pabis	0.989	0.008	0.091	0.994	0.007	0.031	0.998	0.004	0.018
4	Page	0.996	0.003	0.023	0.994	0.007	0.025	0.997	0.004	0.016
5	Logarithmic	0.994	0.004	0.033	0.994	0.007	0.026	0.997	0.004	0.018
6	Demir et al	0.994	0.004	0.038	0.994	0.007	0.027	0.997	0.004	0.018
7	Peleg	0.996	0.003	0.025	0.991	0.010	0.030	0.992	0.012	0.028
8	Newton	0.988	0.009	0.038	0.994	0.007	0.024	0.997	0.005	0.018
9	Weibull	0.997	0.003	0.029	0.994	0.007	0.027	0.997	0.004	0.017

Table 6 Constants for the Haghi & Ghanadzadeh for Yam Drying at Different Temperatures and Sizes

	Parameters		Constants					
No.	Temperature (oC)	Slice Size (mm)	a	b	c	d	e	F
1	65	1.5	0.605	0.216	0.520	2.061E-4	-0.020	0.395
		3.0	2.032	0.008	1.072	-8.908E-6	0.006	-1.036
		4.5	0.674	0.026	0.941	2.488E-6	-0.002	0.327
2	75	1.5	0.715	0.237	0.956	7.913E-5	-0.009	0.285
		3.0	0.286	0.350	0.357	5.756E-5	-0.013	0.714
		4.5	0.555	0.011	1.405	5.676E-6	-0.003	0.445
3	85	1.5	0.673	0.033	2.474	2.057E-4	-0.016	0.327
		3.0	2.709	0.071	0.377	5.179E-5	-0.006	-1.709
		4.5	1.313	0.015	0.920	5.047E-6	0.000	-0.315
4	95	1.5	1.839	0.238	0.263	5.645E-4	-0.022	-0.839
		3.0	0.342	0.012	2.013	1.623E-4	-0.020	0.653
		4.5	1.049	0.022	0.911	1.574E-5	-0.003	-0.048

Table 7 Experimental and Predicted Moisture Ratio at Different Temperatures

S/N	Temperature (oC)	Slice Size (mm)	Relationship	R^2
1	65	1.5	PMR = 0.9957EMR + 0.0007	0.9981
		3.0	PMR = 0.9987EMR + 0.0030	0.9984
		4.5	PMR = 1.0038EMR - 0.0012	0.9994
2	75	1.5	PMR = 0.9985EMR + 0.0016	0.9998
		3.0	PMR = 0.9990EMR + 0.0006	0.9990
		4.5	PMR = 1.0026EMR + 0.0003	0.9996
3	85	1.5	PMR = 0.9965EMR + 0.0027	0.9996
		3.0	PMR = 1.0052EMR - 0.0025	0.9979
		4.5	PMR = 1.0000EMR + 0.0011	0.9986
4	95	1.5	PMR = 0.9967EMR + 0.0023	0.9982
		3.0	PMR = 0.9978EMR + 0.0004	0.9975
		4.5	PMR = 0.9987EMR + 0.0011	0.9982

The Drying Curves

Line plots of the drying curves, i.e., the variation of moisture content with time, for the different yam slice sizes, at 65ºC, 75ºC, 85ºC, and 95ºC are shown in Figures 2, 3, 4, and 5 respectively. Figures 2 – 5 shows that for a given temperature of water in the Refractance Window^{TM} dryer, the moisture content decreased exponentially with time. Meanwhile, as the yam thickness increased from 1.5mm to 4.5mm, an increase in drying time occurred. This is because, as the yam's thickness increases, there is an increase in the amount of moisture that has to be removed from the slice. Therefore, the drying process is prolonged.

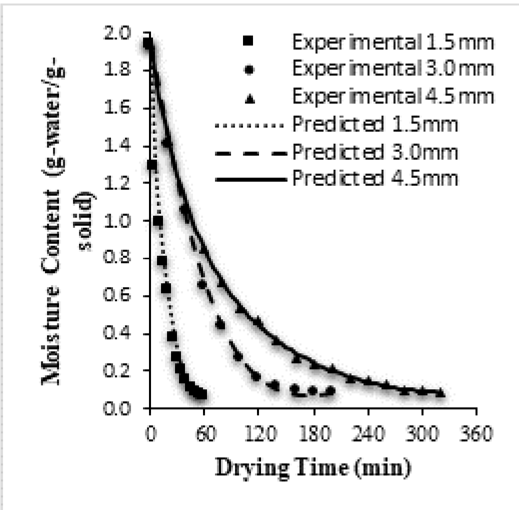

Figure 2 Experimental Drying Curves for Different Yam Slices at 65^{0}C

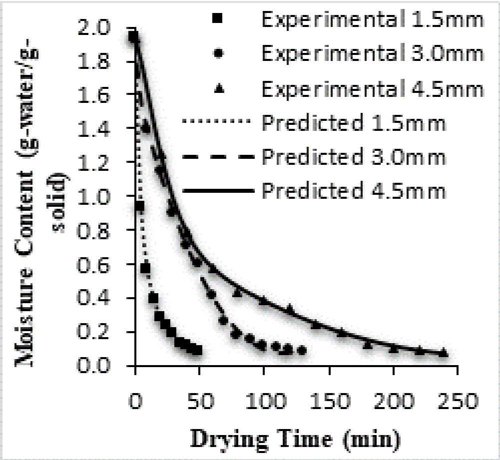

Figure 3 Experimental Drying Curves for Different Yam Slices at 75^{0}C

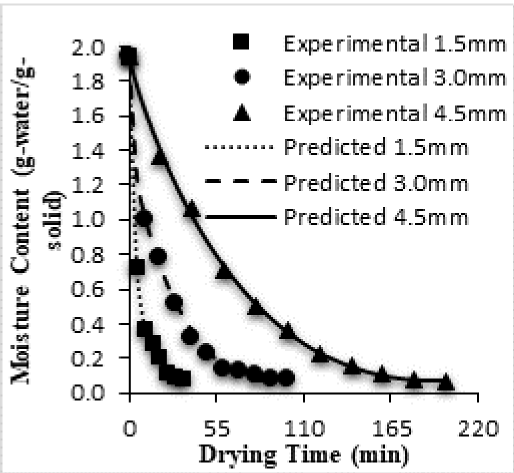

Figure 4 Experimental Drying Curves for Different Yam Slices at 85^{0}C

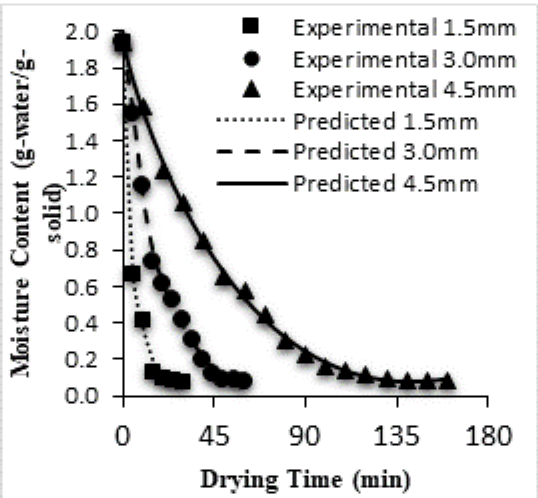

Figure 5 Experimental Drying Curves for Different Yam Slices at 95^{0}C

From the drying curves presented in Figures 2 to 5, the drying times required to dehydrate the yam slices to 0.10g-water/g-solid increases with increasing yam slices thickness for a given temperature. Also, as the drying temperature increases, the drying times decreases for a given yam slice size. Table 8 presents quantitative values of the drying times for different yam slice sizes at different temperatures.

Table 8 Drying Times for Different Yam Slice Sizes at Different Temperatures

	Temperature °C			
	65	75	85	95
Size	Minutes			
1.5 mm	60	45	35	25
3.0 mm	200	130	90	55
4.5 mm	320	240	180	160

Drying Rate Curve

Line graphs for the drying rate curves, i.e., graphs of drying rate against drying time for the 1.5, 3.0, and 4.5 mm thick yam slices with water temperatures of 65°C, 75°C, 85°C, and 95°C in the Refractance Window^{TM} dryer is shown in Figs. 6, 7, and 8, respectively. The line plots were obtained by differentiating the equations for the respective Haghi and Ghanadzadeh (2005) models that fit the experimental data points, as suggested by Kemp *et al.,* (2001). The drying data values were limited; they were, therefore, not used in plotting the drying rate curves. Figs. 6-8 shows that the drying rate rises initially then reaches a peak value and then fall; these are characteristics of a typical drying rate curve (Traub, 2002). In the initial drying rate period, the latent heat of evaporation is transferred to the slice to remove the moisture. In a typical drying curve, the peak drying rate remains constant for a specified period. However, in these set of experiments, this peak drying rate remains constant for a short period, and even appears to be absent. This phenomenon occurs because the unbound moisture on the surface of the slice structure is almost instantly expelled. When the drying rate falls, this is the falling rate period. In the falling rate period, moisture migrates from the inner spaces of each slice to the outer surface before being released. As the free moisture content approached zero, drying rates at 65^{0}C, 75^{0}C, 85^{0}C, and 95^{0}C also gradually dropped to zero, signifying the end of a drying process.

CONCLUSIONS

Thin layer slices of white yam tubers, 1.5, 3.0 and 4.0 mm thick were dried using a Refractance Window^{TM} dryer in which the dehydrating water temperature was 65, 75, 85, and 95°C. The yam slices determined to have an initial moisture content of 1.94 g-water/g-solid, were dehydrated to a moisture ratio of about 0.1 g-water/g-solid. Recorded were the variation in moisture content with dehydration time of the samples during the drying operations. The conclusions are,

1. For a given slice size, an increase in dehydrating temperature causes a decrease in drying time. Also, for a given temperature, an increase in slice size causes an increase in drying time.
2. At 65ºC the drying time when dehydrating 1.5, 3.0 and 4.5 mm thick yam slices was determined to be 60, 200, and 320 minutes respectively.
3. At 75ºC the drying time when dehydrating 1.5, 3.0 and 4.5 mm thick yam slices was determined to be 45, 130, and 240 minutes respectively.
4. At 85ºC the drying time when dehydrating 1.5, 3.0 and 4.5 mm thick yam slices was determined to be 35, 90, and 180 minutes respectively.
5. At 95ºC the drying time when dehydrating 1.5, 3.0 and 4.5 mm thick yam slices was determined to be 25, 55, and 160 minutes respectively.
6. An increase in temperature causes an increase in dying rate. This is expected as moisture movement is higher at elevated temperatures, which consequently, will cause moisture to be expelled faster for the yam sample.
7. In predicting the drying kinetics of the yam slices dehydration process, while regression analysis indicated that no significant difference exists in any of the thin-layer models tested. However, the Haghi & Ghanadzadeh thin-layer model was the most appropriate to use, as it had R^2 closest to unity, and both SSE and RSME closest to zero.
8. As most of the dehydration took place during the falling rate period, the controlling mechanism for the drying is the moisture movement through the interstices of the yam slabs. Hence, internal diffusion may be considered the mechanism by which dehydration occurs during Refractance Window™ drying.

The drying curve and the drying rate curves are fundamental characteristics used in the design and modelling of dryers in the food industry. As limited literature was found on the attributes for the Refractance Window™ drying of yams, this work presents features that will be useful for designing, modelling, and operating such equipment.

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