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Rehydration Curves Characteristics of Beetroot, Sweet Potato and Yam Slices Dried using the Refractance Window^{TM} Method

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Abstract: *This study presents four models' suitability for the rehydration ratio and moisture content history data during the hydration process of beetroot, sweet potato, and yam. The models are the Akinola et al., the Exponential, the Peleg, and the Weibull models. Rehydration occurred at 27°C for the dehydrated sample slices, which had original dimensions of 25 mm × 25 mm × 3.0 mm. During rehydration, the mass/moisture content history data was recorded for the samples. Regression analysis established that the Akinola et al. Model best fit the rehydration ratio/ mixture content changes vs time history data. The study results show a rapid increase in rehydration in the initial hour of the rehydration process. This increase gradually decreases to a contact equilibrium value. For the yam, sweet potato, and beetroot slices, the rehydration ratio values approached 2.1, 2.1 and 6.5, respectively. This study provides a better understanding of the beetroot, sweet potato, and yam slices' rehydration process. Also, knowledge of the rehydration characteristics of the agro-products will be valuable in the design, operation and optimisation of processing equipment and prediction of water absorption with time.*

Keywords: *Rehydration ratio, Moisture content, Beetroot, Sweet Potato, Yam, Exponential, Peleg and Weibull models*

1. Introduction

Root tubers such as cassava yam (*Dioscorea spp.*), (*Manihot esculenta Crantz*), sweet potato (*Ipomoea batatas L.*), and potato (*Solanum spare*) are widely grown and consumed as staple foods in many parts of Africa, Central and South America, the Pacific Islands and Asia. These tubers mentioned above are very nutritious and excellent energy sources and dietary fibre. They are the dominant portion of the standard diet for many people. (USDA, 2017a, 2017b; Subar et al., 1998a, 1998b; Reedy and Krebs-Smith, 2010). Hence, they are used worldwide in many different recipes. For this reason, getting these tubers to many distant locations where they are required is necessary. However, these products are heavy, constituting at least 70% water. Therefore, dehydrating agro-products is an essential post-harvest process before shipping to other places.

Post-harvest dehydration of agro products removes moisture, decreasing bulk, and reduces the moisture content supporting microbial growth, thereby addressing this problem. Moreover, there have been extensive studies on Post-harvest dehydration of agro products. Lin et al. (2007) incorporated freeze-dried yam slices using infrared radiation. The investigation used a 3-factor temperature, thickness and distance design for the experiment to find the optimum drying conditions. The yam slices were 1.5 to 6.0 mm thick. Akinola et al. (2017, 2018) and Akinola and Ezeorah (2016, 2018) dried carrots, yam, cassava and potato slices using the Refractance Window^{TM} drying technique at 60 to 95 °C. In Akinola et al. (2017, 2018) and Akinola and Ezeorah (2016) investigations, the root tuber slice thickness ranged from 1.5 to 6.0 mm; they established that the tuber slices could be dehydrated to a moisture content of 0.01 g-water/g-solid within 45 - 200 minutes, depending on the temperature. In addition to reducing the bulk of the agro-products, dehydration is a method of preserving the product.

There is an increasing need to consume many dried food and agricultural commodities in today's society. Therefore, dehydration is becoming a first choice method of extending the agro product's shelf-life without the product becoming unfit for future use. Thus, rehydration operations are gaining importance as these dried products will need to be rehydrated before use.

Various equations express the rehydration curves' behaviour of foods and agricultural products, namely the Peleg Model (Peleg, 1988; Kuna-Broniowska et al., 2019), the Weibull Model (Machado et al., 1998; Garcıa-Pascual et al., 2006; Corzo and Bracho, 2008), the Exponential Model (Krokida and Marinos-Kouris, 2003; Rafiq et al., 2015; Lopez-Quiroga et al., 2019) and the Akinola et al. Model (Akinola et al., 2019). The design, optimisation, and operations of rehydration processes hinge on using the best mathematical model (Marinos-

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Kouris et al., 1991; Vagenas and Marinos-Kouris, 1991). This study investigates the four models mentioned above with the rehydration ratio and moisture content history data for dehydrated beetroot, sweet potato, and yam. The intention is to obtain the most appropriate rehydration model.

2. Materials and Methods

2.1 Sample Preparation

The investigators purchased beetroot, sweet potatoes, and yams tubers from a local market in Lagos, Nigeria. The tubers were washed with potable water, peeled, and then cut into 25 mm x 25 mm x 3 mm slices. Literature indicated that tubers are cut into slices 1.5 – 6.0 mm thick before dehydrating (Adelaja et al., 2010; Akinola et al., 2017, 2018; Akinola and Ezeorah, 2016, 2018; Lin et al., 2007); therefore, deciding to cut the tubers to 3 mm thick slices seemed appropriate. The cut samples were later soaked in a sodium metabisulphite solution (5%) for about a minute. The soaking in sodium metabisulphite was to prevent decolourisation during dehydration (Kumoro and Hidayat, 2018). Later, in separate runs for each tuber type, a fabricated Refractance Window^{TM} dryer with dimensions 1.17 m × 0.46 m × 0.10 m dehydrated the samples for three hours at a water temperature of 95^{o}C. Akinola et al. (2018) article provides a detailed description of the equipment. Finally, the dehydrated samples were allowed to sit for 24 hours in a room whose humidity ranged from 34 to 45 %, after which the moisture content of the pieces was determined to be about 10% on a dry basis. The moisture content of the tuber slices was determined using an MB45 OHAUS moisture analyser (OHAUS, MB45, OHAUS Corporation, 7 Campus Drive, Parsippany, NJ 07054 USA). The entire procedure was repeated twice for each sample to obtain reproducible results.

2.2 Rehydration Experiments and Equipment

Before starting the rehydration experiments, the researchers brought the temperature of the tuber slices to 27^{o}C and then placed the slices in 50ml glass beakers containing distilled water at 27^{o}C. The beakers containing the dried samples were placed in a 19.5L Thermo Scientific Precisesn™ General-Purpose Thermostatically controlled Water Bath, Model 184/284, manufactured by Fisher Scientific Suwanee, GA 30024, USA (Fisher Scientific, 2014). The bath maintained the water temperature at 27^{o}C. At intervals of 10, 20, 30, 45, 60, 90, 120, 150, 180, 225, 270, and 1,440 minutes respectively, the samples were removed from each beaker. After rehydration, the water in the beakers was drained, and the collected samples were blotted with tissue paper to remove excess surface water. The weight and moisture content of the rehydrated samples was determined by the thermogravimetric method using the German manufactured Memmert UF55 Universal Oven Dryer (Memmert, UF55 GmbH + Co. KG, 2020). The rehydration experiments were performed in triplicates to achieve reproducible experimental results.

2.3 Modelling the Moisture Content and Rehydration Ratio

The moisture content (MC) was calculated using Equation 1, and the rehydration ratio (RR) was computed from Equation 2.

$$MC = \frac{(initial\ mass\ of\ samples - mass\ of\ solids)}{mass\ of\ solids} \tag{1}$$

$$R_r = \frac{M_{rh}}{M_d} \tag{2}$$

Where,

M_{rh} is the sample weight after rehydration, and
M_d is the sample weight of dried material.

Equations 3 to 6 test the rehydration models using rehydration ratio history data. Besides, Equations 7 to10 test the rehydration models using the moisture content history data.

Exponential Model: $$RR = RR_e - (RR_e - 1)\exp(-kt) \tag{3}$$

Peleg Model: $$RR = (RR_e - 1/k_2) + \frac{t}{(k_1 + k_2 t)} \tag{4}$$

Weibull Model: $$RR = RR_e + (1 - RR_e)\exp\left[-\frac{t}{\alpha}\right]^{\beta} \tag{5}$$

Akinola *et al.* Model: $$RR = g\exp(ht) + j\exp(qt) \tag{6}$$

Exponential Model: $$M_t = \left(M_0 - M_e\right)\exp(-kt) + M_e \tag{7}$$

Peleg Model: $$M_t = M_0 + t/(k_1 + k_2 t) \tag{8}$$

Weibull Model: $$M_t = \left(M_e - M_0\right)\left\{1 - \exp\left[-\left(t/\alpha\right)^{\beta}\right]\right\} + M_0 \tag{9}$$

Akinola *et al.* Model: $$M_t = g\exp(ht) + j\exp(qt) \tag{10}$$

Where,

M_0, M_t *and Me* are the initial moisture content, moisture content at time t and equilibrium moisture content respectively (all in kg-water/kg-solid or g-water/g-solid);
RR and RR_e are the rehydration ratio at any time t and equilibrium rehydration ratio (both ratios being dimensionless);
α, β, g, h, j, k, k_1, k_2, *q* are constants observed from regression analysis.

In the statistical analysis of the equations, the best model has the coefficient of determination (R^2) closest to 1, while the sum-of-square-error (SSE) and the root-mean-square error (RMSE) are closest to zero (Togrul and Pehlivan, 2002; Midilli et al., 2002; Demir et al., 2004). Estimating R^2, SSE and RMSE are discussed extensively by Ogunnaike (2011) and Johnson (2017). The MATLAB software developed by MathWorks (2019) estimated the R^2, SSE and RMSE values.

3. Results and Discussion

3.1 Evaluation of Rehydration Ratio Models

The rehydration ratio of the various sample slices increases rapidly initially. After a long time, the rehydrated pieces achieved a constant rehydration ratio value; this was consistent with studies by other authors (Maharaj and Sankat, 2000; Mujaffar and Lee Loy, 2016; Akinola et al., 2019). Therefore, the rehydration ratio at each rehydration time, t, was calculated from the experimental data. First, the rehydration ratios are determined using Equation 2. Then, statistical parameters such as R^2, SSE and RMSE for the Peleg, Exponential, Weibull and Akinola et al. models are estimated using Equations 3, 4, 5 and 6. For sweet potato and beetroot, Akinola et al. (2019) model fit the rehydration ratio versus time data better than the Peleg, the Exponential and the Weibull Models. However, for yam rehydration, the Peleg model presented the best fit. Table 1 summarises the statistical analysis for the rehydration ratio models, and Table 2 shows the model constants (with a 95% confidence level) by fitting the rehydration data to Equations 3, 4, 5 and 6.

The rehydration ratio history data for the Yam slices rehydrated at 27°C (see Table 1) showed R^2 for Peleg and Akinola et al. models to be 0.9907 and 0.9889, respectively, indicating an excellent fit. In contrast, both the Exponential and Weibull models had the same R^2 of 0.9364, also a good fit (George et al., 2016). Furthermore, the Peleg model also had the lowest SSE and RMSE of 0.01055 and 0.03248, respectively, which shows that it is the best of the four models to describe the rehydration behaviour of the yam slices.

Regarding the rehydration ratios, the Akinola et al. model best fits the data for sweet potato slices, with the highest R^2 of 0.9945 and the lowest SSE and RMSE of 0.00745 and 0.03052, respectively. Therefore, it can be considered the best model to describe the rehydration characteristics of the sweet potato slices. The Exponential, Weibull and Peleg models achieved R^2, SSE and RMSE of 0.98900, 0.01485, 0.03674; 0.98900, 0.01485, 0.03853 and 0.94660, 0.07533, 0.08679, respectively.

The Akinola et al. model best fits the rehydration behaviour of the beetroot samples. Statistical analysis of the data estimates an R^2 value of 0.9963 and SSE and RSME values of 0.1075 and 0.1159, respectively. The Peleg model with its R^2, SSE and RMSE of 0.9944, 0.1659 and 0.1288, respectively, was the second-best fit. Finally, the Exponential and Weibull models with R^2, SSE and RMSE of 0.9434, 1.6610, 0.3886 and 0.9434, 1.6610, 0.4076, respectively, were third and fourth.

Figures 1, 2 and 3 show the experimental and predicted rehydration ratio variation with rehydration time for yam, sweet potato, and beetroot. The initial rehydration ratio for each sample is 1.0. Therefore, the plots of the experimental and predicted rehydration ratios versus time are a good fit, and the regression analysis results as shown in Table 1. The rehydration ratio increases rapidly during the first hour and then slows down progressively until it attains equilibrium. A simple linear regression analysis between the experimental and predicted data determines which rehydration model best fits the Rehydration Ratio history data. Table 3 presents the results for the rehydration ratio models.

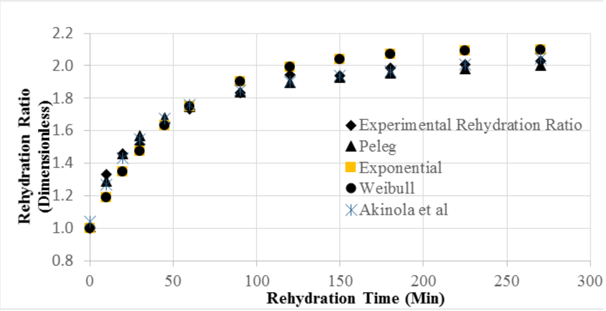

Figure 1. Experimental and Predicted Rehydration Curves of Yam slices (RR)

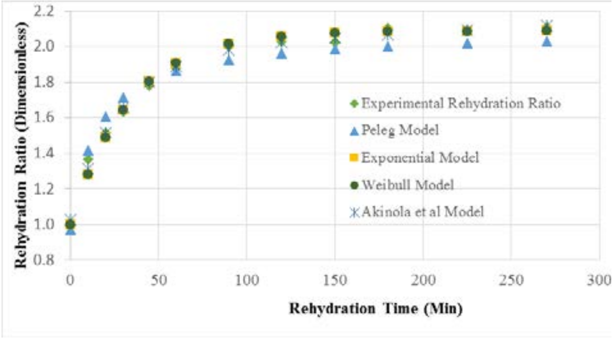

Figure 2. Experimental and Predicted Rehydration Curves of Sweet Potato slices (RR)

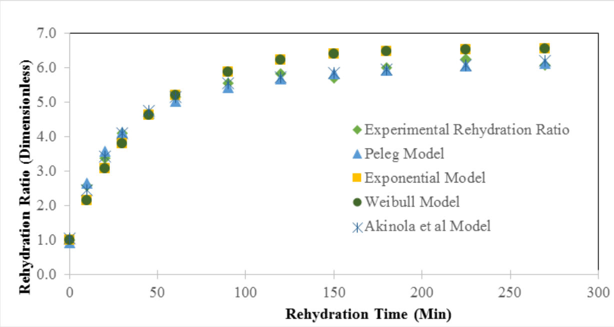

Figure 3. Experimental and Predicted Rehydration Curves of Beetroot slices (RR)

Table 1. Summary of Statistical Analysis (Rehydration Ratio Models)

	Yam			**Sweet Potato**			**Beetroot**		
Model Name	*R^2*	*SSE*	*RMSE*	*R^2*	*SSE*	*RMSE*	*R^2*	*SSE*	*RMSE*
Akinola et al.	0.9889	0.01254	0.03960	0.9945	0.00745	0.03052	0.9963	0.10750	0.11590
Peleg	0.9907	0.01055	0.03248	0.9466	0.07533	0.08679	0.9944	0.16590	0.12880
Exponential	0.9364	0.07223	0.08103	0.9890	0.01485	0.03674	0.9434	1.66100	0.38860
Weibull	0.9364	0.07223	0.08499	0.9890	0.01485	0.03853	0.9434	1.66100	0.40760

Table 2. Model Constants (Rehydration Ratio Models)

Model Name	Model Constant	Yam	Sweet Potato	Beetroot
Akinola et al.	*g*	1.82200	1.97200	5.46500
	h	0.00043	0.00027	0.00047
	j	-0.77760	-0.94350	-4.40500
	q	-0.03226	-0.03504	-0.03703
Peleg	k_1	26.02000	13.49000	4.01900
	k_2	0.91050	0.89370	0.17760
Exponential	*k*	0.01880	0.02985	0.02341
Weibull	*α*	0.85340	0.68140	0.88980
	β	0.01604	0.02034	0.02083

Table 3. Experimental versus Predicted Data Validation (Rehydration Ratio Models)

Sample	Peleg Model	R^2	Exponential Model	R^2	Weibull Model	R^2	Akinola *et al.* Model	R^2
Yam	ERR = 1.0261*PRR - 0.0387	0.9917	ERR = 0.8293*PRR + 0.2804	0.9796	ERR = 0.8293*PRR + 0.2804	0.9796	ERR = 1.0001*PRR - 0.0004	0.9890
Sweet Potato	ERR = 1.0955*PRR - 0.1505	0.9728	ERR = 0.9536*PRR + 0.0833	0.9915	ERR = 0.9536*PRR + 0.0833	0.9915	ERR = 1*PRR - 0.0002	0.9945
Beetroot	1.0186*PRR - 0.0642	0.9949	ERR = 0.8484*PRR + 0.5927	0.9826	ERR = 0.8484*PRR + 0.5927	0.9826	ERR = 1*PMC - 0.0006	0.9963

3.2 Evaluation of Moisture Content *versus* Rehydration Time Models

The moisture content of the various samples increases rapidly initially. However, after a long time, the slices achieved a constant moisture content value; this was consistent with studies by other authors (Maharaj and Sankat, 2000; Mujaffar and Lee Loy, 2016; Akinola et al., 2018).

The moisture content history data obtained from the rehydration experiments performed at 27°C were fitted to the four models (Akinola et al., Exponential, Peleg and Weibull) using Equations 7 to 10. Table 4 presents the statistical analysis correlating the moisture content rehydration history data using the various models. The best model is the one with R^2 closest to 1 and SSE and RMSE values most comparable to zero. The Akinola et al. model again presented the best fit of the experimental rehydration moisture content for all the root tubers. This study found the highest R^2 of 0.9970 for yam, 0.9947 for sweet potato, and 0.9954 for beetroot. Moreover, the SSE and RMSE were the least for the Akinola et al. model. Table 5 shows the model's parameters by fitting the moisture content history data to the models.

A simple linear regression analysis was performed between the experimental and predicted data to determine which rehydration model best fits the moisture content history data. Table 6 presents the results for the moisture content models. Figures 4, 5 and 6 show the variation in moisture content of the samples with time.

Table 4. Summary of Statistical Curve Fitting Analysis (Moisture Content Models)

	Yam			Sweet Potato			Beetroot		
Model Name	R^2	*SSE*	*RMSE*	R^2	*SSE*	*RMSE*	R^2	*SSE*	*RMSE*
Akinola *et al.*	0.997	0.00249	0.01888	0.9947	0.00849	0.03483	0.9954	0.8306	0.3445
Weibull	0.9946	0.00452	0.02241	0.0692	1.491	0.4071	0.9789	3.844	0.6535
Exponential	0.9946	0.00452	0.02242	0.9369	0.1011	0.106	0.9828	3.135	0.5902
Peleg	0.9934	0.0055	0.02473	0.9902	0.0157	0.04177	0.9782	3.972	0.6643

Table 5. Model Constants (Moisture Content Models)

Model Name	Model Constant	Yam	Sweet Potato	Beetroot
Akinola *et al.*	*g*	1.1210	1.5430	14.1000
	h	0.0003	0.0003	0.0002
	j	-0.9007	-1.3300	-14.8900
	q	-0.0182	-0.0246	-0.0266
Peleg	k_1	32.9800	19.0100	2.3900
	k_2	0.7756	0.5583	0.0564
Exponential	*k*	-0.0505	-0.0757	-0.0285
Weibull	*α*	0.7194	0.4224	0.8978
	β	63.4900	0.6690	1.2010

Table 6. Experimental versus Predicted Data Validation (*Moisture* Content Models)

Sample	Validation Criteria	Peleg Model	Exponential Model	Weibull Model	Akinola *et al.* Model
Yam	*Equation*	*EMC = 0.9854*PMC + 0.0142*	*EMC = 0.994*PMC + 0.0035*	*EMC = 0.7924*PMC + 0.2545*	*EMC = 1*PMC - 0.0001*
	R^2	*0.9937*	*0.9947*	*0.9843*	***0.9971***
Sweet Potato	*Equation*	*1.0072*PMC - 0.0101*	*EMC = 1.0276*PMC - 0.0403*	*EMC = 0.5306*PMC + 0.6659*	*EMC = 0.9996*PMC + 0.0004*
	R^2	*0.9903*	*0.9378*	*0.8444*	***0.9947***
Beetroot	*Equation*	*EMC = 1.0493*PMC - 0.6186*	*EMC = 0.9859*PMC - 0.0099*	*EMC = 0.9312*PMC + 0.5468*	*EMC = 0.9998*PMC + 0.0011*
	R^2	*0.9806*	*0.9847*	*0.9876*	***0.9954***

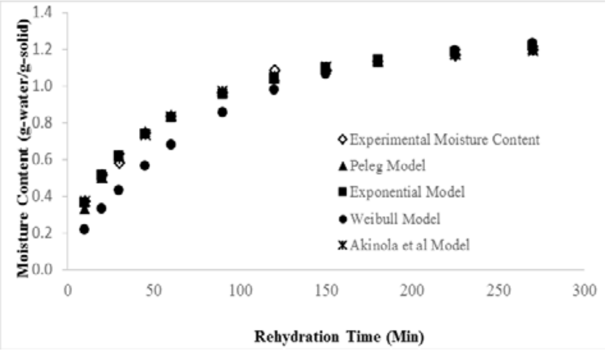

Figure 4. Experimental and Predicted Rehydration Curves of Yam slices (MC)

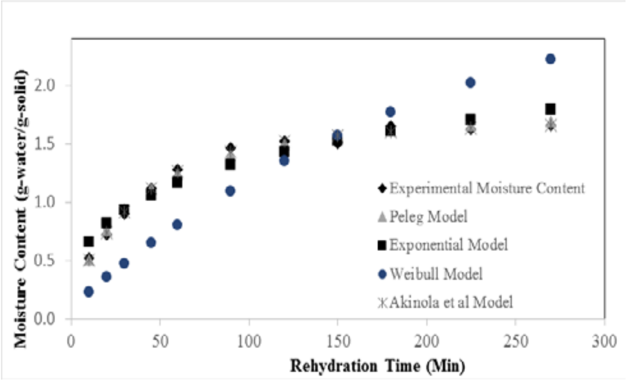

Figure 5. Experimental and Predicted Rehydration Curves of Sweet Potato slices (MC)

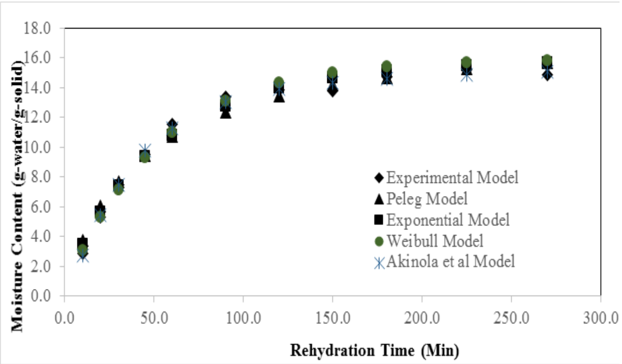

Figure 6. Experimental and Predicted Rehydration Curves of Beetroot slices (MC)

4. Conclusion

Slices of yam, sweet potato, and beetroot measuring 25mm x 25 mm x 3 mm were first dehydrated at 95ºC in a Refractance Window^{TM} dryer. Later, the slices were rehydrated at 27ºC in a thermostatic water bath for different durations. For the four models investigated in this rehydration study, the following conclusions about the rehydration ratio and moisture content changes are,

1. Beetroot attained the highest rehydration ratio, the highest water absorption capacity and the highest moisture content compared to sweet potato and yam.
2. The Akinola et al. model adequately predicted the rehydration behaviour of the root tuber samples in this study.
3. The Akinola et al. model can characterise the rehydration kinetics of root tubers dried with the aid of Refractance Window^{TM} dryers.

Furthermore, studying the Akinola et al. rehydration model for other food and agricultural products dried using other drying methods is essential to understand its applicability better and enrich scientific knowledge.

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