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Determination of Natural Logarithm of Diffusion Coefficient and Activation Energy of Thin Layer Drying Process of Ginger Rhizome Slices

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Abstract

This study is an extension of the previous work done with ARS-680 Environmental Chamber. Drying is a complex operation that demands much energy and time. Drying is essentially important for preservation of ginger rhizome. Drying of ginger was modeled, and then the effective diffusion coefficient and activation energy were determined. For this purpose, the experiments were done at six levels of varied temperatures: 10˚C, 20˚C, 30˚C, 40˚C, 50˚C and 60˚C. The values of effective diffusion coefficients obtained in this work for the variously treated ginger rhizomes closely agreed with the average effective diffusion coefficients of other notable authors who determined the drying kinetics and convective heat transfer coefficients of ginger slices.

Keywords

Activation Energy, Diffusion Coefficients, Ginger Rhizomes, Drying Model, Drying Time, Moisture Ratio, Thin Layer

1. Introduction

One of the most important and most widely used spices worldwide, consumed wholly as a delicacy and medicine is ginger which is the rhizome of the plant *Zingiber officinale*. Nigeria is one of the largest producers and exporters of split-dried ginger [1]. India with over 30% of the global share, now leads in the global production of ginger [2].

Preservation of agricultural crops for future use is essentially done by drying which involves removing enough moisture from them to avoid decay and spoilage. Decreasing the water content to a lower level, so that micro-organisms cannot decompose and multiply in the product, is the major interest in the drying process of ginger rhizomes.

Thin layer drying can be employed to remove volatile liquid from porous materials such as food stuffs, ceramic products, wood and so on. Porous materials have microscopic capillaries and pores which cause a mixture of transfer mechanisms to occur simultaneously when subjected to heating or cooling. The drying of moist porous solids involves simultaneous heat and mass transfer. Heat penetrates into the product and moisture is removed by evaporating into an unsaturated gas phase. Owing to the complexity of the process, no generalized theory currently exists to explain the mechanisms of internal moisture movement [3] [4] [5]. Since the actual process of drying involves simultaneous transfer of both heat and mass; the heat is transferred into the bulk material and mass transferred from the centre of porous solid to the outer layer and consequently into the environment. During drying, the behavior of the material is influenced by temperature, relative humidity, permeability, and sorption-desorption characteristics, and thermo-physical properties of the material being dried.

Prediction of thin layer drying characteristics of ginger rhizomes slices in convective environment was investigated and confirmed the supreme efficacy of convective drying at higher temperatures, as it recorded the lowest moisture content. This research established a clear connection between drying time, temperature, and the moisture content in ginger. The main focal point of this work digs into the complexity of the convective drying process of ginger rhizomes. We're particularly interested in exploring the correlation between moisture content and thermal properties

The thin layer drying simply means to dry as one layer of sample, particles or slices [6]. The temperatures of thin layers are assumed to be of uniformly distributed and very ideal for lumped parameter models [7]. Thin layer drying equations were found to have wide applications due to their ease of use and less data requirements unlike complex data distributed models [8].

Thin layer drying equations may be expressed in the following models: theoretical, semi-theoretical, and empirical. The theoretical study takes into account only the internal resistance to moisture transfer [9], while others are concerned with external resistance to moisture transfer between the product and air [10]. The theoretical models explain drying behaviours of the product succinctly and can be employed in all process situations. They also include many assumptions causing significant errors. Fick's second law of diffusion is used for the derivation of many of the theoretical models. Semi-theoretical models are also derived from Fick's second law of diffusion and modifications of its simplified forms. They are easier and require fewer assumptions due to use of some experimental data and are valid within the limits of the process conditions applied [11].

2. Material and Methods

The ginger rhizomes used were taken from Kachia in Southern Kaduna in Kaduna State of Nigeria. Before being used for the experimentations they were stored at room temperature. The drying experiments were conducted at the Electronic Manufacturing Engineering Laboratory (ERMERG) Hawkes building, University of Greenwich. The ginger rhizomes were given various treatments: (**Figure 1**)

- Blanched
- Unblanched
- Peeled
- Unpeeled

Thin layer drying was conducted at different conditions. The relative humidity of the heating chamber and the heat transfer coefficients were measured simultaneously during the experiments. The results obtained for the dried gingers were compared in terms of their response to heat by convection and their thermal conductivity.

The temperature and humidity chamber are installed at the Hawke building, University of Greenwich was used for the drying of the ginger rhizomes at temperatures of 10˚C - 60˚C for drying times of 2, 4, 8, 10, 14, 18 and 24 hours and the Linear Heat Conduction Experiment was used to measure the thermal conductivity of the sample. The ginger was cut into slices of 30 mm diameter and 18 mm thickness by scoopers designed for this purpose.

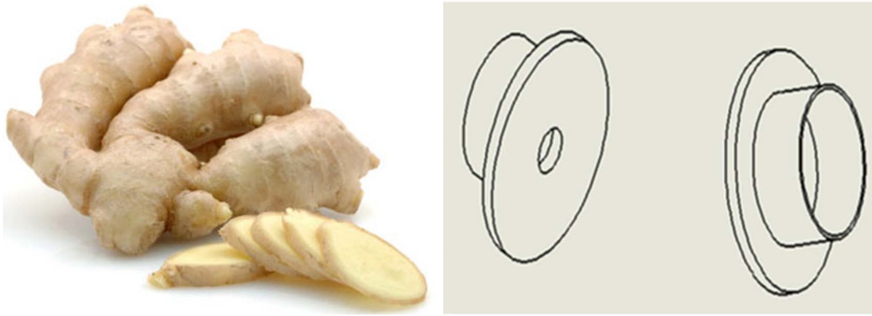
3. Mathematical Modeling of Drying

A) *Determination of the Most Suitable Model for Drying*

Thin layer drying always requires a good understanding of the regression and correlation analysis. Linear and non-linear regression analysis are used to ascertain the relationship between variables MR and t in thin layer drying for selected drying models. The recommended models chosen for applications were further validated using correlation analysis, standard error of estimate (*SEE*) and root mean square error (*RMSE*) analysis respectively. The major indicator for selecting the best models is the determination coefficient (R^2). The highest determination coefficient and lowest *SEE* and *RMSE* values are used to determine the goodness of fit [6] [7] [12]. The R^2; *SEE* and *RMSE* calculations can be performed using the following equations:

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_i - MR_{pre,i}\right)\sum_{i=1}^{N}\left(MR_i - MR_{\exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_i - MR_{pre,i}\right)^2\right] - \left[\sum_{i=1}^{N}\left(MR_i - MR_{\exp,i}\right)^2\right]}} \tag{1}$$

$$SEE = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{d_f} \tag{2}$$



(a) (b)

Figure 1. (a) Raw materials for the experiments (Ginger Rhizomes); (b) Device designed for chopping of ginger rhizomes to the required sizes (18 × 30 mm diameter) for the drying and conduction experiments [2].

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \tag{3}$$

where N is the number of observations, $MR_{pre,i}$ ith predicted moisture ratio values, $MR_{\exp,i}$ ith experimental moisture ratio values, and d_f is the number of degree of freedom of regression model.

B) *Moisture Content* (%) *Calculation Formula*

The moisture content of the materials can be calculated by using two methods: wet or dry basis

1) The wet basis is calculated as:

$$M_{wb} = \frac{w(i) - w(j)}{w(i)} \tag{4}$$

where M_{db} = Moisture Content, wet basis (%); $w(i)$ = mass of the sample before drying (g); $w(j)$ = mass of the sample after drying (g).

2) The dry basis is calculated as:

$$M_{db} = \frac{w(t) - d}{d} \tag{5}$$

Moisture content, dry basis M_{db} is the amount of water per unit mass of dry solids (bone dry) existing in the sample where M_{db} = Moisture Content, dry basis (%); $w(t)$ = mass of wet materials at instant t (g); w = mass of wet material (g); d = mass of dry material (g).

Note that the two moisture contents are related by:

$$M_{db} = \frac{M_{wb}}{1 - M_{wb}} \tag{6}$$

C) *Determination of the Effective Diffusivity and Activation Energy*

The effective diffusivity of agricultural products can be determined using Fick's Second law for slab geometry [13] [14]. The common geometries were also considered. The analytical solution of Fick's Second law for infinite slab is expressed as:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \tag{7}$$

where n is a positive integer, L is the half thickness of samples (m).

Equation (7) can be modified in a logarithmic form as:

$$(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{8}$$

The effective moisture diffusivity can be obtained by plotting $\ln(MR)$ against drying time; this gives a straight line with a slope (*K*) expressed as:

$$K = -\left(\frac{\pi^2 D_{eff}}{4L^2}\right) \tag{9}$$

The dependence of the effective diffusivity on temperature is described by the Arrhenius equation as [13] [14] [15]:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{10}$$

Equation (10) can be expressed in the logarithmic form as:

$$\ln D_{eff} = \left(-\frac{E_a}{RT}\right) + \ln D_0 \tag{11}$$

where D_0 is the pre-exponential factor of Arrhenius equation $(\mathrm{m^2/s})$; E_a is the activation energy in $(\mathrm{kJ/mol})$; R is the universal gas constant $8.314\ \mathrm{J/mol}\,K$; and T is absolute air temperature (*K*).

From (11), plotting of $\ln D_{eff}$ against $(T)^{-1}$ would lead to the evaluation of activation energy for diffusion of moisture during drying and E_a is obtained as: $-(slope \times R) = E_a$, where $(-E_a/R)$ is the slope of (11).

Both theoretical considerations and experimental investigations of drying processes focused on the drying kinetics. The drying kinetics include changes in moisture content and changes in mean temperature with respect to drying time. Drying studies provide the basis for understanding the unique drying characteristics of any particular food material. In the study of drying processes, the moisture content of bio material exposed to a stream of drying air is monitored over a period of time.

Drying models are used for the investigation of the drying kinetics [16] [17] [18] [19] [20] [21] [22]. A number of mathematical models have been developed to simulate moisture movement and mass transfer during the drying of many agricultural products [23]. In this work, the experimental moisture ratio data of the various ginger treatments were fitted to thirteen drying models as shown in **Table 1**.

D) *Drying Rate*

The drying rates at different timing during the environmental chamber can be computed in all experimental conditions using the following relationship [16].

Table 1. Drying models for agricultural products.

S/N	Model Name	Drying Model
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page	$MR = \exp-(kt)^n$
4	Henderson and Pabis	$MR = a \cdot \exp(-kt)$
5	Logarithmic	$MR = a \cdot \exp(-kt) + c$
6	Two term	$MR = a \cdot \exp(-k_o t) + b \cdot \exp(-k_1 t)$
7	Two term exponential	$MR = a \cdot \exp(-kt) + (1-a)\exp(-kat)$
8	Wang and Singh	$MR = 1 + at + bt^2$
9	Diffusion approach	$MR = a \cdot \exp(-kt) + (1-a)\exp(-kbt)$
10	Modified Henderson and Pabis	$MR = a \cdot \exp(-kt) + b \cdot \exp(-gt) + c \cdot \exp(-ht)$
11	Verma *et al.*	$MR = a \cdot \exp(-kt) + (1-a)\exp(-gt)$
12	Midilli *et al.*	$MR = a \cdot \exp(-kt^n) + bt$
13	Austin Approach	$MR = \alpha WktT \exp \beta$

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{avg} = \frac{M_o - M_t}{t} \quad (12)$$

where $\frac{\mathrm{d}M}{\mathrm{d}t}$ is drying rate (kg water/kg of materials), t is the time (min) and M_o and M_t are the initial and final moisture content respectively [16].

The air velocity and temperature effect on the whole drying rate is calculated by statistical method using analysis of variance.

The overall drying rate is computed as ratio of difference in the initial and final moisture content to total drying time. The overall drying rate can be expressed as:

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{o} = \frac{M_o - M_F}{t_1} \quad (13)$$

The moisture content dry basis could have values greater than 100%, because the volume of water present in a sample could be greater than the volume of dry solids present. Dry basis is often used to approximate the percentage moisture content as the moisture-free material, if inert; it does not lose mass during drying. The bone-dry matter therefore specifies a mass-balance tie over a drying process. However, at times the wet basis moisture content is more suitable for usage [21] (**Tables 2-7**).

The slope, K as represented in **Tables 5-10** was obtained from the graphs *In*

MR vs. t as shown in **Figures 2-7**, while $D_{eff}\left(\mathrm{m^2s^{-1}}\right)$ is obtained from (9).

$$D_{eff} = -\left(\frac{4L^2K}{\pi^2}\right) \tag{14}$$

where L is half the thickness of the samples in metres, the thickness of the samples is 18 mm.

4. Results and Discussions

From (11), plotting of In D_{eff} against the inverse of the absolute temperature (**Figure 8**) led to the evaluation of activation energy for diffusion of moisture during drying. The activation energy is obtained by the negative product of the slope of the plot and the universal gas constant (R). The values of activation energies for diffusion of moisture during drying for the variously treated ginger rhizome slices are presented at the bottom of from **Tables 2-15**. "Reference [13] reported activation energies of ginger slices for 0.8 m/s, 1.5 m/s and 3 m/s air velocities as 19.313 kJ/mol, 20.153 kJ/mol and 22.722 kJ/mol respectively. It could be seen that their values and the values obtained in this study are within the same range.

Thin layer drying characteristics of ginger rhizomes slices were determined at varied temperature levels ranging from 10˚C - 60˚C and drying time of 2 hours - 24 hours, and the Linear and non-linear regression analyses were used to ascertain the relationship between moisture ratio and drying time.

Activation energy is the energy that must be available for any chemical, nuclear or physical phenomenon to occur. Any phenomenon exhibiting negative activation energy is taken as barrierless phenomenon. As expected, the activation energies in this work are positive implying that increase in temperature favors high rate of molecular activities within the sliced gingerrhizomes. This high rate of molecular activities lead to high rate of collusion as the moisture tries tovapourize into the environment.

5. Conclusions

Based on the studies and experimental results the following conclusions were made. The values of effective diffusion coefficients obtained in this work for the variously treated ginger rhizomes as presented in **Table 15** closely agreed with the average effective diffusion coefficients of [13] who determined the drying kinetics and convective heat transfer coefficients of ginger slices. Their study results for temperature range of 40˚C to 70˚C were 4.48×10^{-10} m^2/s, 4.96×10^{-10} m^2/s and 5.31×10^{-10} m^2/s; for 0.8, 1.5 and 3 m/s drying air velocity respectively.

The drying rate at higher drying times (24 hours) was 0.889/˚C and 0.4437/˚C for 2 hours drying, giving 50% moisture reduction. The interception which theoretically gives the initial moisture content of 0˚C is lower at 24 hours drying (59.33%) compared to 95.12% on dry basis at 2 hours drying, as expected. The average drying time for the variously treated ginger sample is 2.4 hours.

Table 2. The natural logarithm of moisture ratio of the gingers at 10˚C.

Time (Secs)	Unblanched	Blanched	Peeled	Unpeeled
7200	−0.1206	−0.1675	−0.1195	−0.0934
14,400	−0.1655	−0.2411	−0.1869	−0.1754
28,800	−0.2449	−0.4587	−0.2576	−0.1976
36,000	−0.3056	−0.4708	−0.4529	−0.3091
50,400	−0.4274	−0.6270	−0.5001	−0.3744
57,600	−0.6714	−0.7546	−0.5539	−0.4357
86,400	−0.7022	−0.8884	−0.5814	−0.4745

Table 3. The natural logarithm of moisture ratio of the gingers at 20˚C.

Time (Hrs)	Unblanched	Blanched	Peeled	Unpeeled
7200	−0.1468	−0.1475	−0.1295	−0.1488
14,400	−0.2605	−0.2509	−0.2590	−0.2006
28,800	−0.3331	−0.3893	−0.3170	−0.2662
36,000	−0.3436	−0.4279	−0.4096	−0.4410
50,400	−0.5870	−0.8372	−0.6931	−0.4948
57,600	−0.6958	−0.9524	−0.7400	−0.6319
86,400	−0.7379	−1.0712	−0.9811	−0.7265

Table 4. The natural logarithm of moisture ratio of the gingers at 30˚C.

Time (Sec)	Unblanched	Blanched	Peeled	Unpeeled
7200	−0.1354	−0.1433	−0.1284	−0.1311
14,400	−0.2131	−0.2418	−0.2216	−0.1998
28,800	−0.2721	−0.4273	−0.2900	−0.2988
36,000	−0.3264	−0.4724	−0.4105	−0.3715
50,400	−0.7423	−1.1874	−0.7824	−0.7253
57,600	−0.7974	−1.4069	−0.9584	−0.8343
86,400	−0.9276	−1.7441	−1.2816	−1.1664

Table 5. The natural logarithm of moisture ratio of the gingers at 40˚C.

Time (Sec)	Unblanched	Blanched	Peeled	Unpeeled
7200	−0.2317	−0.3551	−0.2754	−0.2051
14,400	−0.3956	−0.6094	−0.5030	−0.3488
28,800	−0.5863	−0.9014	−0.7054	−0.5558
36,000	−0.8128	−1.2787	−0.7533	−0.9636
50,400	−0.8836	−1.4418	−1.1845	−1.0424
57,600	−0.9934	−1.6697	−1.3090	−1.1239
86,400	−1.2000	−1.7720	−1.4305	−1.3356

Table 6. The natural logarithm of moisture ratio of the gingers at 50˚C.

Time (Sec)	Unblanched	Blanched	Peeled	Unpeeled
7200	−0.3334	−0.4059	−0.4231	−0.3879
14,400	−0.5382	−0.6622	−0.5292	−0.5461
28,800	−0.8554	−0.8010	−0.9216	−0.8916
36,000	−0.9795	−1.1463	−1.2733	−0.9183
50,400	−1.2574	−1.9366	−1.6777	−1.1332
57,600	−1.3653	−2.0565	−1.8018	−1.4393
86,400	−1.7176	−2.2779	−2.0242	−1.8650

Table 7. The natural logarithm of moisture ratio of the gingers at 60˚C.

Time (Sec)	Unblanched	Blanched	Peeled	Unpeeled
7200	−0.2989	−0.4603	−0.3460	−0.2963
14,400	−0.6364	−0.7493	−0.7619	−0.5231
28,800	−0.8637	−1.3284	−1.2076	−0.7644
36,000	−1.0987	−1.7310	−1.4201	−1.1670
50,400	−1.8024	−1.9555	−1.9791	−1.4069
57,600	−1.9052	−2.2711	−2.1594	−1.9885
86,400	−2.7136	−2.4035	−2.4581	−2.8167

Table 8. The slope, k and effective moisture diffusivities, D_{eff} of the ginger samples at 10˚C.

Ginger Sample	Slope	Intercept	R-squared	D_{eff} (m^2s^{-2})
Unbleached	-8×10^{-6}	−0.048	0.91	2.67503E−10
Blanched	-9×10^{-6}	−0.136	0.96	3.00941E−10
Peeled	-6×10^{-6}	−0.124	0.85	2.00627E−10
Unpeeled	-5×10^{-6}	−0.092	0.91	1.6719E−10
Average	−0.000007	−0.1	0.9075	2.34065E−10

Table 9. The slope, k and effective moisture diffusivities, D_{eff} of the ginger samples at 20˚C.

Ginger Sample	Slope	Intercept	R-squared	D_{eff} (m^2s^{-2})
Unbleached	-8×10^{-6}	−0.121	0.91	2.67503E−10
Blanched	-1×10^{-5}	−0.064	0.92	3.34379E−10
Peeled	-1×10^{-5}	−0.059	0.97	3.34379E−10
Unpeeled	-8×10^{-6}	−0.100	0.94	2.67503E−10
Average	−0.000009	−0.086	0.935	3.00941E−10

Table 10. The slope, k and effective moisture diffusivities, D_{eff} of the ginger samples at 30˚C.

Ginger Sample	Slope	Intercept	R-squared	D_{eff} (m^2s^{-2})
Unbleached	-1×10^{-5}	−0.034	0.90	3.34379E−10
Blanched	-2×10^{-5}	0.097	0.94	6.68758E−10
Peeled	-2×10^{-5}	0.043	0.96	6.68758E−10
Unpeeled	-1×10^{-5}	0.024	0.97	3.34379E−10
Average	−0.000015	0.0325	0.9425	5.01569E−10

Table 11. The slope, K and effective moisture diffusivities, D_{eff} of the ginger samples at 40˚C.

Ginger Sample	Slope	Intercept	R-squared	D_{eff} (m^2s^{-2})
Unbleached	-1×10^{-5}	−0.239	0.94	3.34379E−10
Blanched	-2×10^{-5}	−0.395	0.89	6.68758E−10
Peeled	-2×10^{-5}	−0.264	0.92	6.68758E−10
Unpeeled	-1×10^{-5}	−0.198	0.90	3.34379E−10
Average	−0.000015	−0.274	0.9125	5.01569E−10

Table 12. The slope, K and effective moisture diffusivities, D_{eff} of the ginger samples at 50˚C.

Ginger Sample	Slope	Intercept	R-squared	D_{eff} (m^2s^{-2})
Unbleached	-2×10^{-5}	−0.304	0.98	6.68758E−10
Blanched	-3×10^{-5}	−0.269	0.91	1.00314E−09
Peeled	-2×10^{-5}	−0.339	0.92	6.68758E−10
Unpeeled	-2×10^{-5}	−0.281	0.99	6.68758E−10
Average	−0.0000225	−0.29825	0.95	7.52353E−10

Table 13. The slope, K and Effective moisture diffusivities, D_{eff} of the ginger samples at 60˚C.

Ginger Sample	Slope	Intercept	R-squared	D_{eff} (m^2s^{-2})
Unbleached	-3×10^{-5}	−0.094	0.99	1.00314E−09
Blanched	-3×10^{-5}	−0.523	0.89	1.00314E−09
Peeled	-3×10^{-5}	−0.38	0.94	1.00314E−09
Unpeeled	-3×10^{-5}	0.010	0.98	1.00314E−09
Average	−0.00003	−0.24675	0.95	1.00314E−09

Table 14. Moisture diffusivities, D_{eff} of the ginger samples at various temperatures.

Temp (K)	D_{eff}			
	Unblanched	Blanched	Peeled	Unpeeled
283	2.67503E−10	3.00941E−10	2.00627E−10	1.6719E−10
293	2.67503E−10	3.34379E−10	3.34379E−10	2.67503E−10
303	3.34379E−10	6.68758E−10	6.68758E−10	3.34379E−10
313	3.34379E−10	6.68758E−10	6.68758E−10	3.34379E−10
323	6.68758E−10	1.00314E−09	6.68758E−10	6.68758E−10
333	1.00314E−09	1.00314E−09	1.00314E−09	1.00314E−09

Table 15. Natural log of moisture diffusivities, D_{eff} of the ginger samples at various temperatures.

1/Temp (K^{-1})	In(D_{eff})			
	Unblanched	Blanched	Peeled	Unpeeled
0.00353357	−22.0419	−21.9241	−22.3296	−22.5119
0.00341297	−22.0419	−21.8187	−21.8187	−22.0419
0.00330033	−21.8187	−21.1256	−21.1256	−21.8187
0.00319489	−21.8187	−21.1256	−21.1256	−21.8187
0.00309598	−21.1256	−20.7201	−21.1256	−21.1256
0.003003	−20.7201	−20.7201	−20.7201	−20.7201
Slope	**−2471**	**−2524**	**−2763**	**−3132**
E_a (kJ/mol)	**20.54**	**20.98**	**22.97**	**26.04**

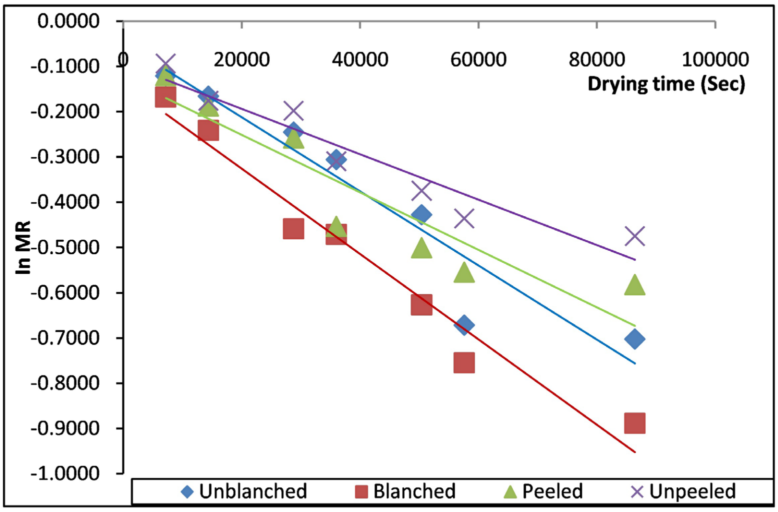


Figure 2. Plot of lnMR against drying time for ginger dried at 10˚C.

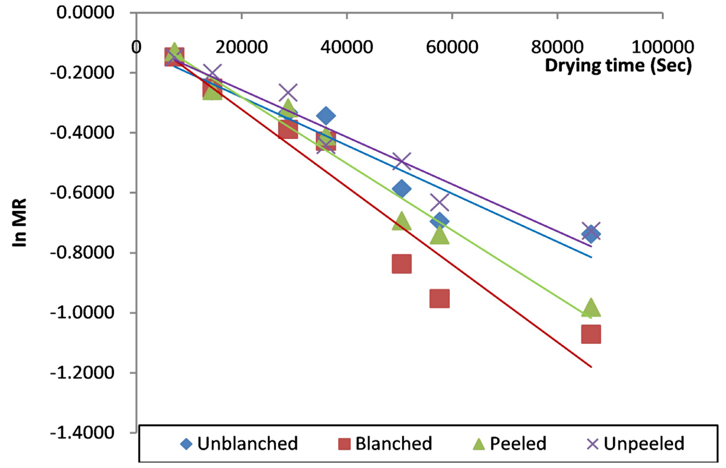


Figure 3. Plot of $\ln MR$ against drying time for ginger dried at 20˚C.

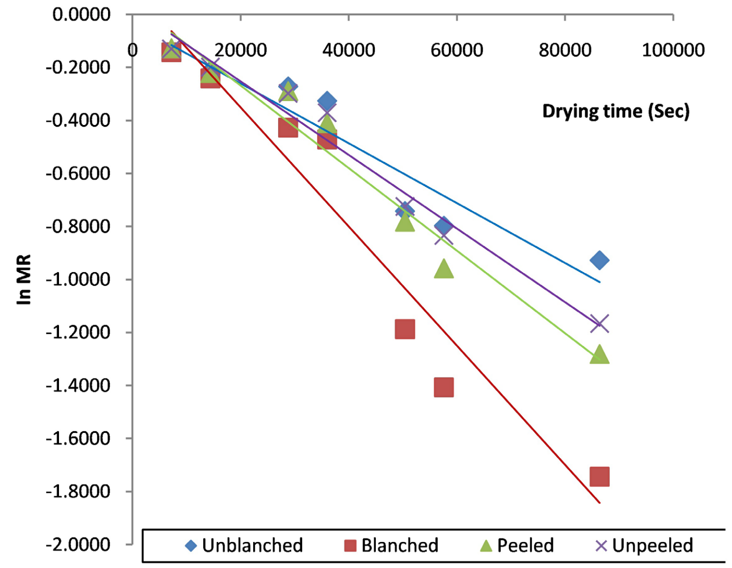


Figure 4. Plot of $\ln MR$ against drying time for ginger dried at 30˚C

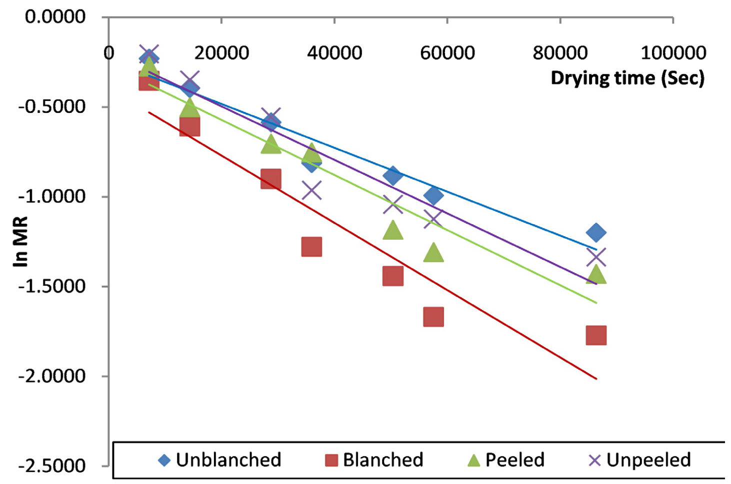


Figure 5. Plot of $\ln MR$ against drying time for ginger dried at 40˚C.

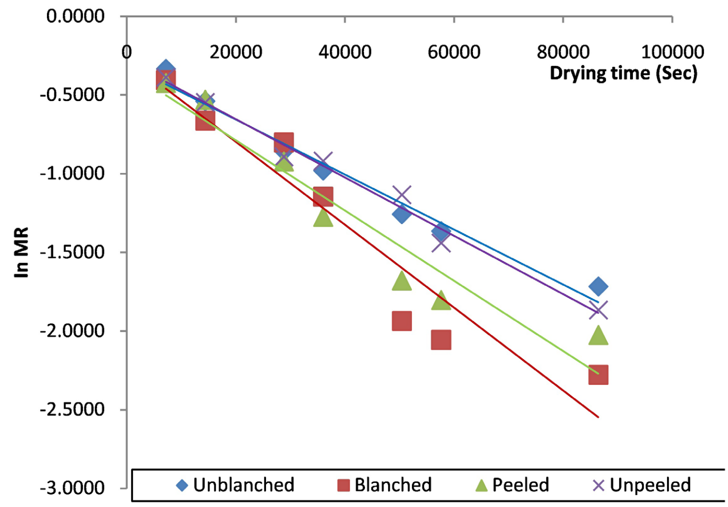


Figure 6. Plot of lnMR against drying time for ginger dried at 50˚C.

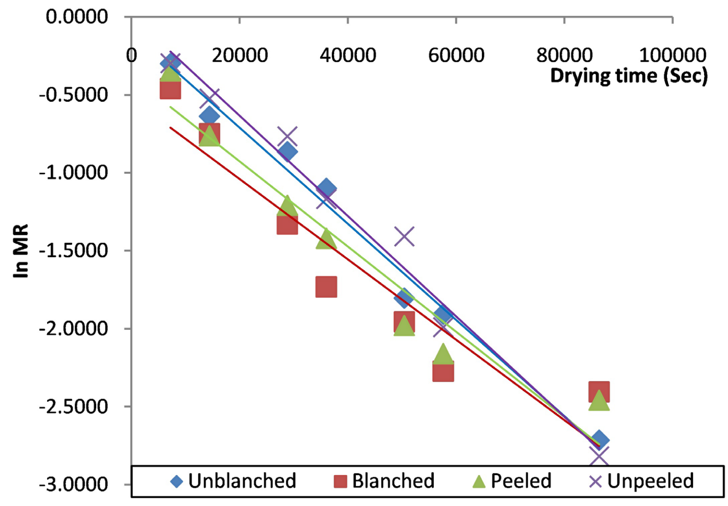


Figure 7. Plot of lnMR against drying time for ginger dried at 60˚C.

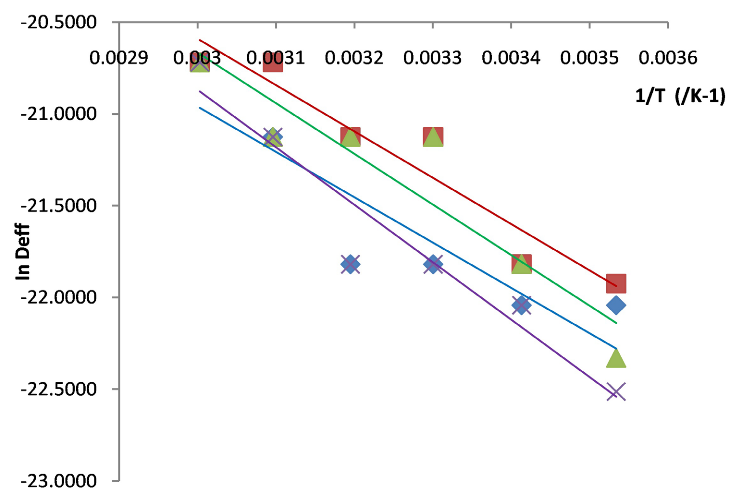


Figure 8. Variation of the natural log of the diffusivity of the sample with temperature.

The result of this study shows that the lowest moisture content (5.98%) is obtained for unpeeled ginger while the highest is the blanched (9.04%) all for 24 hours drying and at 60˚C.

The average moisture content for 2 hours drying at 60˚C was 70.6% while for 24 hours drying; it was an average of 7.55% which is close to the range of 4% - 7% desired for this research. This is better than the result of 22.54% obtained at 50˚C under blanched condition drying for 32 hours. "References [16] [17] reported that the principal processing of ginger rhizomes involved sorting, washing, soaking, splitting or peeling and drying to moisture content 7% - 12%."

The average effective moisture diffusivity and the average activation energy for the variously treated ginger rhizome samples are 5.49×10^{-10} m^2/s and 22.63 kJ/mol respectively.

Dimensionless analysis was used to develop empirical equations relating moisture content to properties of the variously treated ginger rhizomes.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Ravindran, P.N. and Babu, K.N. (Eds.) (2005) Ginger: The Genus Zingiber. CRC Press, Boca Raton, 551.

[2] Gbasouzor A.I. and Omenyi, S.N. (2017) Convective Drying of Ginger Rhisomes. *Proceedings of the World Congress on Engineering and Computer Science* 2017, Vol II, WCECS 2017, October 25-27, 2017, San Francisco. http://www.iaeng.org/publication/WCECS2017/WCECS2017_pp957-964.pdf

[3] Gbasouzor, A.I. (2019) Prediction of Thin Layer Drying Characteristics of Ginger Rhizome Slices in Convective Environment. Ph.D. Thesis, Nnamdi Azikiwe University, Awka.

[4] Gbasouzor, A.I. and Omenyi, S.N. (2019) Convective Drying of Ginger Rhizomes. In: Ao, S. I., Kim, H. and Amouzegar, M. Eds., *Transactions in Engineering Technologies*, Springer, Singapore, 83-98. https://doi.org/10.1007/978-981-13-2191-7_7

[5] Hoque, M., Bala, B., Hossain, M. and Uddin, M.B. (2013) Drying Kinetics of Ginger Rhizome (*Zingiber officinale*). *Bangladesh Journal of Agricultural Research*, **38**, 301-319. https://doi.org/10.3329/bjar.v38i2.15892

[6] Akpinar, E.K. (2006) Mathematical Modelling of Thin Layer Drying Process under Open Sun of Some Aromatic Plants. *Journal of Food Engineering*, **77**, 864-870.

https://doi.org/10.1016/j.jfoodeng.2005.08.014

[7] Erbay, Z. and Icier, F. (2010) A Review of Thin Layer Drying of Foods: Theory, Modeling, and Experimental Results. *Critical Reviews in Food Science and Nutrition*, **50**, 441–464. https://doi.org/10.1080/10408390802437063

[8] Özdemir, M. and Onur Devres, Y. (1999) The Thin Layer Drying Characteristics of Hazelnuts during Roasting. *Journal of Food Engineering*, **42**, 225-233. https://doi.org/10.1016/S0260-8774(99)00126-0

[9] Parti, M. (1993) Selection of Mathematical Models for Drying Grain in Thin-Layers. *Journal of Agricultural Engineering Research*, **54**, 339-352. https://doi.org/10.1006/jaer.1993.1026

[10] Fortes, M. and Okos, M.R. (1980) Drying Theories. In: *Advances in Drying Mujumdar*, Hemisphere Publishing, New York.

[11] Fortes, M. and Okos, M.R. (1981) Non Equilibrium Thermodynamics Approach to Heat and Mass Transfer in Corn Kernels. *Transaction of the ASAE*, **24**, 761-769. https://doi.org/10.13031/2013.34335

[12] Verma, L., Bucklin, R., Endan, J. and Wratten, F. (1985) Effects of Drying Air Parameters on Rice Drying Models. *Transactions of the ASAE*, **28**, 0296-0301. http://elibrary.asabe.org/azdez.asp?JID=3&AID=32245&CID=t1985&v=28&i=1&T=1&refer=7&access=&dabs=Y

[13] Akpinar, E.K. and Toraman, S. (2016) Determination of Drying Kinetics and Convective Heat Transfer Coefficients of Ginger Slices. *Heat Mass Transfer*, **52**, 2271-2281. https://doi.org/10.1007/s00231-015-1729-6

[14] Aregbesola, O.A., Ogunsina, B., Sofolahan, A.E. and Chime, N.N. (2015) Mathematical Modeling of Thin Layer Drying Characteristics of Dika (*Irvingia gabonensis*) Nuts and Kernels. *Nigerian Food Journal*, **33**, 83-89. https://doi.org/10.1016/j.nifoj.2015.04.012

[15] Alam, M.M., Zakaria Hossain, M., Aktar, M., Islam, S. and Hasan, Z. (2014) Drying and Dehydration Kinetics of Ginger. *International Journal of Innovation and Applied Studies*, **9**, 2028-9324.

[16] Shalini, R., Ranjan, A. and Kumar, N. (2008) Studies on the Drying Characteristics of Apple Pomace on Tray Drier. *Proceedings of the* 16*th International Drying Symposium* (*IDS* 2008), Hyderabad, 9-12 November 2008, 1636-1640.

[17] Marinos-Kouris, D. and Maroulis, Z. (2006) Transport Properties in the Drying of Solids. In *Handbook of Industrial Drying* (3rd Edition), CRC Press, Boca Raton. https://doi.org/10.1201/9781420017618.ch4

[18] Midilli, A., Kucuk, H. and Yapar, Z. (2002) A New Model for Single-Layer Drying. *Drying Technology*, **20**, 1503-1513. https://doi.org/10.1081/DRT-120005864

[19] Gbasouzor, A.I., Mallik, S and Dara, J.E. (2019) Determination of Thin Layer Drying Characteristics of Ginger Rhizome Slices at Varied Temperatures. *Proc. World Congress on Engineering and Computer Science*, San Francisco, 22-24 October 2019, 468-476.

[20] Cletus, A.B. (2007) Drying Characteristics of New Zealand Chestnuts. Master's thesis, The University of Waikato, Waikato. http://researchcommons.waikato.ac.nz/bitstream/handle/10289/2268/thesis.pdf?sequence=1&isAllowed=y

[21] Gbasouzor, A.I and Omenyi, S.N. (2019) Modeling and Prediction of Thin Layer Drying Characteristics of Ginger Rhizome Slices in Convective Environment. *Proc. World Congress on Engineering and Computer Science*, San Francisco, 22-24 Oc-

tober, 2019, 477-486.

[22] Eze, J. and Agbo, K. (2011) Comparative Studies of Sun and Solar Drying of Peeled and Unpeeled Ginger. *American Journal of Scientific and Industrial Research*, **2**, 136-143. https://doi.org/10.5251/ajsir.2011.2.2.136.143

[23] Ceylan, I., Aktas, M. and Dogan H. (2007) Mathematical Model of Drying Characteristics of Tropical Fruits. Applied *Thermal Engineering*, **27**, 1931-1936. https://doi.org/10.1016/j.applthermaleng.2006.12.020