Original Research Article

Mathematical Modelling and the Effect of Blanching on the Drying Kinetics of White Yam (*Dioscorea rotundata*)

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ABSTRACT

Many pretreatments methods are employed to reduce the total drying time which is more energy efficient and generate final superior products. Blanching is a long established thermal pretreatments used for processing of agricultural products since it can eradicate enzymes, which cause degeneration reactions, off-flavor and undesirable changes in color, texture and nutrients. The blanching pretreatment effect on the drying kinetics of white yam (*Dioscorea rotundata*) slabs was investigated. Three thin layer models were evaluated and the coefficient of determination (R^2) and residual sum of squares (RSS) were used to study the model efficiency for both raw and blanched samples. A mathematical model to describe the drying kinetics of blanched yam slabs was developed and validated. The Newton, Midilli *et al* and Fick's kinetic models selected for this study were fitted with the experimental data. The results of the experiment carried out, the effective moisture diffusivity coefficient D was obtained as $2.7x10^{-5}m^2s^{-1}$ with blanching effect of 0.001m for the blanched sample, whilst the value of diffusivity, D for the raw sample was $3.4x10^{-5}m^2s^{-1}$. Newton's model gave the best fit among the three models and regressed well with the experimental data, with high value of R^2 of 0.9969 and low RSS of 0.0138. These results depict that blanching as a pretreatment method can decrease the total drying time and improve the effective moisture diffusivity as well as the final product quality compared to the raw samples.

Keywords: Blanching; Drying kinetics; Pretreatment methods; Agricultural poducts; Mathematical model, Drying time.

1. INTRODUCTION

Yam (*Dioscorea spp*) is an annual or perennial tuber-bearing and climbing plants with over 600 species out of which six are economically important in terms of food and medicine [1]. It is of the "*Dioscorea*" genus and the family "*Dioscoreaceae*". It is a tropical crop with many species, which originated in South East Asia and was brought to West Africa in the 16th century. It is a principal tuber crop in the economy of Nigeria, in terms of land under cultivation and in the volume and value of production [2]. Yam is cultivated on 5 million hectares in about 47 countries of the world and Nigeria being the leading world producer [3,1].White yam (*Dioscorea rotundata*) is an important food security crop in Western part of Africa being a nutritious, economical and a healthy crop.

Drying is one of the major preservation processes commonly used for food products that are easily deteriorated [4]. Drying can also preserve food quality by lowering their water activity, thus avoiding contamination and spoilage during transportation and storage. It is a process of moisture reduction in agricultural products to extend its shelf life [5]. High moisture contained in edible products increases the activities of micro-organisms, chemical, and biochemical reactions [6]. During drying of a wet agricultural product, two phenomena occur simultaneously; transfer of heat energy to the product and movement of internal moisture to the surface of the product were it is evaporated. Dried white yam can be stored for a longer period, used as instant yam flour for cooking, and extraction of resistant starch [7,8]. The three (3) major drying processes based on heat transfer are; conduction, convection, and radiation [9]. Some of these technologies which have been used for agricultural products include; sun drying, hot air convective drying, vacuum drying, microwave drying, infrared drying and their mixtures [10,6]. Hot air convective drying has two major standing; efficient removal of surface water and low operating cost, involves blowing heated air over food materials to eradicate moisture has been used regularly in food dehydration [11,10].

Pretreatment methods are employed in order to mitigate quality attributes degradation [4, 12]. They can also reduce the total drying time, which is more energy efficient and generate final products with high standard. A great deal of natural or synthetic chemicals are used for dipping pretreatments before drying such as ascorbic acids [13], potassium metabisulphide and alkaline ethyl oleate [14]. Alternatively, raw foods and vegetables can also be pretreated by thermal methods such as blanching with hot water before drying. Generally, thermal blanching is carried out by exposing samples either at low temperature for a long time (LTLT) or high temperature for a short time (HTST). This method is the most frequently used thermal pretreatments before processing of agricultural products as it can destroy enzymes that cause deterioration reactions, off-flavour and undesirable changes in color, texture and nutrients [12]. In addition, blanching can also enhance the rate of drying by removing intercellular air from the tissues, softening the texture or by dissociating the wax on the products skin [15, 16].

Mathematical modelling is a relatively suitable and sustainable approach for describing the mechanism of the drying process [17]. Recent theoretical advances in mathematical modelling of drying have shown that the process of drying (mathematical fitting) of agricultural products requires specific statistical methods for the accurate explanation of drying kinetics [18]. Therefore, in general, thin layer models are widely used models to explain the water loss phenomenon and heat penetration mechanism during the hot air oven drying process [19]. Among the thin layer models, semi-empirical models, such as Lewis, Page, Henderson–Pabis, logarithmic, Midilli *et al*., simplified Fick's diffusion, and two-term models, are used to illustrate the moisture transfer from agricultural materials [20].

Several studies on the experimental and mathematical modelling of the characteristics of drying of various food products have been conducted. Fang Sheng *et al* [21] investigated the influence of blanching pretreatment on the drying kinetics of Chinese yam (*Dioscorea opposita*). Akinoso and Edun [22] also worked on the effect of temperature on drying and size on energy consumption during cooked yam dehydration. Some researchers investigated the influence of superheated steam blanching on the kinetics of drying and quality of yam slices under air impingement drying [12]. Dagde *et al* [23] presented the use of microwave on the drying of yam slabs using experimental approach. They investigated the effect of time on the reduction in the mass of the yam slab medium low conditions. A theoretical model to illustrate the microwave drying of the yam slab was developed and then validated using the experimental data [23]. However, the effects of steam blanching on the characteristics of drying and its modelling for white yam (*Dioscorea rotundata*) slices have not been reported.

Therefore, this research investigated the effect of blanching pretreatment on drying time and the development and validation of a mathematical model describing the characteristics of mass transfer during microwave drying of blanched yam slabs. The three thin layer-drying models were fitted using experimental data in order to evaluate the best model using statistical analysis to describe the moisture removal behavior during microwave drying of blanched yam under study.

2. MATERIAL AND METHODS

2.1 Material

The white yam tuber (*Dioscorea rotundata*) used was bought from Aba main market in Abia state. The yam tuber was washed with water and then peeled using a knife.

2.2 Experimental Apparatus

The major Apparatus used for the experiment includes; Microwave oven, Weighing balance, Knife, crucible and scale rule. The materials used for the experiment are the yam tubers and water.

2.3 Experimental Procedures

The yam tuber was cut to the required thickness (5cm×2cm×1cm) with a knife and scale rule. Two samples were prepared, of which one was blanched while the other was not; they were dried in a microwave oven at the Department of Chemical and Petroleum Engineering, University of Uyo, Nigeria.

Blanching was done at 90^oC (using wise stir High Torque Stirrer HT50AX) for five minutes and cooled immediately in cold water at room temperature 31^oC for five minutes to remove excess heat.

The microwave oven was allowed to run at 650watts for about 5 minutes on zero loads before the drying experiment commenced. The samples were weighed to obtain the initial weight using weighing balance before the samples were placed inside a crucible and placed in the oven for drying; one after the other for 2minutes. After which weighing (using Adam weighing balance) were done and recorded. These steps were repeated until there was no notable change in weight of the samples or burning was observed.

2.4 Model Development

The drying characteristic of agricultural products in falling rate period is very well described by using Fick's second law of diffusion.

Assumptions:

- Uniform initial moisture content
- Negligible shrinkage and external resistance

- Mass transfer is by diffusion only
- Moisture diffusion occurs in the vertical direction

Ficks second law of diffusion is given as:

$$\frac{\partial c}{\partial t} = \frac{D\,\partial^2 c}{\partial x^2} \qquad 1$$

By using appropriate initial and boundary conditions, Crank [24] gave the analytical solutions for various geometries and the solution for slab object with constant diffusivity is given as:

$$\frac{m_t - m_e}{m_1 - m_e} = \frac{8}{\pi}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[\frac{-(2n+1)^2\pi^2 Dt}{4L^2}\right] \qquad 2$$

Where m_t is the mass at any time of drying (g), m_e is the equilibrium mass (g), m_1 is the initial mass (g), D is the effective moisture diffusivity (m^2s^{-1}), L is the half thickness (drying from both sides) of yam slabs (m) [(L=0.5+s), where s represents the increase in thickness due to blanching], and t is drying time (min). For long drying times, n=1, Equation 2 is written as:

$$\frac{m_t - m_e}{m_1 - m_e} = \frac{8}{\pi}\exp\left[\frac{-\pi^2 Dt}{4(0.5+s)^2}\right] \qquad 3$$

$$m_t = m_e + \frac{8}{\pi}(m_1 - m_e)\left[e^{-Dt\left(\frac{\pi}{2(0.5+s)}\right)^2}\right] \qquad 4$$

Equation 4 is the model equation that describes the drying kinetics of blanched yam slabs.

2.5 Determination of Diffusion Coefficient

Nonlinear Least square method using the SOLVER tool based on the Generalized Reduced Gradient (GRG) method of iteration available in Microsoft Excel [25] was used to compute the value of the effective moisture diffusivity D and estimate the value of s (increment in thickness due to blanching).

2.6 Kinetic modelling

The experimental dimensionless moisture ratio was regressed against the drying time according to the selected model presented in Table 1 of the three thin layer-drying models used to describe the effect of blanching on drying kinetics so that they can be compared.

Table 1:Thin layer drying models used to describe drying kinetics of the yam slab

Model	**Equation**	**References**
Newton	$MR = e^{-kt}$	[26]Liu and Bakker-Arkema,1997
Midilli *et al*	$MR = ae^{(-kt^n)} + bt$	[27]Midilli *et al*, 2002
Simplified ficks diffusion equation	$MR = ae^{\left(\frac{-kt}{l^2}\right)}$	[28]Diamante and Munro, 1993

2.7 Statistical Analysis and Validation of Model

Statistical analysis Nonlinear Least square method in Microsoft Excel [25] was used to fit th**e** experimental data to both the developed model and selected models**.** For evaluating the goodness of fit, two statistical parameters were used: Residual sum of squares (RSS) and Coefficient of Determination (R^2) as primary criterion. The values of R^2 were one of the primary criterions for validating and testing the linear relationship between experimental and model predicted values [29]. High R^2 (closer to 1) value represents the best fit. The value of R^2 was calculated from the plot of predicted values against experimental values using Microsoft excel 2013 [25].

$$\boldsymbol{RSS} = \sum_{i=1}^{N}\left(\frac{(m_{pred,i} - m_{exp,i})^2}{(m_{exp,i})^2}\right) \qquad 5$$

$$\boldsymbol{R}^2 = \frac{\sum_{i=1}^{n}(m_{pred,i} - m_{avg})^2}{\sum_{i=1}^{n}(m_{exp,i} - m_{avg})^2} \qquad 6$$

Where $m_{exp,i}$, $m_{pre,i}$ and mavg are the experimental predicted and average mass at any observation i. In nonlinear regression RSS is the important parameter and the ideal value is zero [30]. Lower values of RSS indicate the closeness of experimental value with predicted value and the goodness fit [31, 32].

3. RESULTS AND DISCUSSION

3.1 EFFECT OF BLANCHING PRETREATMENT ON DRYING TIME OF YAM SLABS

The effect of blanching on drying time is shown in Figure 1. The initial mass of the white yam (*Discorea Rotundata*) attained was 16.76g, which decreased to 6.23g and 14.36g, which reduced to 2.88g for the blanched and normal yam respectively. This agrees with Fang Sheng *et al* [21] they reported that blanching could also enhance rate of drying by removing intercellular air from the tissues, softening the texture or by dissociating the wax on the products skin. Apart from the drying time reduction, it was also observed that it preserves the quality of the final product as compared to the raw samples, agreeing with [21].

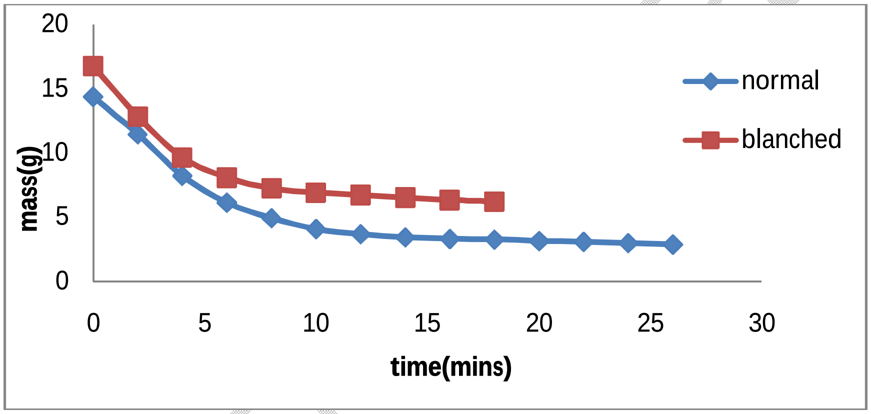

Fig 1: A plot of mass against drying time for both blanched and raw samples

3.2 Validation of Mathematical Model

Figure 1 shows the comparison of the experimental data to the model result as described in Equation 4. Using the SOLVER tool based on the method of iteration in Microsoft Excel [25] was used to determine the effective moisture diffusivity D and estimate the value of s (increment in thickness due to blanching) for the blanched and raw yam slices at different drying temperatures. The value of D for the blanched sample was $2.7\times10^{-5}m^2s^{-1}$ with blanching effect of 0.001m. On the other hand, the value of D for the raw sample was $3.4\times10^{-5}m^2s^{-1}$.

Substituting these values into the model for the blanched sample, we have

$$m_t = m_e + \frac{8}{\pi}(m_1 - m_e)\left[e^{-2.7\times10^{-5}t\left(\frac{\pi}{2(0.5+0.001)}\right)^2}\right] \qquad 7$$

The effective moisture diffusivity values lie within the general range of 10^{-11}-10^{-6} m^2/s reported by Zogzas *et al.,* [33] and Marinos-Kouris and Maroulis [34] for food materials. The differences between the results could be explained by the method of drying, type, composition and tissue characteristics of the yam and the proposed model used for calculation.

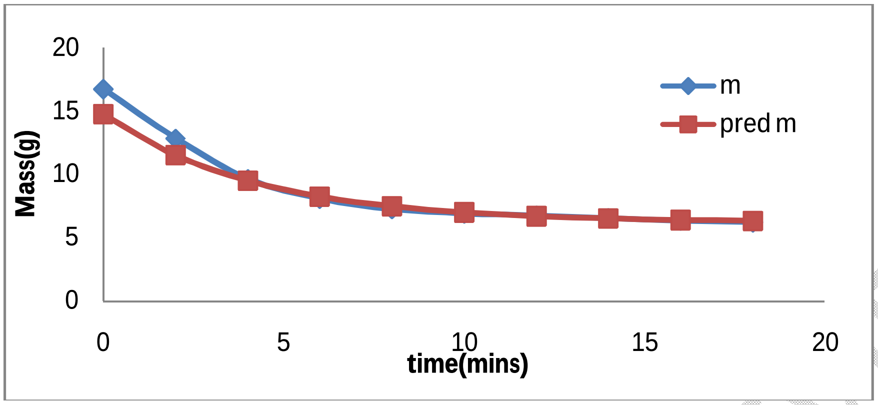

Fig 2: A plot of experimental mass against time showing the curve for the experimental data and predicted result

To validate the developed mathematical model, experimental data was fitted into the model using Microsoft Excel [25] from which the RSS was calculated to be 0.0274. This low value of RSS represents the closeness of the experimental value to the predicted value and the goodness fit of the model. Figure 3 shows a plot of predicted against experimental data also gave R^2 to be 0.9941 confirming the validity of the model.

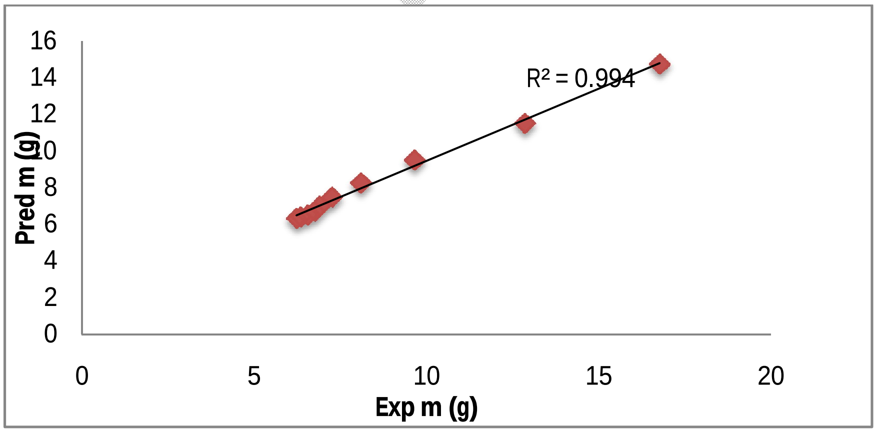

Fig. 3: A plot of predicted against experimental data

Three thin layer drying kinetic models listed in Table 1 were fitted with the experimental drying data of white yam slab. These models are frequently used in literatures for the description of drying. The statistical parameters R^2 and RSS obtained for three models are shown in Table 2 and 3 for blanched and raw samples. The best model that can describe the hot air drying on the characteristics of yam slabs should be with the highest R^2 and lowest values of RSS.

The results in Table 2 showed that the values of R^2 are all greater than 0.90, indicating a good fitness. The values of R^2 and RSS for different models for raw yam slabs are ranged from 0.9693 to 0.9944, and 0.2523 to 0.4959, respectively. Better results were obtained for blanched yam slabs, the values of $R^2$and RSS are ranged from 0.9049 to 0.9969, and 0.0138 to 5.5 respectively.

Newton's model showed the good fit and regressed well with the experimental data of yam slab, followed by the simplified Fick's diffusion model and Midilli *et al* [27] model fitted fairly well for both raw and blanched yam slabs. Hence, the Newton's model could be selected as the most acceptable model to represent the thin-layer hot air drying behavior of the yam slices. Newton's model appears to be the most flexible for describing the kinetics of drying for both raw and blanched samples. For the convenience of calculation, the input parameters of the three models are shown in Table 2 and 3 for blanched and raw yam slab.

Table 2: Kinetic constants of models for blanched yam samples

Model	Coefficients				R^2	RSS
	k	a	b	n		
Newton	0.2743	-	-	-	0.9969	0.0138
Midilli *et al*	0.3505	0.0367	0	0.2328	0.9049	5.5000
Fick	0.0673	0.9700	-	-	0.9969	0.1869

Table 3: Kinetic constants of models for raw yam samples

Model	Coefficients				R^2	RSS
	K	a	b	n		
Newton	0.2011	-	-	-	0.9944	0.4959
Midilli *et al*	0.3422	1.1097	3.33e-0.6	0.8205	0.9693	0.2523
Fick	0.0474	0.8477	-	-	0.9935	0.4203

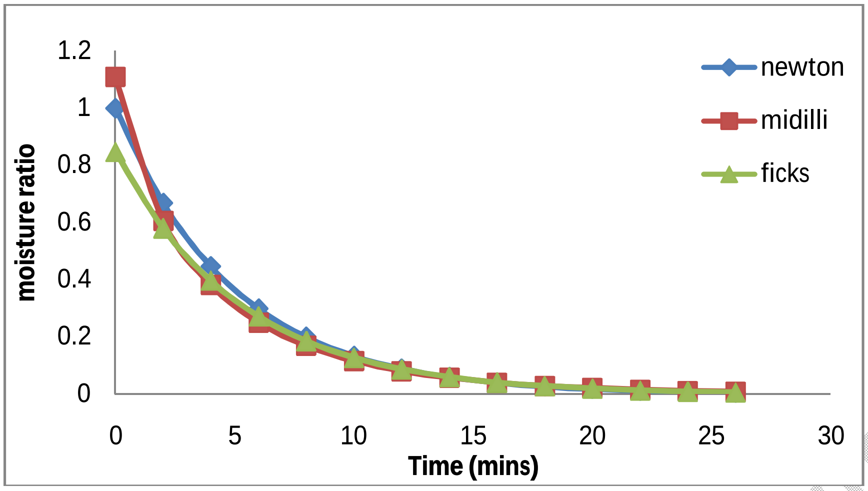

Fig 4: A plot showing predictions of the three tested models (raw samples)

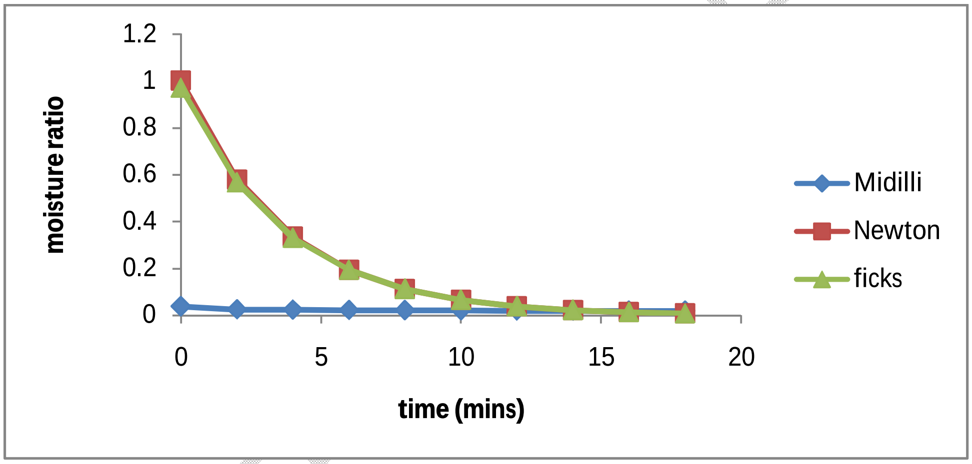

Fig 5: A plot showing predictions of the three tested models (blanched samples)

Figure 4 and 5 shows the prediction of the three-tested model for raw samples and blanched samples respectively. In the two figures, moisture content decreases as the initial drying time increases owing to higher vapor pressure gradient, which diminishes as drying progresses till equilibrium moisture content was reached. Blanched yam slabs showed shorter drying time compared to raw yam slabs as shown in Figures 4 and 5. It is believed that the blanching pretreatment can loosen the cellular network and separate along the middle lamella in organic materials which then result in the softening of tissues [14,12,15,16].

4. CONCLUSION

Drying of food products is essential for the preservation of the food products for long periods of time. The effect of pretreatment on the drying characteristics of yam slabs was investigated. The results displayed that blanching pretreatment can drop the total drying time and improve the quality of the final product compared with the raw samples. A mathematical model was developed and validated using experimental data. The experimental data was fitted into the model developed and using nonlinear least square method in Microsoft Excel, the RSS was calculated to be 0.0274 and R^2 to be 0.9941 confirming the validity of the model. Experimental data were fitted to three thin layer drying models to describe the effect of blanching on drying kinetics. Newton's model gave the best fit among the three models with high value of R^2 of 0.9969 and low RSS of 0.0138. The effective moisture diffusivity was obtained as $2.7\times10^{-5}m^2s^{-1}$ with blanching effect of 0.001m for the blanched sample, while the value of D for the raw sample was $3.4\times10^{-5}m^2s^{-1}$.

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