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Optimum Process Parameters and Thermal Properties of Moisture Content Reduction in Water Yam Drying

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The determination of optimum process parameters for moisture content reduction in water yam drying using a hot air dryer was the aim of this work. Gravimetric method was used to determine the moisture content. Design of experiment was used with slice thickness, airspeed and temperature as the independent factors. Thermal properties such as effective moisture diffusivity and activation energy were determined. The result showed that slice thickness, airspeed and temperature have significant influence on the moisture content reduction. The effective moisture diffusivity ranged from 2.84×10^{-5} m^2/s to 8.10×10^{-5} m^2/s. The activation energy was 30.592kJ/mol. Minimum moisture content value of 11.98% was obtained at slice thickness of 2mm, airspeed of 2 m/s and temperature of 70^oC. The quadratic model best described the drying process. The hot air dryer can conveniently be used for moisture content reduction in water yam slices which will increase its shelf life.

Keywords: Water yam; drying; optimization; effective moisture diffusivity; thermal properties.

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1. INTRODUCTION

One of the major challenges facing growers of food crops is how to prevent the food products from spoilage and ensure availability all year round for human consumption. Most food and agricultural products contain about 80% moisture content at harvest and are therefore highly perishable if stored or left for a long time in that state [1]. This is because the microorganisms that destroy agricultural products require high moisture content to live, survive, and act. Reducing the moisture content creates unfavourable environment for microorganisms and enzymes, which are mainly responsible for food spoilage. Without water, food items become inhospitable to the growth and activities of microorganisms [2]. This will in turn increase the shelf life of the food products.

Water Yam (*Dioscoreaalata*) is one of the most economically important yam species which serve as a staple food for millions of people in tropical countries such as Nigeria, Cameroun, etc. It is the most widespread yam species that serves as food in West Africa and the Caribbean more than in Asia and in America where it originated. It seems it was first domesticated in the highlands of New Guinea. It competes with other important species like *Dioscorea rotundata* in terms of importance [3]. It is a tuberous root crop which belongs to the genus *Dioscorea* and contains starch between 70 and 80% of dry matter. Water yam contains nutrients which are of benefits to human beings. It is a crop with potential for increased consumer demand due to its low sugar content necessary for diabetic patients. Water yam is highly susceptible to deterioration because of its high moisture content (65-76%) hence the need to increase its preservation through drying.

Drying is one of the oldest methods of food preservation [4]. The basis goal in drying food and agricultural products is the removal of moisture from the material, down to a safe level to inhibit the growth and activities of microorganisms, which will prevent deterioration reactions and microbial spoilage while increasing the shelf life [5-7]. It plays an important role in the preservation of agricultural products because it greatly increases storage life, product diversity and leads to substantial volume and weight reduction as well as enhanced storage, packaging and transportation [8-12].

It enhances the resistance of high humid products against dehydration by decreasing their water activity. It is a thermos-physical and physio-chemical process whose dynamic principles are governed by simultaneous heat and mass transfer law both inside and outside the products [13]. They are important in quantitative evaluation of energy requirements and energy losses in drying systems [14]. The drying air absorbs moisture from the solid only if its relative humidity is below saturation [15].

The drying process depends on some process parameters that significantly affect the moisture content reduction in the food products. Most works on drying have focused on the study of the influence of these factors using one factor at a time method (OFAT). The OFAT method is cumbersome, time-wasting, and cannot adequately predict the optimum process parameters [16-17]. Therefore, there is need to use intelligent models such as response surface methodology (RSM), in modeling and predicting the reduction of moisture content in water yam which will enhance the post-preservation of the water yam.

RSM aids in the simultaneous analysis of process parameters that affect a process even in the presence of complex interactions. It is used to generate a mathematical model that can significantly establish optimum operating conditions for any process. It requires few experimental runs to establish the optimum conditions [18-20]. The optimization of the drying operation leads to an improvement in the quality of the output product, a reduction in the cost of processing as well as the optimization of the throughput [21].

2. MATERIALS AND METHODS

2.1 Sample Preparation

Water yam was sourced from a yam farm in Awka, Nigeria. It was manually washed with water and peeled after which it was cut into 2, 4 and 6mm thick slices using a metered board and fixed knife.

2.2 Determination of Moisture Content

The initial moisture content of the water yam was determined using gravimetric method because it gives accurate result relative to the initial moisture content. Sample of the slices water yam was weighed (M_1) and then dried in a Memmert Oven at 120^{o}C for 10hours till when there was no significant change in the mass. The dried sample was weighed again and recorded as M_2. This was done in triplicates and the average determined. The moisture content was calculated using equation 1.

$$MC = \frac{M_1 - M_2}{M_2} \times 100 \quad (1)$$

Where
MC is the moisture content of the sample after drying (db).
M_1 is the initial mass before drying
M_2 is the mass after oven drying

2.3 Determination of Moisture Ratio

Moisture ratio is the ratio of the moisture content at any given time to the initial moisture content (both relative to the equilibrium moisture content). It was calculated using equation 2:

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

Where

MR is the moisture ratio (dimensionless)
M_t is the moisture content at any given time (kg water/kg solid)
M_e is equilibrium moisture content (kg water/kg solid)
M_i is the initial moisture content

2.4 Determination of Thermal Properties

The specific heat capacities were calculated according to equation 3 [22].

$$C_p\ (\text{kJ/kgK}) = 1.42X_c + 1.549X_p + 1.675X_f + 0.837X_a + 4.187X_w \quad (3)$$

Where; C_p is the Specific heat capacity (KJ/kgK) and X_c, X_p, X_f, X_a, and X_w are the respective mass fractions of carbohydrate, protein, fat, ash and water obtained from the proximate analysis.

The thermal conductivity (k) of the samples was calculated using equation 4 [23].

$$k\ (\text{W/mK}) = 0.25X_c + 0.155X_p + 0.16X_f + 0.135X_a + 0.58X_w \quad (4)$$

The thermal diffusivity (α) of the samples was determined using by equation 5 [22].

$$\alpha\ (\text{m}^2/\text{s}) = k/\rho C_p \quad (5)$$

where C_p is the Specific heat capacity, k is the thermal conductivity and ρ is the density of the product.

The proximate analysis of the water yam was determined according to the method of Association of Analytical Chemists (AOAC) as reported by Nwabanne [23].

2.5 Determination of Effective Moisture Diffusivity

The effective moisture diffusivity was determined using a modification of Fick's second law as given in equation 6 [6].

$$\ln MR = \ln\frac{8}{\pi^2} - \left(\frac{\pi}{2H}\right)^2 D_{eff} t \quad (6)$$

where MR is the moisture ratio at time, t and H is half thickness of the slice (m)

Hence, by plotting the experimental data in terms of ln (MR) against drying time (t), the effective moisture diffusivity D_{eff} was determined using the slope in equation 7.

$$D_{eff} = \frac{-\text{slope}}{\left[\frac{2.4674}{H^2}\right]} \quad (7)$$

2.6 Determination of Activation Energy

According to Onu et al. [6] and Nwajinka et al. [1], temperature dependence of the effective moisture diffusivity D_{eff} can be represented by an Arrhenius relationship as in equation 8.

$$D_{eff} = D_o \exp\left[-\frac{E_a}{RT}\right] \quad (8)$$

Where D_o is the pre-exponential factor of the Arrhenius equation in m^2/s,

E_a is the activation energy in kJ/mol, R is the universal gas constant (8.314×10^{-3} kJ/mol K), and T is the absolute air temperature (° K).

Using natural logarithm to transform equation 8 into a linear equation gives equation 9.

$$\ln D_{eff} = \ln D_o - \frac{E_a}{R}.\frac{1}{T} \quad (9)$$

Using the data of effective moisture diffusivities and absolute air temperatures to plot ln (D_{eff}) against 1/T, the activation energy E_a can be

Table 1. Factor levels used in the design of experiment

Parameter	-α	Low	Medium	High	+α
Slice thickness (mm)	1.0	2.0	4.0	6.0	7.0
Airspeed (m/s)	1.5	2.0	3.0	4.0	4.5
Temperature (^oC)	45	50	60	70	75

determined using the slope of the plot. The correlation coefficient was used to determine the validity of the equation.

2.7 RSM Modeling

Central composite design (CCD) of the response surface methodology (RSM) was used to model the drying process. Drying time, temperature, and airspeed were the independent variables while the moisture content was the dependent variable or response. The CCD was used to study the interaction between the process variables and to obtain a suitable model that can describe the drying process [24]. It is a five-level experimental design comprising of two factorial levels (+1 and -1), two axial levels (+α and –α), and a central level (0). Hence, the independent variables were varied at these five different levels as shown in Table 1.

A pure quadratic model was used to describe the relationship between the moisture content (MC) reduction and the independent variables as given in equation 10.

$$MC\ (\%) = \beta_o + \sum\beta_i X_i + \sum\beta_{ii} X_i^2 + \sum\beta_{ij} X_i X_j + \varepsilon \quad (10)$$

Where β_o is the model constant coefficient, β_i,β_{ii}, and β_{ij} represent the linear, quadratic, and interactive coefficients respectively while ε is the random error term that allows uncertainties between the experimental and predicted values.

Thenumber of experimental data sets N, in RSM-CCD can be obtained using equation 11. [25,26]

$$N = 2^n + 2n + n_c \quad (11)$$

Where n is the number of input factors and 2^n, 2n and n_c represent the factorial points, axial points, and center points respectively

3. RESULTS AND DISCUSSION

3.1 Proximate Analysis

The compositions of water yam (WY) were determined by proximate analysis of the sample and presented in Table 2. The moisture content of the raw sample of water yam was 71.45%. This decreased to as low as 24.9% after the drying. This was expected because the primary purpose of drying is to reduce the moisture content. The ash and protein contents increased from 2.83% to 5.05% and 3.94% to 4.55%, respectively. The crude fibre showed a slight increase after drying. There was a major increase in the carbohydrate content from about 12.54% to 54.4%. This is because most of the percentage moisture lost was gained by the carbohydrate. Similar observation was reported by Luther et al. [22].

WC is the water content; AC is the ash content; PC is the protein content, CF is the crude fibre; FC is the fats content, and CC is the carbohydrate content

3.2 Thermal Properties

Some of the thermal properties of water yam analyzed were the specific heat capacities, thermal conductivities and thermal diffusivities as presented in Table 3. These values are necessary in the design of a conventional dryer.

3.2.1 Specific heat capacities

The specific heat capacity obtained before and after the drying were 3.3564 kJ/kgK and 2.0535 kJ/kgK respectively. The values indicated a decrease after the drying because the presence of moisture has a significant impact on the specific heat capacities [22]. The values obtained in this work are similar to those obtained

Table 2. Proximate analysis of water yam

Material	WC	AC	PC	CF	FC	CC
Raw WY	71.45	2.83	3.94	3.15	6.09	12.54
Dried WY	24.93	5.05	4.55	3.64	7.43	54.4

By Ademiliyu et al. [27] who reported a specific heat capacity value in the range of 1.085 to 1.284 kJ/kgK for bone dry fermented ground cassava cultivars.

3.2.2 Thermal conductivities

The thermal conductivity decreased on drying from 0.4654 W/mK to 0.30635 W/mK. This showed that the ability to allow movement of heat decreased with loss of moisture content. This is in accordance with the results obtained by Luther et al. [22] who stated that the thermal conductivities of most food materials are in the range of 0.2 to 0.5 W/mK.

3.2.3 Thermal diffusivity

The thermal diffusivity of the raw water yam was 1.0 x 10^{-4} m^2/s which increased to 1.6 x 10^{-4} m^2/s with drying. The range of values obtained in this work is slightly lower than that obtained by Nwabanne [23] who reported values between 9.0 x 10^{-4} m^2/s and 2.0 x 10^{-4} m^2/s.

3.3 Effective Moisture Diffusivity

The calculated values of the effective moisture diffusivity are shown in Table 4. The result showed that at airspeed of 2.0 m/s, as the temperature increased from 50 ^oC to 70 ^oC, the effective moisture diffusivities increased as well. However, the effective moisture diffusivity remains unchanged after 70 ^oC. At 50 ^oC, the effective moisture diffusivity at 2.0, 2.5, and 3.0 m/s were 0.0000324, 0.0000284, and 0.0000284 m^2s^{-1}, respectively. The results were fairly constant at 70 and 80^oC. Increasing the temperature of the drying at constant air speed initially increases the effective moisture diffusivity. It was observed that the maximum effective diffusivity was obtained at 70^oC, after which there was no longer change in the effective moisture diffusivity with temperature rise.

3.4 Activation Energy of the Sample

The activation energy of the samples was determined at airspeed of 3.0 m/s from the slope of linear plot of D_{eff} against $^1/_T$ given in Fig. 1 [1].

The activation energy obtained was 30.529 kJ/mol. The R^2 obtained was 0.859 showing that 85.9% of the total variability was predicted by the independent variable. According to Aghbashlo et al. [28], the values of activation energy of most food materials lie between 12.7 to 110kJ/mol. Thorat et al., [29] and Bablis et al. [30] reported similar result on drying ginger slice and figure respectively.

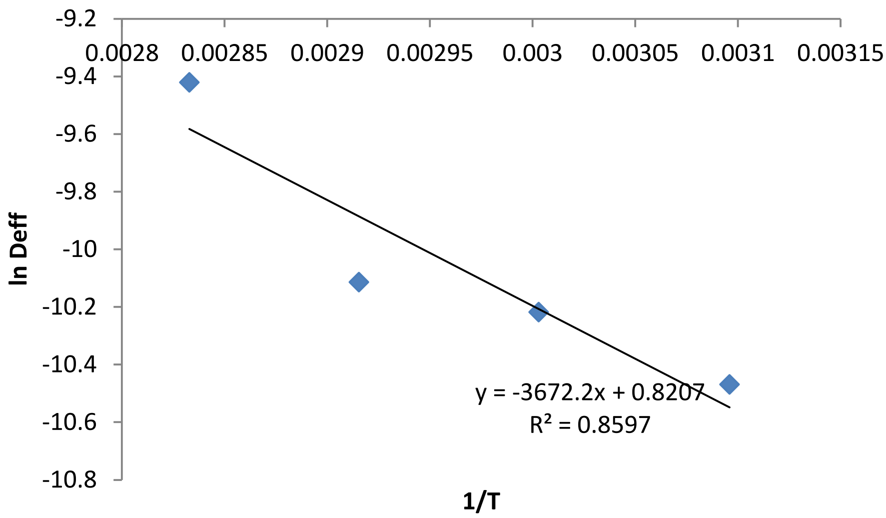

Fig. 1. The plot of effective moisture diffusivity against temperature

Table 3. Thermal properties of the sample

Material	Specific heat capacity (kJ/kgK)	Thermal conductivity (W/mK)	Thermal diffusivity (m^2/s)
Raw WY	3.3564	0.46543	0.00010
Dried WY	2.0535	0.30635	0.00016

Table 4. Effective moisture diffusivity of the water yam

Temp (^oC)	Deff (m^2/s)		
	2.0 m/s	**2.5 m/s**	**3.0 m/s**
50	0.0000324	0.0000284	0.0000284
60	0.0000365	0.0000365	0.0000365
70	0.0000405	0.0000405	0.0000405
80	0.0000405	0.0000405	0.000081

Table 5. Result of design of experiment

Run No.	Slice thickness (mm)	Airspeed (m/s)	Temperature (^oC)	Experimental MC (%)	Predicted MC (%)
1	2	4	70	14.44	14.24
2	4	3	60	55.38	55.51
3	4	1.5	60	58.48	58.14
4	6	2	50	70.18	70.50
5	4	3	60	55.42	55.51
6	6	2	70	44.94	45.10
7	4	3	60	55.64	55.51
8	6	4	70	33.82	34.30
9	6	4	50	47.48	47.12
10	1	3	60	14.33	14.46
11	2	4	50	26.10	26.06
12	4	3	60	55.32	55.51
13	4	3	60	55.45	55.51
14	4	4.5	60	41.81	41.94
15	4	3	45	51.22	51.57
16	7	3	60	55.08	54.73
17	4	3	60	55.68	55.51
18	2	2	70	11.98	12.46
19	2	2	50	37.22	36.86
20	4	3	75	24.22	23.66

3.5 RSM Modeling

Central composite design (CCD) was chosen to investigate the combined influence of the independent variables by 20 sets of experiments. The experimental value of moisture content (%) under various experimental conditions is shown in Table 5**.** Design Expert 10.0.6.2 was used in the RSM-CCD modeling of the system. The optimum minimized moisture content of 11.98% was obtained at slice thickness, airspeed and temperature of 2mm, 2.0m/s, and 70^{o}C, respectively.

3.5.1 CCD Regression Model for water yam drying

Four models, which were linear, 2FI, quadratic, and cubic, were used to model the drying process. The result of the four models is given in Table 6. The quality of the models developed was evaluated based on the value of coefficient of determination (R^2) and the standard deviation. The cubic model was not suggested because the CCD do not contain enough runs that will support it [31]. Quadratic model was suggested because the R^2 value of the quadratic model was 0.9997 with standard deviation of 0.4135. This implied that 99.97% of the variations of the moisture content reduction were explained by the independent variables. The high R^2 value indicated that the models obtained were able to give a convincingly good estimate of the response in the studied range. The predicted R^2 and adjusted R^2 values showed acceptable significance; hence the quadratic model suggested was adequate [32].

3.5.2 Analysis of variance

The result of the analysis of variance (ANOVA) shown in Table 7, was used to assess the significance of the model and the process parameters and equally identify the important factors in a multi-significant model.

Table 6. Model summary statistics of the process

Source	Std Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS
Linear	10.62984	0.671708	0.610153	0.508747	2705.317
2FI	11.26307	0.700536	0.562322	0.007914	5463.386
Quadratic	0.413545	0.999689	0.99941	0.997431	14.14635
Cubic	0.185989	0.999962	0.999881	0.994818	28.53829

Table 7. ANOVA of the drying process

Source	Sum of squares	df	Mean Square	F - Value	p-value Prob> F
Model	5505.26	9	611.6955	3576.768	< 0.0001
A-Slice Thickness	2252.681	1	2252.681	13172.11	< 0.0001
B-Airspeed	364.338	1	364.338	2130.394	< 0.0001
C-Temperature	1082.055	1	1082.055	6327.103	< 0.0001
AB	79.1282	1	79.1282	462.6864	< 0.0001
AC	0.5	1	0.5	2.923651	0.1181
BC	79.1282	1	79.1282	462.6864	< 0.0001
A^2	890.1014	1	890.1014	5204.691	< 0.0001
B^2	60.91822	1	60.91822	356.2072	< 0.0001
C^2	651.9244	1	651.9244	3811.998	< 0.0001
Residual	1.710191	10	0.171019		
Lack of Fit	1.604507	5	0.320901	15.18222	
Pure Error	0.105683	5	0.021137		
Cor Total	5506.97	19			
C.V (%)	0.957				
Adeq Precision	198.47				
Predicted R^2	0.9974				

The significance of each coefficient was determined using the F-test and p-value. The corresponding variables would be more significant if the absolute F-value becomes greater and the p-value becomes smaller [33]. The contribution of quadratic model was significant. The model p-value of <0.0001 and F-value of 3576.77 implied that the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case, only the interaction of slice thickness and temperature (AC) was not significant because the F-value was greater than 0.05. If there are many insignificant model terms, model reduction may improve the model. The value of adjusted R^2 was 0.9994 which indicated a good degree of correlation between the experimental and predicted values. Coefficient of variation (CV) is a standard deviation expressed as a percentage of the mean. The lower the CV, the smaller residuals relative to the predicted values [34]. In this study, the CV value obtained was 0.96 suggesting a good precision and high reliability of the experiment performed [35].

Adequate precision compares the range of predicted values at the design points to the average prediction error. An adequate precision ratio value greater than 4 indicates adequate model efficacy [36]. The results showed that the adequate precision ratio of 198.47 which was well above the recommended minimum which suggested good model efficacy [17,31]. This was in agreement with the report of Kiomars et al. [37].

Multiple regression analysis was used to correlate the responses (moisture content) with the three variables (slice thickness, air velocity and temperature) studied using a second order polynomial equation. The quadratic regression model given in equation 12, was used to model the moisture content reduction in water yam slices with slice thickness, air velocity and temperature as the process parameters.

Moisture content (%) = +55.51 + 13.42A – 5.40B – 9.30C – 3.14AB – 0.25AC + 3.15BC –9.29A – 2.43B – 7.95C (12)

Positive sign in front of these factors shows that the percentage moisture content is favoured by increase in such a factor, while negative sign represents decrease in such factors. The coefficients with one factor (slice thickness, air velocity or temperature) represent the effect of that particular factor on the drying of water yam. The coefficients with two factors (combinations of these factors) and others with second order terms show the interaction between the two factors and quadratic effect, respectively.

From the ANOVA discussion, only the interaction of slice thickness and temperature were insignificant. Therefore, the insignificant term can be removed to give the final model term as expressed in equation 13.

Moisture content (%) = +55.51 + 13.42A – 5.40B – 9.30C – 3.14AB – 0.25AC + 3.15BC –9.29A – 2.43B – 7.95C (13)

The normal probability plot shown in Fig. 2, was used to identify substantive departures from normality. The normal probability plot indicated whether the residuals follow a normal distribution, in which case the points will follow a straight line [38]. In a normal probability plot, the sorted data are plotted against values selected. This plot is necessary in order to make the resulting image look close to a straight line if the data are approximately normally distributed. Deviations from a straight line suggest departures from normality [38].

From the plots, it was observed that the data were closely distributed within the straight line of the plot. Definite pattern like an "S-shaped" curve was also observed in the plot. This indicated that the model was adequate for predicting the moisture content reduction within the range of the variables studied. Plot of predicted against actual experimental moisture contents given in Fig. 3 confirms the adequacy of the quadratic model in describing the drying process.

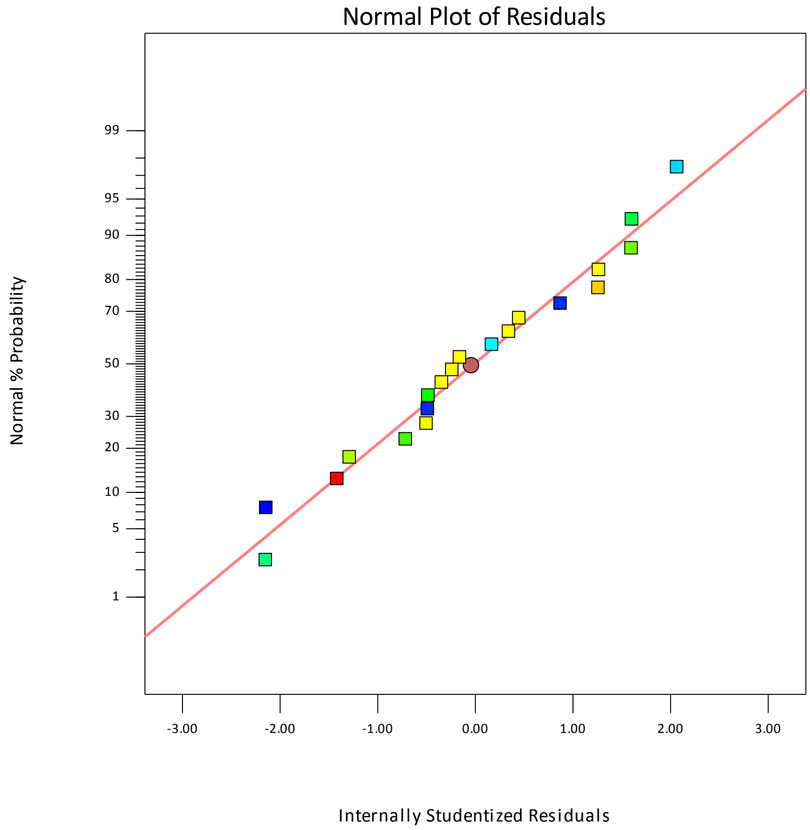

Fig. 2. Normal probability plot of the drying process

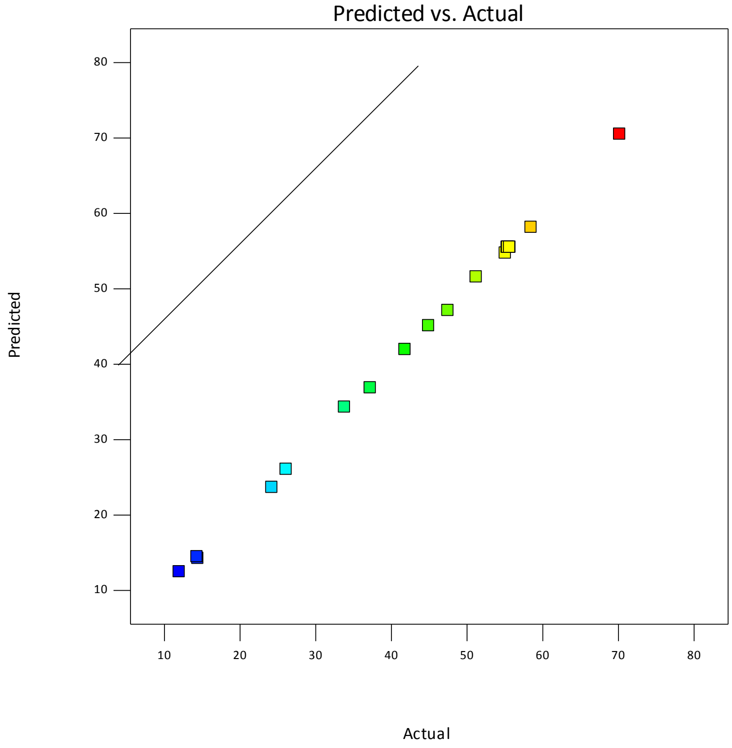

Fig. 3. Plot of predicted against actual result

4. CONCLUSION

This work determined the optimum drying condition of water yam slices. The focus was on moisture content reduction as the response while slice thickness, airspeed and temperature were the independent variables. With correlation coefficient of 0.9997 and standard deviation of 0.4135, the quadratic model proved to be the best in modeling the drying process. The predicted result closely tracked the experimental result in the quadratic model. Activation energy was determined as 30.592 kJ/mol while the effective moisture diffusivity was between 2.84 x 10^{-5} m^2/s to 8.10 x 10^{-5} m^2/s. The specific heat capacity, thermal conductivity, and thermal diffusivity calculated were all within the ranged reported by other authors. The study successfully modeled the drying of water yam slices in a hot air dryer.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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