Response Surface Methodology For optimisation of hot air drying of water yam slices

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Abstract: Response surface methodology was used to investigate the effects of temperature, thickness and time on the drying of water yam slices and to determine the optimised condition for hot air drying. The predominant falling rate drying regime was observed. Experiments were performed at air temperature of 60°C, 70°C and 80°C, slice thickness of 4, 6 and 8mm and drying times of 60, 165 and 270minutes. Based on response surface and desirability functions, the optimum conditions for water yam drying were: air temperature70°C, 74.9°C, slice thickness 6mm, 6.6mm and drying time 165minutes, 116.1minutes for untreated and treated water yam respectively. At this point, the predicted responses for drying rate were 0.000345kg/m^{2}s, 0.000358kg/m^{2}s respectively.

Keywords: water yam, temperature, slice thickness, drying time, hot air drying, optimisation.

1.0 INTRODUCTION

Water yam is the most economically important yam species which serve as a staple food for millions of people in tropical and subtropical countries. It is a crop with potential for increased consumer demand due to its low sugar content necessary for diabetic patients (Oluwole et al, 2017). In Nigeria, Water yam (D. alata) is another important species of the dioscoreacea family grown in some parts of Nigeria for its large roots with fine edible white fleshes. It seems unnoticed when compared to other varieties of yam and is often regarded as food for the poor (Hoover, 2000). According to Baah, 2009 water yam contains high level of Total Dietary Fibre (TDF) which makes it suitable for management of pile, constipation and diabetes. It is also rich in Vitamin C, beta carotene, vitamin E, calcium, potassium, magnesium, copper and antioxidants. These nutrients are known to play vital role in general body upkeep as well as immune functioning, wound healing, suppression of blood sugar, bone growth and anti-ageing. Dried water yam slices are used as an excellent source of starch, which provides calorific energy, suitable for producing weaning foods. Processed water yam flour and slices have a high market price internationally than cassava slices (Baah, 2009). They provide protein three times more superior than the one of cassava and sweet potato. Processing of the tubers into a more stable product will increase shelf life and availability, and enhance its utilization. One potential problem in processing of water yam into chips is the discolouration and darkening of the product. This has been attributed to enzymic browning reactions as a result of the presence of water soluble phenolic substances in yam (Akubor, 2013). Pretreatment methods such as blanching, sulphating and dripping into oil have contributed to the improved mass and heat transfer as well as product characteristics (colour, texture, vitamin retention, etc) of food (Kaymak-Ertekin,2002, Taiwo et al, 2002)

Drying is a complex process accompanied by physical and structural changes. There is a continuous change in the dimensions of differently shaped food particulates during drying as a result of water removal and internal collapse of the particulates (Senadeera et al., 2005). The drying process is the use of products with low water activity, thereby inhibiting the production of microbial reproduction and enzyme activity, and can give the flavor of a good product to achieve long-term storage, easy to transport, easy to consumer spending. (Aboltins,and Upitis, 2011) Optimisation is required to ensure rapid processing while maintaining optimum product quality. Response surface methodology is a powerful tool for optimizing of many engineering applications probably because of its high efficiency, simplicity, and comprehensive theory. It can save a lot of time and can build models accurately and quickly in an optimization design (Nazghelichi et al, 2011). It has been frequently used in the optimisation of food processes(Varnalis et al, 2004,Wani et al, 2008). The aim of this study was :(a)to investigate drying behaviour of water yam (b) to study the effect of independent variable on the dependent variable and (c) optimization of the water yam drying in a hot air dryer.

2. MATERIALS AND METHODS

2.1 Sample preparation: Good quality freshly harvested water yam used for the experiments were procured from New Market, Enugu. Hot air dryer were used for the experiment. Proximate analyses of the samples were conducted according to the AOAC, 2004.

2.2 Experimental procedure: The samples were peeled with a stainless knife and cut into chips of different thickness of 4mm, 6mm and 8mm using vernier caliper. The sliced samples was pretreated by soaking for 5 min in 0.5% sodium metabisulphite ($Na_2S_2O_5$) solution..There were treated and untreated samples for each. The initial moisture content was determined according to official method (AOAC, 2004). The chips were loaded into the hot air dryer for drying process. Steady state of temperatures was achieved in the dryer before the chips were loaded. The drying process was performed at 60^0C, 70^0C and 80^0C. The samples were removed from the dryer and weighed manually at 30 minutes interval to monitor moisture loss. Drying process was truncated when two consecutive sample weights remained constant. The experiments were replicated.

2.3: Experimental design matrix: The experiment was designed using Response surface methodology (RSM) of design expert software 11. Central Composite Design (CCD), face center, tool was used in the design process. Temperature, thickness and time were the considered factors while moisture content and drying rate were the expected responses of the study. The design matrix for the experiments is shown in Table 1. The RSM was used to analyze the responses. The ANOVA and graphical analyses of the drying were carried out. The mathematical models in terms of coded were obtained. The models in terms of coded factors were used to make predictions about the response for given levels of each factor. The high levels of the factors were coded as +1 and the low levels of the factors were coded as -1. Optimum drying parameters were also obtained, and the results were validated using percentage deviation.

Table 3.1: Experimental Design Matrix

Std	Run	Factor 1 A: Temperature ^{0}C	Factor 2 B: Thickness Cm	Factor 3 C: Time Minutes	Response 1 Moisture Content g water / g solid	Response 2 Drying Rate kg/m^{2}s
9	1	60	0.6	165		
16	2	70	0.6	165		
8	3	80	0.8	270		
5	4	60	0.4	270		
18	5	70	0.6	165		
12	6	70	0.8	165		
19	7	70	0.6	165		
4	8	80	0.8	60		
14	9	70	0.6	270		
2	10	80	0.4	60		
15	11	70	0.6	165		
6	12	80	0.4	270		
13	13	70	0.6	60		
20	14	70	0.6	165		
1	15	60	0.4	60		
3	16	60	0.8	60		
17	17	70	0.6	165		
11	18	70	0.4	165		
7	19	60	0.8	270		
10	20	80	0.6	165		

2.4 Effective moisture diffusivity

The simplified equation of Fick's law of moisture diffusion was adapted to determine the effective moisture diffusion from the samples during drying. It is simplified according to Srikiatden and Roberts, (2005) which is represented thus:

$$MR = \frac{M-Mo}{Mo-Me} = \frac{8}{n^2}\sum\frac{1}{(2n-1)^2}\, exp\ \frac{(-\,2n-1)^2\pi^2 D_{eff}t}{41^2} \quad ---------- 2.1$$

Where Deff is the moisture diffusivity (m^2/s), t is the drying time (s), l is the half of the slab thickness (m), MR= dimensionless moisture ratio, Mi = instantaneous moisture content (g water/g solid), Me =equilibrium moisture content (g water/ g solid), Mo = initial moisture content (g water/ g solid). However, due to continuous fluctuation of relative humidity of the drying air in the dryer, equation 5 is simplified in equation 6 according to Dimente and Munro, (1993) and Goyal et al., (2007).

$$MR = \frac{Mi}{Mo} = \frac{8}{n^2}\sum\frac{1}{(2n-1)^2}\, exp\ \frac{(-\,2n-1)^2\pi^2 D_{eff}t}{41^2} \quad ---------- 2.2$$

The effective moisture diffusivity (Deff) was calculated from the slope of plot of ln MR against drying time (t) according to Doymas, (2004) and is represented in equation 2.3

$$\mathrm{k} = \frac{Defft}{41^2} - - - - - - - - - - - - - - - - 2.3$$

Where k is the slope. The model that best described the drying behaviour of the samples was used to evaluate the moisture diffusivity of the samples**.**

3 RESULTS AND DISCUSSION

3.1 Proximate analysis of water yam

The proximate analyses of the water yam are presented in Table (3.1). Proximate analysis was used to characterize each of the samples in terms of moisture, ash, lipid, fiber, protein and carbohydrate contents. Table shows the characteristics of the raw samples with moisture content having the highest percentage in all the cases. Table presents also the proximate analyses (at drying temperature of 60^0C,70^0C and 80^0C) of the treated and untreated food samples respectively. The moisture content reduced drastically with corresponding increase in percentage of the carbohydrate. The application of heat caused the evaporation of water from the samples. This observation is in agreement with previous findings (Kared and Lund (2003), Velic et al., 2007. It was also revealed that the reductions of moisture content were relatively higher in the treated samples compared to the untreated samples.

Table 3.2: Proximate analysis for treated and untreated water yam

Sample	Moisture (%)	Ash (%)	Lipid (%)	Fiber (%)	Protein (%)	Carbohydrate (%)
Raw Water Yam	76.34	1.83	2.86	2.70	1.93	12.77
Treated Water yam @ 60^0C	4.55	1.60	2.50	2.55	1.76	87.04
Untreated Water yam @ 60^0C	3.90	1.50	2.40	2.50	1.70	88.00
Treated Water yam @ 70^0C	3.70	1.30	2.35	2.55	1.60	88.50
Untreated Water yam @ 70^0C	3.20	1.20	2.25	2.18	1.50	89.67
Treated Water yam @ 80^0C	2.80	1.25	2.15	2.18	1.48	90.14
Untreated Water yam @ 80^0C	2.20	0.77	2.05	1.49	1.43	92.06

3.2 Moisture Contents of the samples

The results of the moisture content versus time of the treated samples at various temperatures and thickness are presented in Figures 3.1-3.6. From the graphs, moisture content decreases with time in an exponential manner. The graphical results revealed that moisture content continued to decrease till the equilibrium point. The final moisture content of each of the sample represent moisture equilibrium between the sample and drying air under dryer conditions, beyond which any changes in the mass of sample could not occur (Akipnar and Toraman 2013). Moisture content at equilibrium usually decreases with increases in temperature (Barbosa-Canovas and Juliano, 2007). The results gotten are in agreement with the observation of many researches (Doymaz 2005, Togrul and Pehlivan 2004). The result from the study indicated that samples pretreated with sodium metabisulphite dried faster than the untreated samples. Again, the treated samples showed high degree of lightness. This implies that sodium metabisulphite pretreatment results in some degree of bleaching or prevention of enzymatic browning of the chips. A similar situation was reported by Buckman *et al.*, (2015).

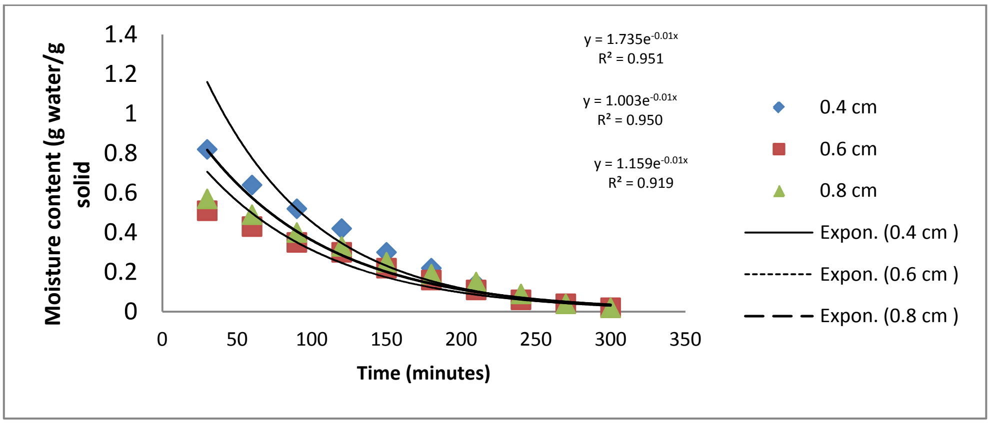


Fig. 3.1: Moisture Content versus Time,Untreated Water Yam at 60 ^{0}C

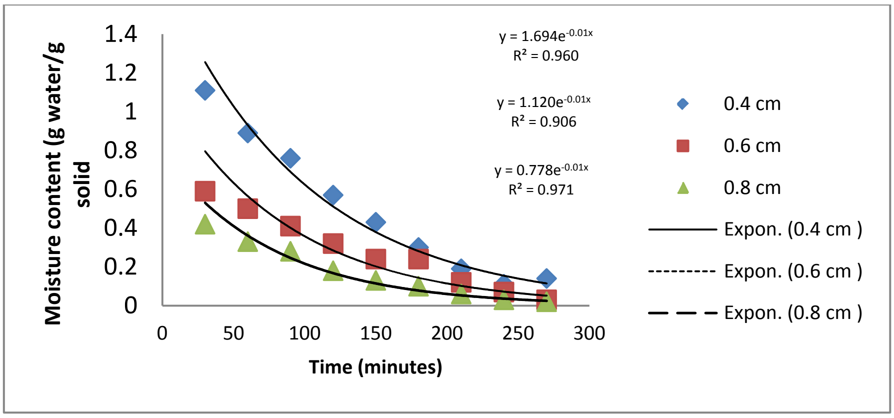


Fig. 3.2: Moisture Content versus Time, Untreated Water Yam at 70 ^{0}C

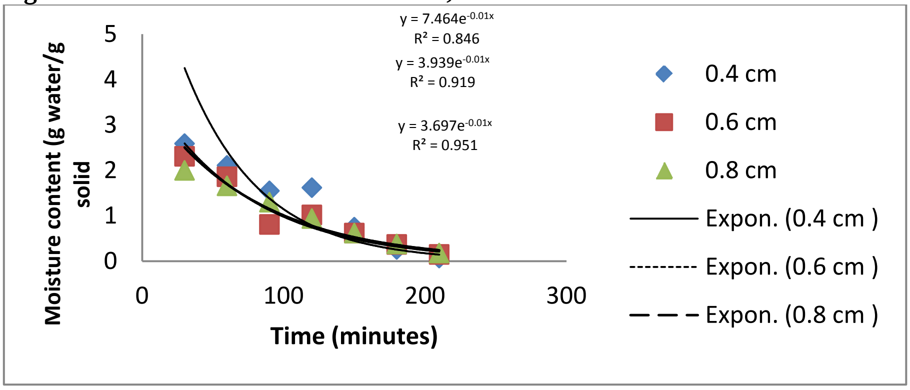


Fig. 3.3: Moisture Content versus Time, Untreated Water Yam at 80 ^{0}C

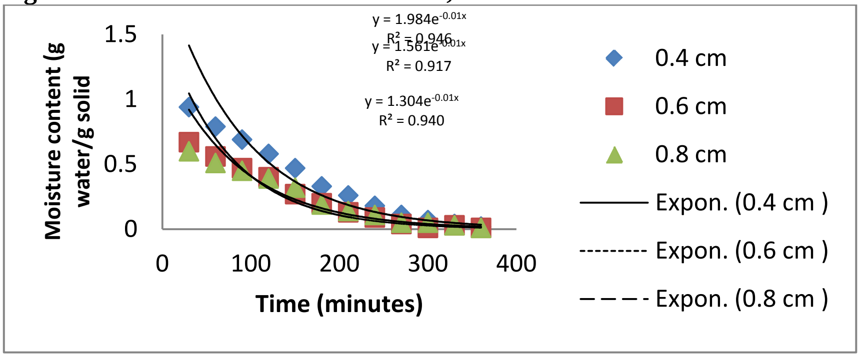


Fig. 3.4: Moisture Content versus Time, treated Water Yam at 60 ^{0}C

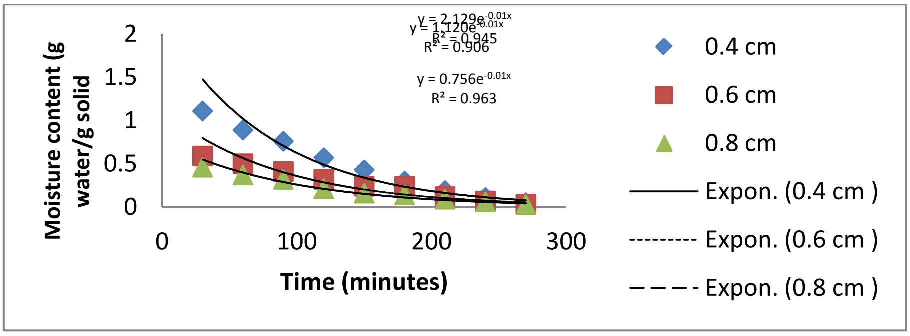


Fig. 3.5: Moisture Content versus Time, treated Water Yam at 70 ^{0}C

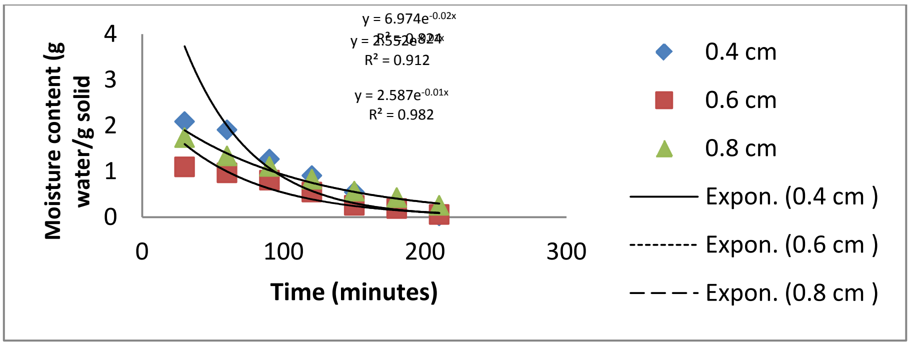


Fig. 3.6: Moisture Content versus Time, treated Water Yam at 80 ^{0}C

3.3 Relationship between Moisture Ratio and Drying Time

The graphs of ln(MR) versus time of the food samples are presented in Figures 3.7-3.12. For each sample, graphs were plotted at various temperatures (60 ^{0}C, 70 ^{0}C, 80 ^{0}C) and sample thickness (0.4cm, 0.6cm and 0.8cm). To attain linear graphs, the data involving dry basis moisture content versus time were transformed to ln(MR) versus time (Akipnar and Toraman, 2013).

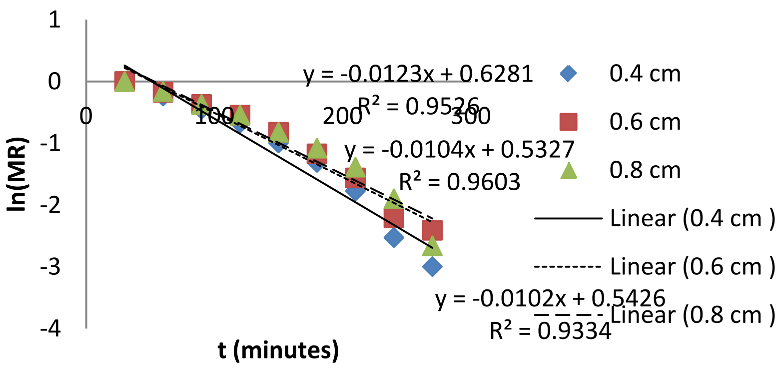


Fig. 3.7: ln (MR) versus Time of Untreated Water Yam at 60 ^{0}C

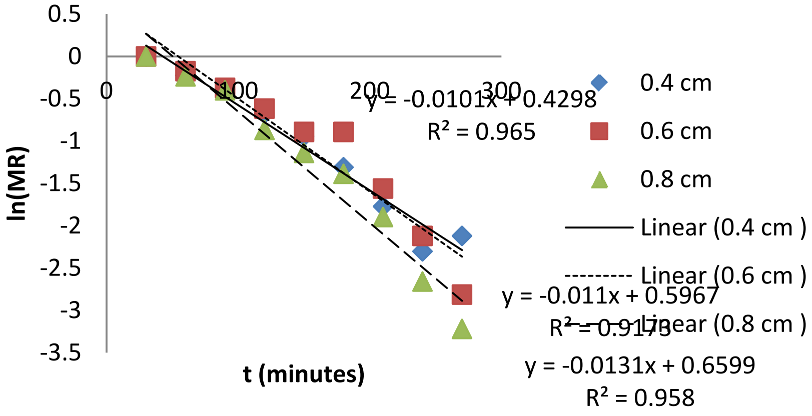


Fig. 3.8: ln(MR) versus Time of Untreated Water Yam at 70 ^{0}C

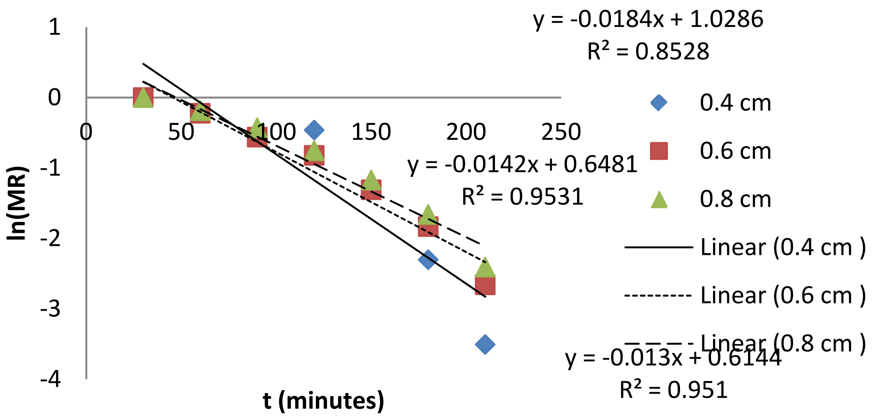


Fig. 3.9: ln(MR) versus Time of Untreated Water Yam at 80 ^{0}C

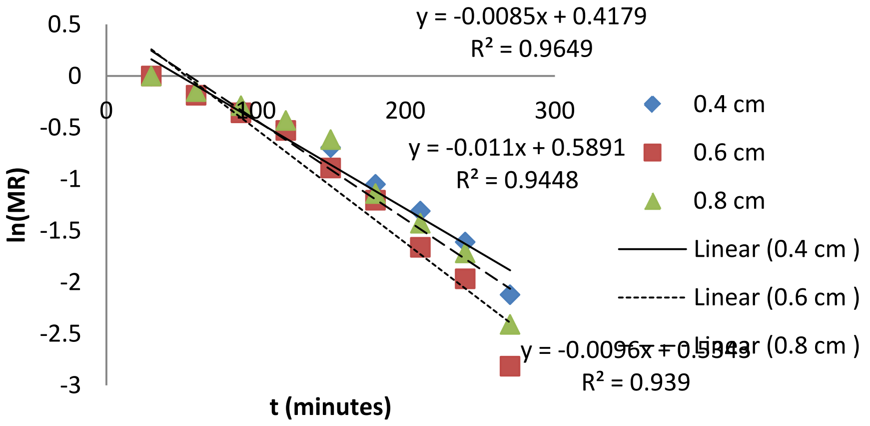


Fig. 3.10: ln(MR) versus Time of treated Water Yam at 60 ^{0}C

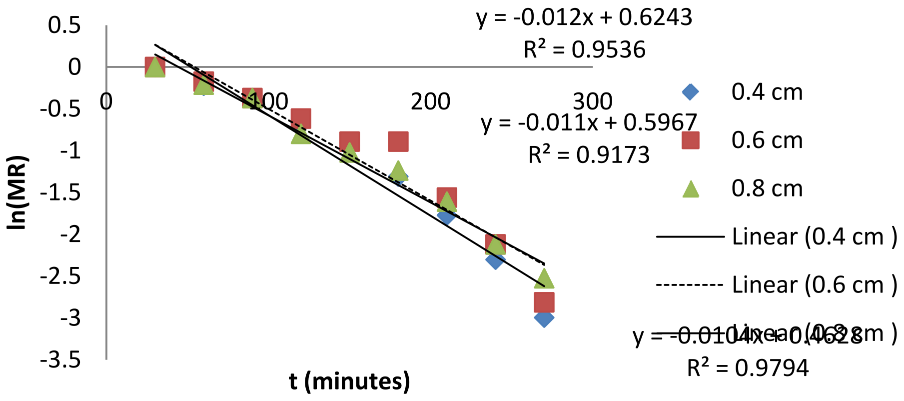


Fig. 3.11: ln(MR) versus Time of treated Water Yam at 70 ^{0}C

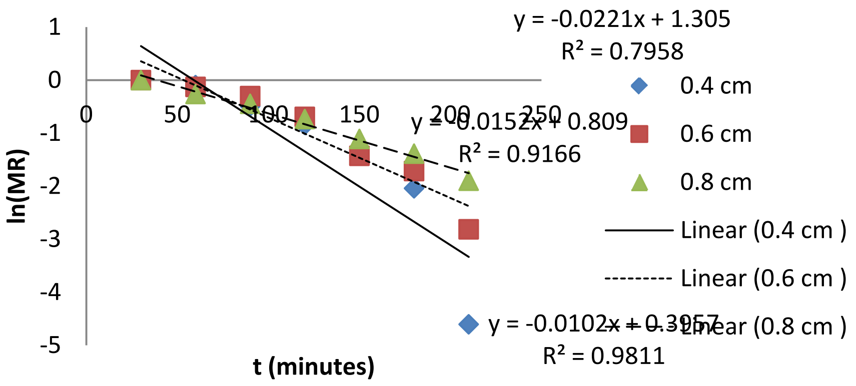


Fig. 3.12: ln(MR) versus Time of treated Water Yam at 80 ^{0}C

3.4: Effective Moisture Diffusivity for untreated and treated water yam

Experimental diffusivities was determined by plotting experimental drying data in terms of In MR against time (minutes).The effective diffusivity was calculated using the method of slopes. Effective moisture diffusivity depends on the moisture content and increases with decrease in moisture content. The values of effective diffusivity for hot air drying of wateryam ranges from 1.1 x 10^{-9} to 9.23 x 10^{-10}. This is similar to other crops like apricot, agape and figs (Mahmutoglu et al, 1995, Babalis and Belessiotis 2004).

Table 3.3: Effective moisture diffusivity for untreated and treated water yam

Sample	**Temperature**	**Effective Moisture Diffusivity X 10^{-10} m^2/s**		
Untreated water yam	**(K)**	**Thickness, 0.4cm**	**Thickness, 0.6cm**	**Thickness, 0.8cm**
	333 333	**3.32**	**6.32**	**0.11**
	343	**2.73**	**6.68**	**0.14**
	353	**4.97**	**8.26**	**0.14**
Treated Water Yam	**333**	**2.29**	**6.68**	**0.10**
	343	**3.24**	**6.68**	**0.11**
	353	**5.97**	**9.23**	**0.11**

3.5: RSM Results of the Samples

The results of the Response Surface Methodology (RSM) are presented in Tables (3.3-3.4). Each of the Tables presents experimental data of moisture content and drying rate obtained at various drying conditions (factors) of temperature, thickness and time. Unlike data of one factor at a time, the RSM results show the effects of the interaction of the considered factors on the responses. Tables (3.3) present the data for the treated food samples, while those of the untreated samples are shown in Tables (3.4). The variations of drying rate of the treated and untreated samples can be attributed to structural adjustment of the compositions of the treated samples.

Table 3.4: RSM Results for the Untreated Water Yam

Std	Run	Factor 1 A: Temperature ^{0}C	Factor 2 B: Thickness Cm	Factor 3 C: Time minutes	Response 1 Moisture Content g water / g solid	Response 2 Drying Rate kg/m^{2}s
9	1	60	0.6	165	0.12	0.000345
16	2	70	0.6	165	0.13	0.000343
8	3	80	0.8	270	0.01	0.000623
5	4	60	0.4	270	0.04	0.000314
18	5	70	0.6	165	0.13	0.000343

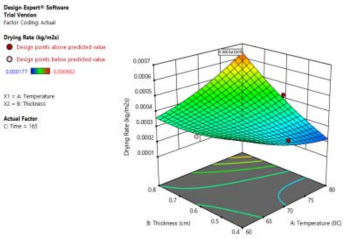
12	6	70	0.8	165	0.07	0.000443
19	7	70	0.6	165	0.13	0.000343
4	8	80	0.8	60	1.66	0.000682
14	9	70	0.6	270	0.03	0.000282
2	10	80	0.4	60	2.11	0.000265
15	11	70	0.6	165	0.13	0.000343
6	12	80	0.4	270	0.02	0.000177
13	13	70	0.6	60	0.5	0.000439
20	14	70	0.6	165	0.13	0.000343
1	15	60	0.4	60	0.64	0.000566
3	16	60	0.8	60	0.49	0.000439
17	17	70	0.6	165	0.13	0.000343
11	18	70	0.4	165	0.24	0.000321
7	19	60	0.8	270	0.04	0.000331
10	20	80	0.6	165	0.34	0.000423

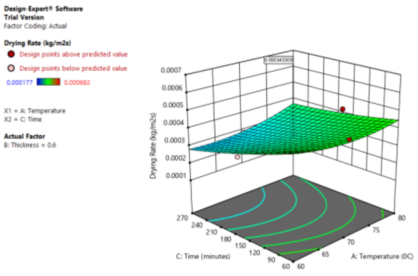
Table 3.5: RSM Results for the Treated Water Yam

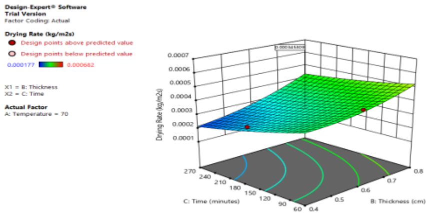
Std	Run	Factor 1 A: Temperature ^{0}C	Factor 2 B: Thickness Cm	Factor 3 C: Time minutes	Response 1 Moisture Content g water / g solid	Response 2 Drying Rate kg/m^{2}s
9	1	60	0.6	165	0.15	0.000309
16	2	70	0.6	165	0.13	0.000374
8	3	80	0.8	270	0.06	0.000319
5	4	60	0.4	270	0.11	0.000308
18	5	70	0.6	165	0.13	0.000374
12	6	70	0.8	165	0.09	0.000353
19	7	70	0.6	165	0.13	0.000374
4	8	80	0.8	60	1.34	0.000341
14	9	70	0.6	270	0.03	0.000318
2	10	80	0.4	60	1.91	0.000106
15	11	70	0.6	165	0.13	0.000374
6	12	80	0.4	270	0.02	0.000152
13	13	70	0.6	60	0.5	0.000439
20	14	70	0.6	165	0.13	0.000374
1	15	60	0.4	60	0.79	0.000439
3	16	60	0.8	60	0.51	0.000444
17	17	70	0.6	165	0.13	0.000374
11	18	70	0.4	165	0.24	0.000384
7	19	60	0.8	270	0.05	0.000306
10	20	80	0.6	165	0.14	0.000312

3.6: Graphical Results of the RSM

The 3-D plots of the drying plots of drying rate versus the considered factors of temperature, thickness and time in Figures 3.13 and Figures 3.14 for the untreated and treated water yam respectively.

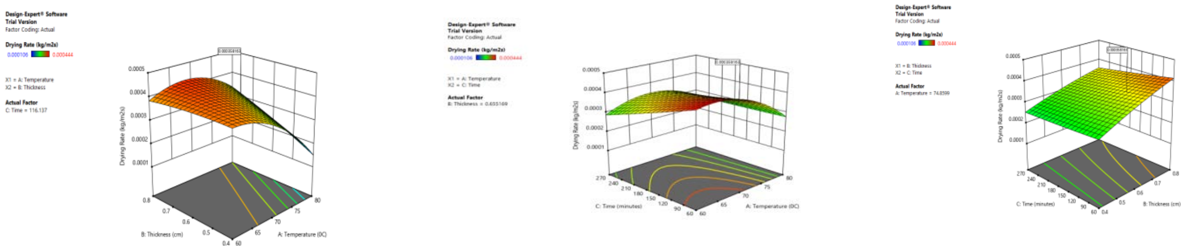






(a) (b) (c)

Fig 3.13:Profile of response surface and contour plots for drying rate versus (a) temperature and thickness (b) temperature and time (c) thickness and time of the untreated water yam.



(a)
(b)
(c)

Fig 3.13:Profile of response surface and contour plots for drying rate versus (a) temperature and thickness (b) temperature and time (c) thickness and time of the treated water yam

Table 3.6: ANOVA for Drying Rate of Untreated Water Yam

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	2.757E-07	9	3.064E-08	60.78	< 0.0001	Significant
A-Temperature	3.063E-09	1	3.063E-09	6.08	0.0334	
B-Thickness	7.656E-08	1	7.656E-08	151.90	< 0.0001	
C-Time	4.409E-08	1	4.409E-08	87.47	< 0.0001	
AB	1.183E-07	1	1.183E-07	234.79	< 0.0001	
AC	5.671E-09	1	5.671E-09	11.25	0.0073	
BC	3.741E-09	1	3.741E-09	7.42	0.0214	
A^2	3.413E-09	1	3.413E-09	6.77	0.0264	
B^2	3.036E-09	1	3.036E-09	6.02	0.0340	
C^2	3.782E-10	1	3.782E-10	0.7504	0.4067	
Residual	5.040E-09	10	5.040E-10			
Lack of Fit	5.040E-09	5	1.008E-09			
Pure Error	0.0000	5	0.0000			
Cor Total	2.808E-07	19				
Std. Dev.	0.0000	**R^2**			0.9820	
Mean	0.0004	**Adjusted R^2**			0.9659	
C.V. %	5.83	**Predicted R^2**			0.7701	
		Adeq Precision			31.3573	

The Model F-value of 60.78 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC, BC, A^2, B^2 are significant model terms. The Predicted R^2 of 0.7701 is in reasonable agreement with the Adjusted R^2 of 0.9659; the difference is less than 0.2. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 31.357 indicates an adequate signal. This model can be used to navigate the design space.

Table 3.7: ANOVA for Drying Rate of treated Water Yam

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.167E-07	9	1.297E-08	7.35	0.0022	Significant
A-Temperature	3.318E-08	1	3.318E-08	18.80	0.0015	
B-Thickness	1.399E-08	1	1.399E-08	7.93	0.0183	
C-Time	1.340E-08	1	1.340E-08	7.59	0.0203	
AB	1.990E-08	1	1.990E-08	11.28	0.0073	
AC	1.073E-08	1	1.073E-08	6.08	0.0333	
BC	7.031E-10	1	7.031E-10	0.3984	0.5420	
A^2	1.208E-08	1	1.208E-08	6.84	0.0258	
B^2	1.882E-10	1	1.882E-10	0.1067	0.7507	
C^2	8.205E-12	1	8.205E-12	0.0046	0.9470	
Residual	1.765E-08	10	1.765E-09			
Lack of Fit	1.765E-08	5	3.529E-09			
Pure Error	0.0000	5	0.0000			
Cor Total	1.344E-07	19				
Std. Dev.	0.0000	R^2				0.8687
Mean	0.0003	Adjusted R^2				0.7505
C.V. %	12.40	Predicted R^2				-0.0728

		Adeq Precision	9.7024

The Model F-value of 7.35 implies the model is significant. There is only a 0.22% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC, A² are significant model terms Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 9.702 indicates an adequate signal. This model can be used to navigate the design space.

3.7: Final Equation in Terms of Coded Factors

Mathematical models (with significant model terms) of the drying rates as function of temperature (A), thickness (B) and time (C) are expressed in Equations (4.1) – (4.20). . In all the sample models, the highest power of the variables is two, indicating that quadratic model is adequate for the description of the drying rate with respect to temperature, thickness and time. It was also observed that there were interactions of the factors in the drying process. The positive signs in the models indicate synergetic effects, while the negative signs show antagonistic effects of the factors. The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor.

Untreated Water Yam

$$\text{Drying Rate} = +0.0003 + 0.0000A + 0.0001B - 0.0001C + 0.0001AB + 0.0000AC + 0.0000BC + 0.0000A^2 + 0.0000B^2 \quad (3.1)$$

Treated Water Yam

$$\text{Drying Rate} = +0.0004 - 0.0001A + 0.0000B - 0.0000C + 0.0000AB + 0.0000AC - 0.0001A^2 \quad (3.2)$$

3.8: Optimum Parameters of the Drying Rates

The optimum parameters of temperature, thickness and time with corresponding drying rates of the samples are shown in Table 3.8

Samples	Optimum Temperature ^{0}C	Optimum Thickness Cm	Optimum Time minutes	Optimum Drying Rate kg/m^{2}s
Untreated Water Yam	70.0	0.60	165.0	0.000345
Treated Water Yam	74.9	0.66	116.1	0.000358

3.9: Validation of the Results

The validation of the results is presented in Table 3.8. The model of the drying rate was validated by considering the percentage deviation of the predicted data from the experimental data. In all the samples, percentage deviation is less than 5%, which confirm that the models are adequate for the description of the drying process.

Table 3.8: Validation of Optimum Results

Samples	Optimum Temperature ^{0}C	Optimum Thickness Cm	Optimum Time Minutes	Predicted Drying Rate kg/m^{2}s	Experimental Drying Rate kg/m^{2}s	Percentage Deviation %
Untreated Water Yam	70.0	0.60	165.0	0.000345	0.000348	0.86
Treated Water Yam	74.9	0.66	116.1	0.000358	0.000364	1.65

CONCLUSION

Response surface analysis was effectively used to determine the effect of temperature, drying time and slice thickness on drying rate. The air temperature of 70^{o}C, slice thickness of 6mm and drying time of 165minutes was proposed as the optimum independent variable for un treated water yam, while 74.9^{O}C,6.6mm and 116.1minutes for treated water yam. At this optimum condition, the predicted response for drying rate was 0.000345kg/m^{2}s and 0.000358kg/m^{2}s for untreated and treated water yam respectively.

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