Effective moisture diffusivity and rehydration characteristics of osmo- air dehydrated tomato

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Abstract: This study investigated the effect of osmotic dehydration on effective moisture diffusivity (EMD) and rehydration characteristics of osmo-air dehydrated tomato using a locally developed forced convection cabinet dryer. Sliced *Hausa* tomato variety of uniform 10 mm thickness were deseeded, blanched at 90°C and immersed in honey and sugar hypertonic solution under different levels of osmotic concentrations of 20, 30, 40, 50 and 60°Bx, temperature of 10°C, 20°C, 30°C, 40 °C and 50°C and duration of 10, 20, 30, 40, and 50 min. Samples were dried in a hot-air cabinet dryer at 65°C for 10 h to attain an equilibrium moisture content of 3%-5%, which was considered safe for long term storage. The experiment was designed using central composite design (CCD) of response surface methodology (RSM) of Design expert software version 6.0.6. Statistical analysis and regression models were done using the software at $p \leq 0.05$ significance level. Results showed that EMD and rehydration ratio (RR) of *Hausa* tomato for all samples ranged between 1.40×10^{-9} to 4.19×10^{-8} $m^2 s^{-1}$ and 0.60 – 2.00, respectively. The maximum values *EMD* and *RR* of 3.42×10^{-8} $m^2 s^{-1}$ and 1.81 were achieved at osmotic concentration of 20°Bx, osmotic duration of 42 mins and osmotic temperature of 50°C, respectively, through optimization with desirability of 83.6%. This would aid faster drying rate thereby preserving more of foods quality parameters with reduced energy consumption and saves time.

Keywords: tomato, effective moisture diffusivity, rehydration ratio, osmotic dehydration, honey and sugar solution, slice thickness.

Citation: Obajemihi, O. I., and A. A. Asipa. 2020. Effective moisture diffusivity and rehydration characteristics of osmo-air dehydrated tomato. Agricultural Engineering International: CIGR Journal, 22(4): 184-192

1 Introduction

Drying of agricultural products is an age long food processing technique and of high economic significance, most especially in Sub-Saharan Africa. Tomato is a fruit that is widely cultivated in Nigeria and normally have high yields which cannot be totally consumed freshly at the time of harvest thus leading to high rate of post-harvest wastages incurred yearly since there is poor post-harvest handling and storage (Muhammad et al., 2012). Drying of fruits is important, as it is termed to be cheap, safe and easy to store and transport. However, it is termed a complex process phenomenon as it involves heat and mass transfer. This process causes some changes in the product quality parameters' such as the rehydration, texture, nutritional and sensory attributes. Rehydration is a complex process which can reflect the physical and chemical changes in food induced by drying treatments

Received date: 2019-07-19 **Accepted date**: 2020-01-20

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and can be used as a quality index (Seremet(-Ceclu) et al., 2015; Azarpazhooh and Ramaswamy, 2010). The methods employed in processing fruits are responsible for the extent of these changes. Tomato requires moderate temperature for its drying, as the fresh fruit is rich in flavonoids and bio-active compounds such as vitamin C, lycopene and beta-carotene (Van Wagenberg et al., 2017), which can be easily lost if the fruit is subjected to unfavourable conditions during processing. This makes production of dried tomato in a cabinet dryer time consuming, as the fruit has high moisture content, as low temperature takes more time and leads to prolonged exposure of the fruit to air and light which causes degradation of some of its compounds like the lycopene (Trivedi et al., 2011). Therefore, pretreatment that is capable of preserving quality parameters of tomato during drying at higher temperatures is desirable for tomato fruits' processing. It has been found that dehydrating tomato samples in osmotic solutions of salt and sugar prior to drying in a hot-air cabinet dryer have proved to minimize the negative effects of processing conditions on the quality parameters of the end-products, as it improves its overall quality for consumers appreciation (Idah and Obajemihi, 2014; Aktas et al., 2004). However, study on the use of hypertonic solution of honey and sugar as pre-drying treatment of fruits and vegetables prior to drying is apparently not available in the literature. The efficacy of osmotic pretreatment on foods depends on some parameters such as the size and shape of food material, osmotic agent type and concentration, osmotic solution temperature, immersion duration and agitation (Azarpazhooh and Ramaswamy, 2010).

Effective moisture diffusivity (EMD) is the movement of moisture internally within the material during drying (So'bah et al., 2017); moisture migrates towards the surface of the food where it can diffuse into the surrounding atmosphere. EMD is a function of the moisture content present in food material and temperature being supplied to it (Jangam et al., 2010). EMD tends to decrease when the free moisture in the food has been evaporated into the surrounding; as a result, the bounded moisture in the food tissues gradually becomes free and migrates to the surface where evaporation occur. It would be difficult for drying process of food to be completed without internal movement of moisture to foods surfaces for evaporation to occur; as this may results in a case hardening phenomenon where by foods materials are seen to be dried at the surfaces but wet internally. This poses serious dangers during storage as enzymatic reactions and microbial activities would be high in the innermost part of the food and will start to deteriorate. *Hausa* tomato variety is an important variety in Nigeria as it is found to be dominant in most markets in the urban settlements, when other varieties of tomatoes are no longer available, scientific investigations on the drying characteristics of the fruit are limited hence, this study investigated the effects of osmotic pretreatment on the EMD and rehydration characteristics of osmo-air dehydrated tomato.

2 Materials and methods

2.1 Materials

Fresh tomato samples of *Hausa* variety were obtained from a field located in Oteh, Ilorin province, Kwara State (latitude 8° 30'N, longitude 5° 00'E), Nigeria. Samples were stored in a refrigerator at 15°C prior to commencement of the experiment. The initial moisture content of the samples was determined using a digital infra-red laboratory moisture meter (Model: LSC-50, by NAPCO, China) at a temperature of 130°C for 8 min in triplicate. Natural honey characterized as grade A according to Fasasi (2012) was bought from the University of Ilorin, Nigeria Apiary Unit. Commercial grade sugar used was bought from AMB, a local provision store in Ilorin. Other materials used include distilled water, stainless steel knife and tray, rubber nets and plastic osmotic bowls.

2.2 Equipment

Digital weighing scale (Model: NBL-2602e, sensitivity ±0.0001 by ADAM, China, accuracy 0.01 g) was utilized for weight measurement, volumetric flask and beaker were used in measuring distil water and osmotic solution volume, and a table top refractometer (Model: M10481 by ABBE MARK II, USA) was used for determination of brix concentration, water bath (Model: W20M-2, by AL-TAR, USA) was used for maintaining constant osmotic temperature above ambient, and a refrigerator (Model: HR-195B, by THERMOCOOL, Nigeria) was used to achieve constant osmotic temperature below ambient, a forced convection cabinet dryer (FCCD) shown in Figure 1 was used for drying the samples, thermo-hygrometer sensor (Model: QC4114, by ACURITE, China) was used to monitor drying air temperature and relative humidity in the drying chamber, electricity generating set (Model: RD2910, by SUMEC FIRMAN, China) was used as an alternative power source, laboratory stop watch (Model: 501, by NAHITA, China) used to monitor osmotic time. Moisture meter (Model: LSC-50, by NAPCO, China) was used determination of samples initial and final moisture contents. Desiccator used for temporary storage of samples before laboratory analysis.

The FCCD was developed in Agricultural and Biosystems Engineering Department, University of Ilorin; it has an overall dimension of 1610 mm by 600 mm made from mild steel. It has six major sections, which include; drying chamber with 4 trays, combustion chamber (blower of 2 m s^{-1} and 2 heaters of 1.8 kW power ratings each), 3 solid state relays (EARU SSR-40DA) for the two heaters and blower, a micro controller box, weight sensing mechanism (4 load cells) and thermo-hygrometer sensor. The drying chamber has a rectangular cross section double walled and lagged with fibre glass of 25 mm thickness to minimize heat loss to the surrounding. The weight loss, drying air relative humidity and temperature in the drying chamber were logged throughout the drying process on the PC.

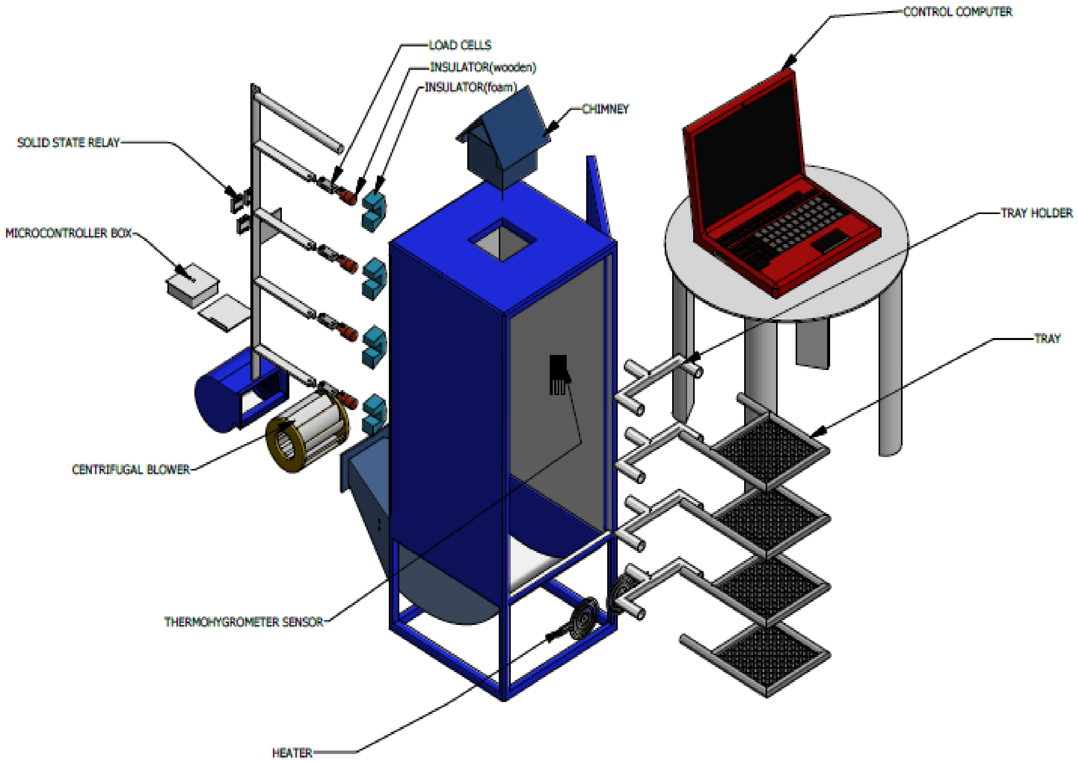

Figure 1 Forced convection cabinet dryer

3 Experimental procedure

The experiment was conducted in the month of August in the food processing laboratory of Food Engineering Department, University of Ilorin, Ilorin, Nigeria. The ambient relative humidity and temperature were found to be 0.93 and 29°C.

The samples were sorted, washed under a running tap, and drained before slicing to uniform thickness of 10 mm with a stainless knife, after deseeding; the samples were osmotically pre-treated in a solution of honey and sugar (2:1) at different osmotic concentrations of 20, 30, 40, 50 and 60°Bx, osmotic temperature of 10°C, 20°C, 30°C, 40°C and 50°C and osmotic duration of 10, 20, 30, 40, and 50 min. Samples were withdrawn and drained on wire gauze for 10 min and weight loss due to osmotic dehydration was recorded. Thereafter, the samples were loaded on the trays in the drying chamber of the cabinet dryer as shown in Figure 2. Weight of samples were monitored as drying progresses, 15 min interval for the first 1 h, 30 min for the next 4 h and 1 h for the remaining hours until weight becomes constant and no appreciable weight loss was recorded. The picture of dryer's control system is shown in Figure 3.

Figure 2 Samples loaded on the FCCD trays

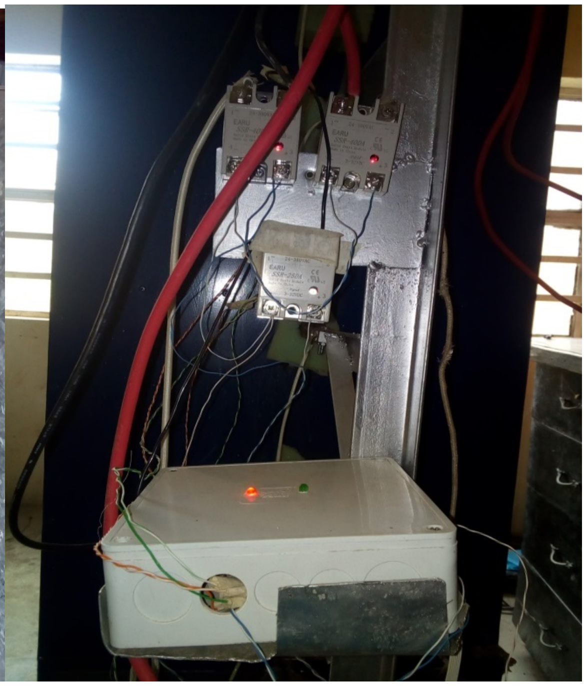

Figure 3 Control system of the FCCD

3.1 Drying rate

The drying rate of tomato in the cabinet dryer is important as prolonged residence time of the samples in the dryer can result to reduction in quality and more energy demand, after the experiment the drying rate was calculated according to Idah et al. (2014) as presented in Equation 1:

$$R = \left(\frac{dM}{dt}\right) = \frac{m_i - m_f}{t} \quad (1)$$

Where: R is the drying rate (g h^{-1}), dM is change in mass (g), dt is change in time (h), t is total time (h), m_i is initial mass tomato samples (g) and m_f is final mass of tomato samples (g).

3.2 Instantaneous Moisture Content

The instantaneous moisture content (M_t) is the moisture content of the tomato samples at any time during the drying experiment and was calculated according to Ojediran and Raji (2010) using the Equation 2:

$$M_t = \frac{M_i m_i - w_i}{m_i - w_i} \quad (2)$$

Where: M_t is the moisture content at time, t (% w.b.), M_i is initial moisture content (% w.b.), m_i is initial weight of product (g), w_i is weight loss at time t (g). The moisture content was converted to moisture ratio.

3.3 Moisture ratio

Moisture ratio is the ratio of sample's moisture content at any time t to the initial moisture content of the sample before drying, since the equilibrium moisture content is relatively small and becomes negligible for tomato drying, which took longer drying period, therefore, moisture ratio of tomato slices was calculated according to Taheri-Garavand et al. (2011), using Equation 3:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{M_t}{M_o} \quad (3)$$

Where: M_t is moisture content of the tomato samples at any time t (% db), M_e is moisture content of the tomato samples (% db) and M_o is the initial moisture content of the samples before drying (% db).

3.4 Effective Moisture Diffusivity

According to Taheri-Garavand et al. (2011), drying of food occurs usually in falling rate period. Prediction of moisture transfer during falling rate period was done using the simplified mathematical Fick's second law of diffusion in slab geometry by Crank (1975), with the assumption that during drying of tomato slices as a slab.

Fick's equation used for computing EMD of tomato is as follows (Equation 4):

$$MR = \frac{M_t}{M_O} = \frac{8}{\pi^2}\sum_{n-1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[\frac{(2n-1)^2\,\pi^2 D_{eff}\,t}{4L^2}\right] \quad (4)$$

Where: MR is the moisture ratio, M_t is moisture content at any time t (% db), M_o is moisture content (% db), n= 1, 2, 3, … the number of terms taken consideration. D_{eff} is the effective moisture diffusivity (m^2 s^{-1}), L is the geometric mean radius of the slice (m).

Furthermore, Equation 4 was simplified to give Equation 5 and used to compute the EMD since the drying process involved a long term drying due to high moisture content present in tomato, according to Taheri-Garavand et al. (2011).

$$MR = \frac{8}{\pi^2}\exp\left[\frac{\pi^2\, D_{eff}\, t}{4L^2}\right] \quad (5)$$

Equation 5 was further linearized and Equation 6 was derived as follows:

$$Ln\, MR = Ln\left[\frac{8}{\pi^2}\right] + \left[\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (6)$$

From Equation 6, the slope (K_o) of the graph was calculated by plotting ln (MR) versus time (t) according to Equation 7:

$$K_o = \frac{\pi^2 D_{eff}}{4L^2} \quad (7)$$

3.5 Re-hydration Characteristics of Dried Tomato Fruit

In order to assess the reconstitution quality of dried tomato slices, re-hydration test was conducted. Five g of dried tomato slices were soaked in an adequate volume of water of 30 mL for 10 min at room temperature. The ratio of mass of re-hydrated and the test sample was computed according to Abano and Sam-Amoah (2011), to determine re-hydration ratio of the tomato samples as shown in Equation 8:

$$R_r = \frac{A}{B} \quad (8)$$

Where: *A* is the mass of samples after soaking (g) and *B* is the test mass of samples before soaking (g).

3.6 Experimental design

The experiment was designed with Design expert 6.0.6 software; the central composite design (CCD) of response surface methodology (RSM) was used. Experimental input parameters include osmotic solution concentration (A), osmotic duration (B) and osmotic temperature (C), the coded values of the experimental design were interpreted for each input parameter as presented in Table 1. The experiment design had 20 runs altogether.

Table 1 Coded values and corresponding actual values used in CCD design

Input Parameters	Coded Levels				
	-1	-0.5	0	0.5	1
A:Osmotic Conc. (°Bx)	20	30	40	50	60
B:Osmotic Time (min)	10	20	30	40	50
C:Osmotic Temp. (°C)	10	20	30	40	50

3.7 Statistical analysis

Design expert software version 6.0.6 was used to analyse experimental data statistically, using analysis of variance (ANOVA) and regression analysis at 95% confidence level.

4 Results and discussion

The moisture content of fresh *Hausa* variety of tomato was found to be 0.88, and effects of the independent variables (osmotic concentration, duration and temperature) on the dependent variables (EMD and RR) of tomato slices were studied and reported as follows:

4.1 Influence of osmotic dehydration process conditions and model development for the effective moisture diffusivity (EMD) of tomato

The EMD of dried *Hausa* tomato samples occurred in the range of 1.40×10^{-9} to 4.19×10^{-8} m^2 s^{-1} during drying, this is similar to the findings of Jaiyeoba and Raji (2012) on tomato and in agreement with Ong and Law (2010) that the EMD of most food materials do occur in the range of 10^{-12} to 10^{-8} m^2 s^{-1}. 3-D plots showing how the process parameters influenced the EMD of tomato are presented in Figures 4 and 5. Figure 4 shows that EMD increases slightly as the osmotic duration increases from 10 to 50 min and decreases sharply as the osmotic concentration increases from 20 to 50°Bx; this is in agreement with the findings of Singh et al. (2007). This may be due to the decreasing moisture and increasing solids content. Figure 5 further revealed that EMD increases exponentially as osmotic temperature increases from 10 °C to 50°C; this may be due to more moisture being loosely bound to the food matrix at higher temperature, which favoured moisture diffusion; it is similar to the findings of Jaiyeoba and Raji (2012) on tomato fruits. Statistically, Table 2 shows that the single effect of osmotic concentration (A) was significant on the EMD value of the dried samples, also the interactive effects of osmotic concentration and temperature (AC) and osmotic duration and temperature (BC) were also significant at $p \leq 0.05$. However, the single effects of osmotic duration (B) and temperature (C), their quadratic effects including that of osmotic concentration (A) and the interaction between AB were not significant at $p \leq 0.05$.

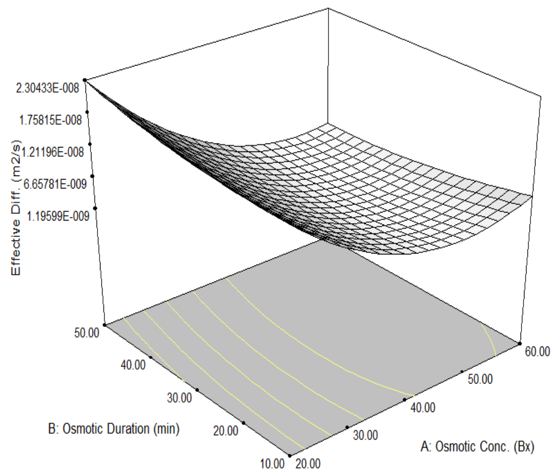

Figure 4 Effect of osmotic duration and conc. on effective moisture diffusivity

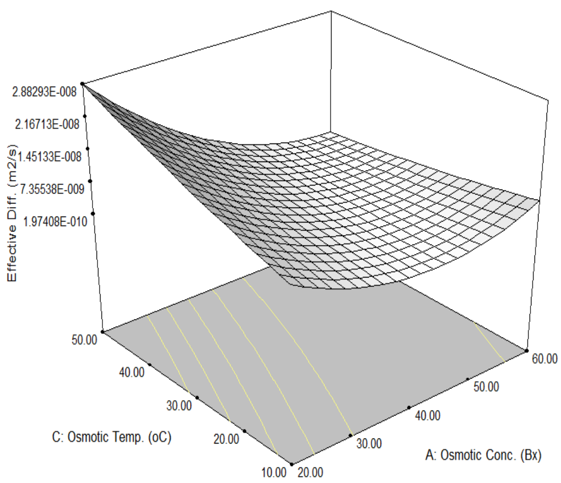

Figure 5 Effect of osmotic temp and time on effective moisture diffusivity

Table 2 shows that the model developed for the prediction of EMD of tomato was significant having an F-value of 6.60 and insignificant lack of fit. R^2 value of 0.8559 and R^2_{Adj} of 0.7263 were considered to be high. The Predicted Sum of Square (PRESS) and the coefficient of variation values were low. These suggests that the model has goodness of fit which was supplied with adequate signal as adequate precision value of 10.79 was higher than the required 4. The developed model equation was presented in Equation 9:

Effective Diff. = 3.760 × 10-8-8.144 × 10-9A+1.415 × 10-10 B+2.704 × 10-9 C+7.290 × 10-9 A2 +1.344 × 10-9B2+7.591 × 10-10 C2-2.364 × 10-9AB-6.172 × 10-9AC+5.295 × 10-9BC (9)

Table 2 Analysis of variance for effective moisture diffusivity of tomato

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1.59E-15	9	1.77E-16	6.601	0.0034*
A	5.64E-16	1	5.64E-16	21.012	0.0010*
B	1.70E-19	1	1.70E-19	0.006	0.9381**
C	6.22E-17	1	6.22E-17	2.317	0.1590**
A^2	9.92E-18	1	9.92E-18	0.37	0.5567**
B^2	3.37E-19	1	3.37E-19	0.013	0.9130**
C^2	1.08E-19	1	1.08E-19	0.004	0.9508**
AB	4.47E-17	1	4.47E-17	1.666	0.2258**
AC	3.05E-16	1	3.05E-16	11.36	0.0071*
BC	2.24E-16	1	2.24E-16	8.361	0.0161*
Residual	2.68E-16	10	2.68E-17		
Lack of Fit	1.34E-16	5	2.67E-17	0.993	0.5031**
Pure Error	1.35E-16	5	2.69E-17		
Cor Total	1.86E-15	19			

Note: * Significant and ** Not Significant at $p \leq 0.05$

4.2 Influence of osmotic dehydration process conditions and model development for the rehydration ratio of tomato

The rehydration ratio (RR) of the dried *Hausa* tomato variety was obtained within the range of 0.60 to 2.00, close to findings of Mozumder et al. (2012) on the RR of tomato for 30 min. The disparity of the RR of the samples studied in the course of this experiment can be related to their process conditions most especially during osmotic dehydration prior to drying. The osmotic duration has significant effect on the RR of the dried tomato slices at $p \leq 0.05$ as shown in Table 3. Figures 6 and 7 further revealed its influence on the RR in a 3-D plot, which shows that as osmotic duration increases from 10 to 50 min, the RR of dried tomato samples also increases exponentially, this is in agreement with the findings of Krokida and Marinos-Kouris (2003). However, Figure 6 shows that this pattern was not applicable to the osmotic concentration which forms a convex response surface pattern revealing that the value of RR decreases slowly at higher concentration between 30-40ºBx after 20ºBx but increases between 50- 60ºBx. Nevertheless, maximum RR was attained at 20ºBx osmotic concentration. The reason for this would be as result of low impregnation of sub-surface tissue layer with honey and sugar at 20ºBx than at higher concentrations (Azarpazhooh and Ramaswamy, 2010) and as a result few solutes were leached into the solution and more water was absorbed (Mozumder *et al.*, 2012). Figure 7 show that RR increases sharply with increase in osmotic temperature of the solution, this is in agreement with the findings of Krokida and Marinos-Kouris (2003).

However, as shown in Table 3, statistically at $p \leq 0.05$ individual effects of osmotic concentration and temperature, quadratic effects of osmotic concentration, duration and temperature, and also the interaction between osmotic concentration and duration were not significant on the RR. But the interaction between osmotic concentration and temperature, and osmotic duration and temperature were significant.

Quadratic model was fitted to the experimental data obtained for RR as shown in Table 4 the model was significant at $p \leq 0.05$, from the table the coefficient of determination, R^2 for RR is 0.8140 and the R^2_{adj} is 0.6466, this show that the model can satisfactory explain a higher percentage of the variation. R^2_{pred} value of 0.2303, PRESS value of 1.15 and coefficient of variation of 12.28 are considerably low and good for a model.

Table 3 Analysis of variance for rehydration ratio of dried tomato

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1.21	9	0.13	4.86	0.0106*
A	0.02	1	0.02	0.68	0.4290**
B	0.23	1	0.23	8.32	0.0163*
C	0.00	1	0.00	0.10	0.7636**
A2	0.05	1	0.05	1.73	0.2184**
B2	0.02	1	0.02	0.58	0.4632**
C2	0.00	1	0.00	0.06	0.8124**
AB	0.05	1	0.05	1.62	0.2313**
AC	0.41	1	0.41	14.62	0.0034*
BC	0.41	1	0.41	14.62	0.0034*
Residual	0.28	10	0.03		
Lack of Fit	0.14	5	0.03	1.08	0.4681**
Pure Error	0.13	5	0.03		
Cor Total	1.49	19			

Note: * Significant and ** Not Significant at $p \leq 0.05$

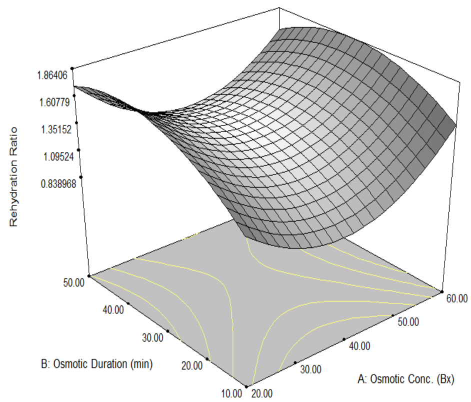

Figure 6 Effect of osmotic duration and conc. on rehydration ratio

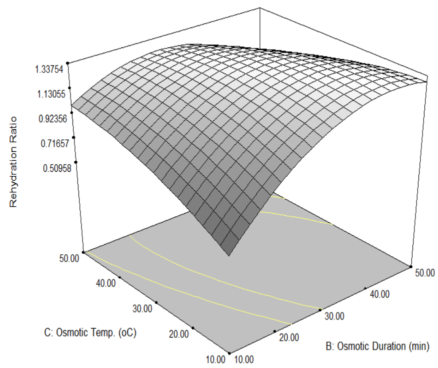

Figure 7 Effect of osmotic temperature and duration on rehydration ratio

Also, the model has adequate signal and lack of fit was not significant; these parameters point at the model and indicated that it was of good fit and satisfactorily explained the *RR* characteristics of dried tomato. The model equation is shown in Equation 10:

$$\text{Rehydration Capacity} = 1.30 + 0.047A + 0.16B + 0.018C + 0.51A^2 - 0.29B^2 - 0.094C^2 - 0.075AB - 0.23AC - 0.23BC \quad (10)$$

Table 4 Results for fitting quadratic models to the data for the responses

Statistics	Effective moisture diffusivity	Rehydration ratio
R^2	0.8559	0.8140
R^2_{Adj}	0.7263	0.6466
R^2_{Pred}	-1.0633	0.2303
PRESS	3.84E-15	1.15
Model F-value	6.6	4.86
Model P-value (Prob.>F)	0.0034*	0.0106*
Adequate Precision	10.786	11.245
Coeff. of Variation	66.81	12.28
Lack of Fit (Prob.>F)	0.5031**	0.4681**

Note: * Significant and ** Not Significant at $p \leq 0.05$

4.3 Optimization of the process conditions for the responses

The process condition was optimized for EMD and RR of *Hausa* variety of tomato to ensure easy duplication of the experiment. Numerical optimization was done as shown in Table 5, solutions were generated after running the experiment, and solution 1 had the highest desirability function and was selected since it was the closest to unity. Therefore, a process combination of 20°Bx osmotic concentration, 42 min osmotic duration and 50°C osmotic temperature, gave EMD of 3.42×10^{-8} m^2 s^{-1} and 1.81 RR was suggested as the optimum.

Table 5 Central composite design optimmization results

No.	Osmotic Conc. (°Bx)	Osmotic Time (min)	Osmotic Temp. (°C)	Effective moisture diffusivity (m^2 s^{-1})	Rehydration Ratio	Desirability
1	20	42	50	3.42×10^{-8}	1.809	0.836*
2	20	47	50	3.63×10^{-8}	1.721	0.831
3	20	34	50	3.03×10^{-8}	1.905	0.816
4	21	41	50	3.25×10^{-8}	1.788	0.808
5	21	34	50	2.93×10^{-8}	1.851	0.784
6	60	15	10	1.36×10^{-8}	1.560	0.456
7	60	15	10	1.35×10^{-8}	1.571	0.455

Note:* Selected based on the best desirability function

5 Conclusion

The influence of osmotic dehydration process on the EMD *and* RR of dried tomato samples was ascertained. The EMD *and* RR of *Hausa* variety of tomato were obtained within the range of 1.40×10^{-9} - 4.19×10^{-8} m^2 s^{-1} and 0.60 – 2.00 respectively. EMD *and* RR increased with increase in osmotic duration, and EMD decreases gradually as osmotic concentration increased, also both EMD *and* RR increased exponentially as the osmotic temperature was raised from 20°C - 50°C. The models developed were significant and satisfactorily described the EMD and RR of tomato samples. EMD had R^2 and R^2_{adj} values of 0.8559 and 0.7263, while RR had R^2 and R^2_{adj} values of 0.8140 and 0.6466 respectively. The optimized process condition gave EMD of 3.42×10^{-8} m^2 s^{-1} and RR of 1.81 at 20°Bx osmotic concentration, 42 min osmotic duration and 50°C osmotic temperature. This will help in minimizing overall energy usage and drying time as high EMD will give room for faster drying rate, and also high RR depicts better quality attributes of the dried samples for human consumption.

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