Adsorption and desorption isotherms of noodles produced from composite flour of wheat and water yam (*Dioscorea alata*)

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Adsorption and desorption isotherms of wheat-yam noodles at 32 and 37ºC were estimated with the standard static-gravimetric method. The composite flour of wheat and water yam *(D. alata*) were mixed at ratios of 75:25, 50:50, and 25:75% to produce the noodles with the use of a locally fabricated extrusion-like hand-operated machine. Experimental data were fitted to four mathematical models (Guggenheim, Anderson and de Boer; modified Guggenheim, Anderson and de Boer; Oswin and modified Oswin). The constants of the sorption equations were evaluated using nonlinear regression analyses. The moisture sorption isotherms were sigmoidal in shape and influenced by temperature. The equilibrium moisture content increased as the relative humidity increased in adsorption and desorption isotherms. The sorption models evaluated predicted the adsorption and desorption isotherms of wheat-yam noodles at the evaluated temperatures adequately, with $R^2 \geq 0.9680$. Thus, these models are suitable for predicting the equilibrium moisture content of wheat-yam noodles under the practical storage conditions studied.

Keywords: Adsorption isotherm, desorption isotherm, noodles, water yam, isotherm models

Noodle, a breakfast cereal-based product, is a traditional food that originated from China and other Asian countries and has been favoured by the Chinese people for over 2000 years (Li et al. 2016). Noodle is consumed by both adults and children due to its nutritional content and convenience. The primary raw material used for noodles production is hard wheat flour; however, different noodle types exist based on the other ingredients added, such as colourant or flavour. Noodles are rich in carbohydrates and contain substantial protein and vitamin levels (Effiong et al. 2018). The changes in lifestyle and rapid urbanisation in recent years have increased the consumption of noodles in developing countries like Nigeria. However, the availability and cost of importation of wheat flour have been posing a problem in countries where wheat is not produced. Thus, it is of economic advantage if wheat importation is reduced by substituting it with other suitable materials. This would reduce the dependency on wheat importations and increase the livelihoods of local farmers who produce crops that may be used for its substitute.

Yam flour, which is abundantly available in Nigeria, is one of the promising substitutes for wheat flour. Yams belong to the genus *Dioscorea* of the family *Dioscoreaceae*, with approximately 600 species. However, only a few are known for their use in human consumption, *D. alata*, *D. cayenensis*, *D. rotundata*, *D. dumetorum*, *D. esculenta*, and *D. bulbifera* (Mignouna and Dansi 2003). Out of these species, Mignouna and Dansi (2003) reported that water yam (*D. alata*) is a widely distributed species and the world's third most utilised white yam after *D. rotundata* and *D. cayenensis*. The tuber has a high moisture content hence the name "water yam". The high moisture content (65 – 76 % per 100 g edible

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tuber portion) of the yam tubers makes it highly perishable, prompting the need to process it into a flour as an intermediate product to enhance its shelf stability and utilisation (Harijono et al. 2013). Scott et al. (2000) also reported that increased utilisation of water yam through processing into novel or convenience food products and advancements in the marketing channels could influence the productivity of yam and bring the benefits from the crop to a broader range of consumers.

In the past years, researchers have been engaged in increasing the utilisation of yam flour in the manufacturing of noodles in the oriental and many developing countries (Li et al. 2012; Akonor et al. 2017; Djeukeu et al. 2017; Sun et al. 2019). However, water yam flour has been underutilised due to its quality and higher moisture contents when compared with other yam flour; this thereby affects its acceptability and storage stability. Adsorption and desorption isotherms are used for several purposes in food research, and these include drying time estimation, prediction of mixing ingredient ratio, prediction of the type of packaging, modeling changes in moisture that occurs during storage, and prediction of shelf-life stability of agricultural products such as, gari, fufu, tapioca, maize, sorghum, and yam flour (Sanni et al. 1999; Adebowale et al. 2007; Oyelade et al. 2008; Owo et al. 2017). Storage conditions in terms of heat and humidity have a direct effect on moisture adsorption and desorption behaviours, hence understanding the relationship between the changes of dried food products under various storage conditions can be very useful in the prediction of quality and selection of suitable preservative and packaging materials. Moisture sorption isotherm behaviours are often dependent on material and processing.

A fundamental property of a biological material that affects storage stability and dehydration is its water sorption characteristics. Oyelade et al. (2008) reported that the sorption characteristics are influenced by environmental conditions like temperature and relative humidity. Thus, the data relating to equilibrium moisture content and relative humidity are required in the design handling, storing and dehydrating systems for hygroscopic materials. Also, with knowledge of adsorption and desorption isotherms, the prediction of the maximum moisture that the vegetable could gain during storage is possible (Sobowale et al. 2017). Additionally, moisture sorption isotherms are extremely valuable tools needed by scientists, because they can be effectively used in predicting the potential changes in biological materials. The data of the adsorption isotherm can be used as a storage index while the data of the desorption isotherm can be used in drying analysis. Sobowale et al. (2017) reported that moisture sorption isotherm fitting equations are of special interest in wide areas of food preservation and dehydration.

Therefore, it is relevant to investigate the sorption isotherm characteristics of wheat-yam noodles. This will provide important insights into, and make an essential contribution to, the different operations that need to be optimised to process wheat-yam noodles. This study aims to obtain moisture sorption equilibrium data for wheat-yam noodles at temperatures of 32 and 37^{o}C and to model equilibrium moisture content data for the wheat-yam noodles at the specified temperatures using widely recommended isotherm mathematical relationships.

Materials and methods

Materials

Tubers of water yam *(D. alata*) were sourced from the teaching and research farm of Ladoke Akintola University of Technology, Ogbomoso. The tubers were harvested at full maturity and processed immediately into flour.

Yam flour production

The yam tubers were peeled and sliced (4 cm length, 2 cm breadth, and 2 cm thick) into water containing sodium metabisulphite (0.25% w/v) to prevent browning reactions. All the yam slices were drained and dried at 60°C for 48 hours in a cabinet dryer (Model LEEC F2, SciQuip, UK). The cabinet chamber was insulated and fitted with perforated trays that allowed hot air to circulate through the cabinet at 3 m/s per m^2 tray area. To ensure uniform air circulation, the duct and baffles technique was adopted in directing the hot air through each tray. The dried yam chips were subsequently milled into a fine flour with a laboratory hammer mill (8" LAB MILL, England), and then passed through a mesh of 150 µm screen size. The yam flour samples were stored in airtight containers at 4°C until needed.

Noodle production

Wheat flour (*Tritium aestivum*) and yam flour were mixed at ratios of 75: 25, 50: 50, and 25: 75 of wheat and yam flour, respectively. Warm water (40°C) and 5% carboxymethyl cellulose were added and mixed to form the dough. The formed dough was allowed to rest for 20 minutes and then kneaded and rolled with a rolling pin to form sheets. The sheets were extruded with the use of a locally fabricated extrusion-like hand-operated machine to produce the noodles. The extruded noodle strands were then dried in a cabinet dryer (60°C) and used for the various analyses.

Experimental design

A completely randomised design was used to design the experimental layout for the production of noodles from *D. alata.* Noodles of the three mixture ratios were each produced three times. The nine products were each divided into six giving 54 samples; half of these (27) were stored at 32°C and half were stored at 37°C.

Determination of equilibrium moisture content and moisture sorption isotherms

The equilibrium moisture content (EMC) of the samples was determined using the static gravimetric method as described by Pawar et al. (1992) at temperatures of 32 and 37°C. The temperatures were chosen to simulate variations in the temperatures across the Nigeria. Triplicate noodle samples, 20 g each, were placed on the top of a wire mesh inside a desiccator containing saturated salt solutions in the water activity range of 0.11 – 0.96. The different salt solutions reported by Oyelade et al. (2008) were adopted. The desiccators containing the samples were kept in an incubator (Genlab M75CPD, Cheshire, England) to maintain the desired temperatures of 32 and 37°C. The samples were weighed daily, and the equilibrium conditions were considered to be attained when values were constant in three consecutive readings. The EMC of the equilibrated samples was calculated as a percentage with respect to dry weight basis by the formula reported by Sobowale et al. (2017).

$$EMC\ (\%) = \frac{Adsorbed\ moisture}{Weight\ of\ sample} \times 100$$

The moisture content of the equilibrated samples was plotted against water activity to obtain an isotherm curve. The same set of samples used for adsorption was used for desorption isotherm experiments. This was done by step-wise transferring of the equilibrated samples after adsorption at the highest water activity (1.0) to the lower water activity range of 0.8 – 0.1. The desiccators were placed in an incubator (Genlab M75CPD, Cheshire, England) for desorption until equilibrium conditions were reached (i.e. when constant weights were obtained in three consecutive readings).

Modelling and isotherm equations

Many models have been reported in the literature for predicting the moisture sorption isotherms. However, four widely used isotherm equations (Guggenheim, Anderson and de Boer, GAB; modified Guggenheim, Anderson and de Boer, MGAB; Oswin, OE; and modified Oswin, MOE) that could adequately fit the moisture sorption isotherm of yam-based foods were selected. The equations are shown in Table 1 in the form of $X = f(a_w T)$.

Table 1: Sorption isotherm equation used for the modelling process (Oyelade et al. 2008; Sobowale et al. 2017)

Model	Model equations
Guggenheim, Anderson and de Boer	$X = \frac{abca_w}{(1-ca_w)(1-ca_w+bca_w)}$
Modified Guggenheim, Anderson and de Boer	$X = \frac{a(c/t)ba_w}{(1-ba_w)[(1-ba_w)+(c/t)ba_w)]}$
Oswin	$X = a\frac{a_w}{(1-a_w)^c}$
Modified Oswin	$X = (a + bT)(\frac{a_w}{1-a_w})^c$

Where, X is the equilibrium moisture content (%, dry basis), a_w is the water activity, a, b, and c are the models constant parameters, and T is the temperature (°C).

Validation of the models

The modelling of the EMC data was estimated using non-linear regression procedure of SPSS version 21. Thereafter, the models were validated using the coefficient of determination (R^2), residual sum of squares (RSS), mean square error (MSE), and standard error of estimate (SEE) between the experimental and calculated EMC of the products (Oyelade et al. 2008; Sobowale et al. 2017).

$$R^2 = 1 - \frac{RES}{TES}$$

$$RSS = \sum_{i=1}^{n}(X_{cal} - X_{pred})^2$$

$$MSE = \frac{\sum_{i=1}^{n}(X_{cal}-X_{pred})^2}{N}$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(X_{cal}-X_{pred})^2}{N}}$$

Where X_{cal} = EMC of experiment (%, dry basis),
X_{cal} = EMC of experiment (%, dry basis),
RES = residual sum of squares,
TES = total error sum of squares, and
N = number of experiments.

Results and discussion

Adsorption and desorption isotherm of wheat-yam noodles

The adsorption and desorption isotherm curves of wheat-yam noodles at 32 and 37°C are depicted in Figures 1, 2, and 3. The curves show that the moisture contents were increasing as the level of yam flour increased, indicating that the moisture content of yam flour was higher than that of wheat flour. Thus, the wheat-yam noodles with a lower percentage of yam flour inclusion were expected to have higher storage stability. The isotherm curves also showed that EMC increased with an increase in the water activity at constant temperature and decreased with an increase in the temperature at constant water activity for both adsorption and desorption isotherms. This behaviour could be explained by considering the excitation states of water vapour molecules surrounding the wheat-yam noodles. The molecules become more excited at a higher temperature, which aided an increase in the intermolecular distance and a decrease in the attractive forces between them. Therefore, this process could promote a reduction in the degree of water sorption by the noodles with increasing temperature at the given water activity. This result corroborated with what was reported by Arslan and Togrul (2005) for stored macaroni and Li et al. (2016) for Chinese instant noodles. The hydroscopic nature of the water yam flour used in noodles production could also be attributed to the decrease in moisture content with an increase in the temperature (Owo et al. 2017; Okeleye et al. 2019).

Figures 4, 5, and 6 show the Henderson plots, which indicate the moisture content, and water activity level at which LI breaks occurred and this was used to demarcate of the isotherm curves to LI – I, LI – II, and LI – LIII (Henderson, 1952; El-Nemr et al. 2010). The moisture content and their related water activities were traced to the x-axis and y-axis to obtain the moisture content and water activity at first and second break moisture contents. Table 2 shows the moisture content and water activity at which LI breaks occurred in the Henderson plots and their corresponding relative humidity for each wheat-yam noodle. These values are the range of water activity in which the wheat-yam noodles can be stored and the relative humidity of the local isotherm boundary for the stability of the noodles during storage. The sorption isotherms of wheat-yam noodles showed the typical sigmoidal shape, which conformed to Type II in the Brumaire Emmett Teller (BET) classifications, as Iglesias and Chirife (1982) reported. The sigmoidal shape of the sorption isotherm was also reported in the literature for most food products (Arslan and Togrul 2005; Oyelade et al. 2008; Li et al. 2016; Sobowale et al. 2017; Okeleye et al. 2019). From the adsorption and desorption isotherm data, EMC increased as relative humidity increased. This trend in EMC conformed to the statement that the more the water activity, the more the quantity of adsorbed moisture (Sobowale et al. 2017). Owo et al. (2017) also reported that at higher water activity more water was readily available for binding at the active site of the solid. Most foods cannot support the growth of microorganisms at water activity lower than 0.60 and for formation of moulds at water activity equal to 0.80. The difference obtained in the EMC values for the wheat-yam noodles may have arisen from the individual values for the components of the composite flour used for production. The hysteresis effects of the sorption isotherms at the two temperatures were distinctly expressed. The increasing temperature in adsorption and desorption isotherms showed a decrease in moisture content.

The BET plots of wheat-yam noodles at 32 and 37°C shown in Figures 7, 8, and 9 were used in determining the monolayer moisture content (Brunauer et al. 1938; Sobowale et al. 2017). They could thus help predict the likelihood of microbial spoilage rate in the product (Sobowale et al. 2017). The low monolayer moisture values obtained fell within what is expected of wheat-yam noodles; hence better storage stability is expected. High monolayer moisture is expected to enhance the spoilage tendency in food due to the presence of more water, which was not the case in this study. The R^2 of the BET plots were all over 0.98, this showed that the BET equations obtained were justifiable within the water activity range or even over a wider range. This result corroborated with what was reported in the literature that the BET model was considered to be justifiable within the water activity range of 0.1 – 0.5 (Bup et al. 2012). Figures 10, 11, and 12 show the water stability plots and the stability of ΔEMC against EMC for the wheat-yam noodles at 32 and 37°C. Based on these plots, wheat-yam noodles could be said to have good storage stability at the investigated temperature values.

Table 2: Moisture content and water activity at which LI breaks occur in the Henderson plots for wheat-yam noodles

Samples	Temperature (°C)	1st B.M.C (% d.b.)	a_w	2nd B.M.C (% d.b.)	a_w	LI – III Boundary (% R.H.)
75W:25Y	32	6.31	0.33	7.08	0.60	60
	37	4.79	0.32	6.68	0.58	58
50W:50Y	32	6.61	0.33	7.08	0.60	60
	37	6.03	0.32	6.76	0.61	61
25W:75Y	32	6.61	0.33	7.26	0.60	60
	37	6.31	0.33	6.81	0.61	61

Where;

1st B.M.C = first break moisture content
2nd B.M.C = second break moisture content
a_w = water activity
R.H. = relative humidity
d.b = dry basis

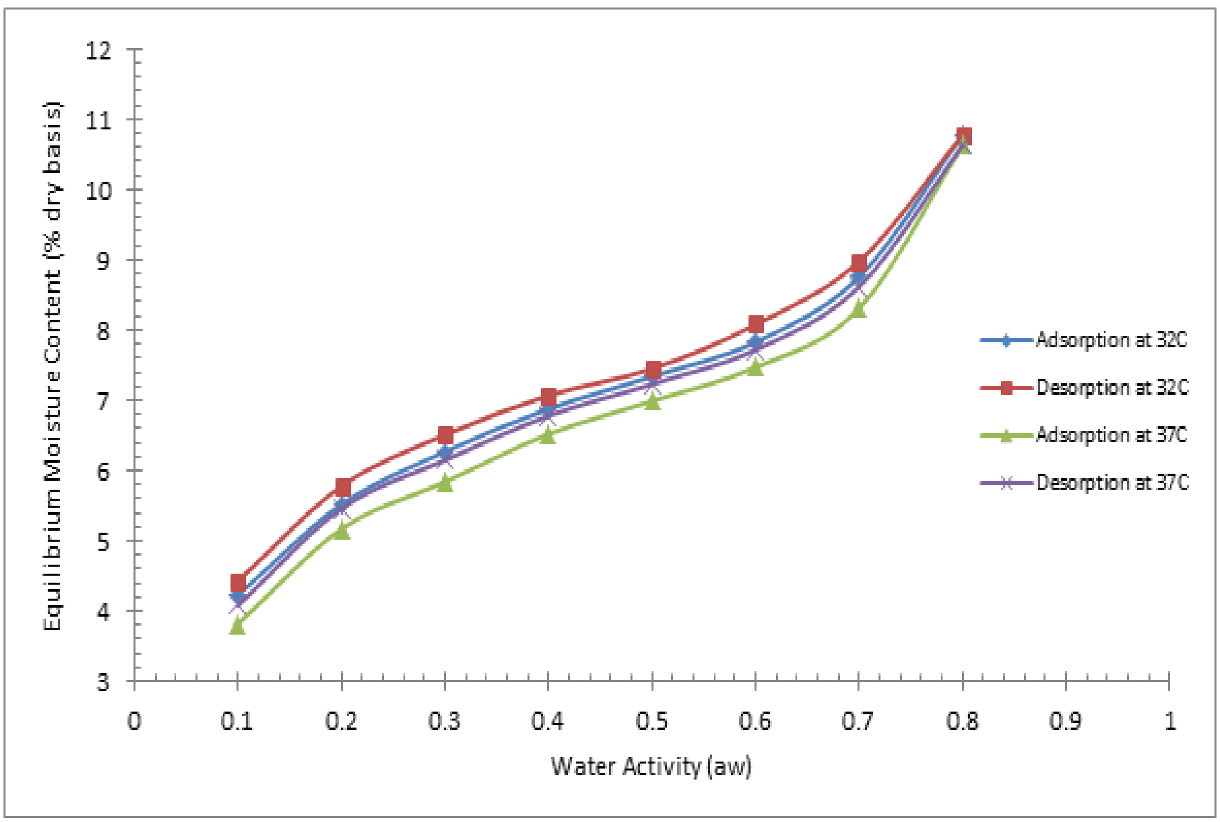

Figure 1: Isothermal curve of wheat-yam (75:25) noodles at 32 and 37°C

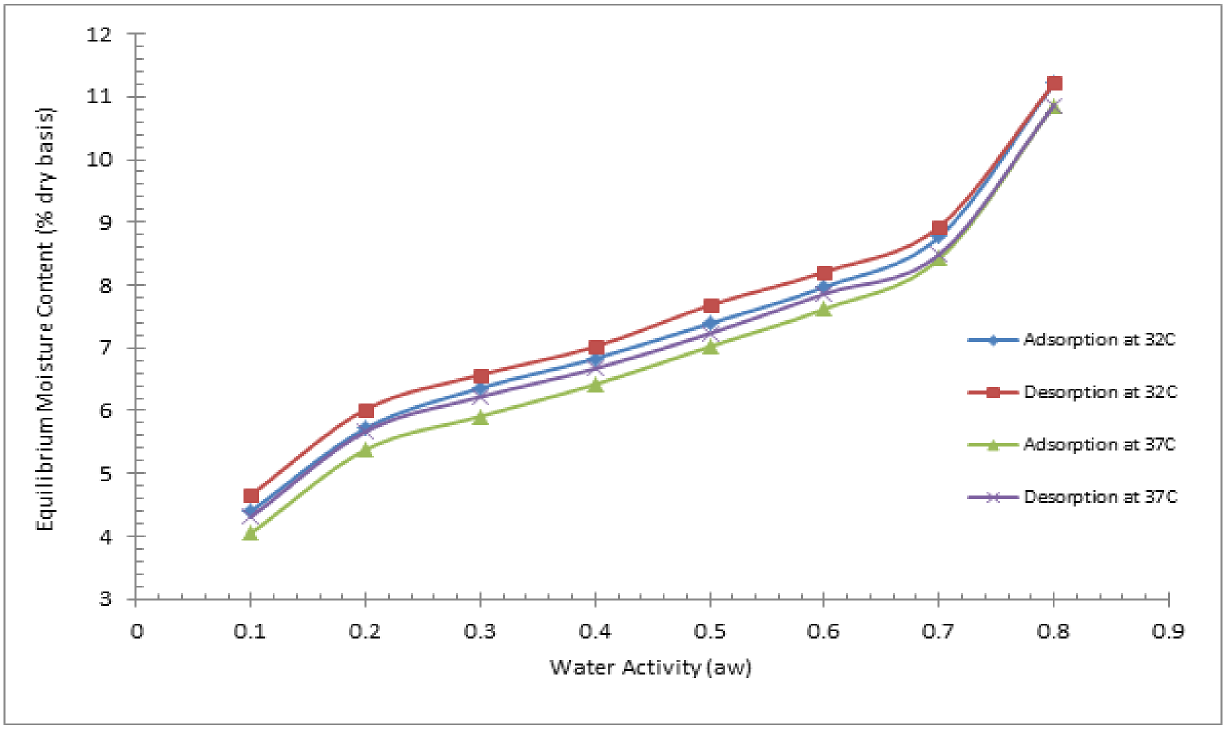

Figure 2: Isothermal curve of wheat-yam (50:50) noodles at 32 and 37ºC

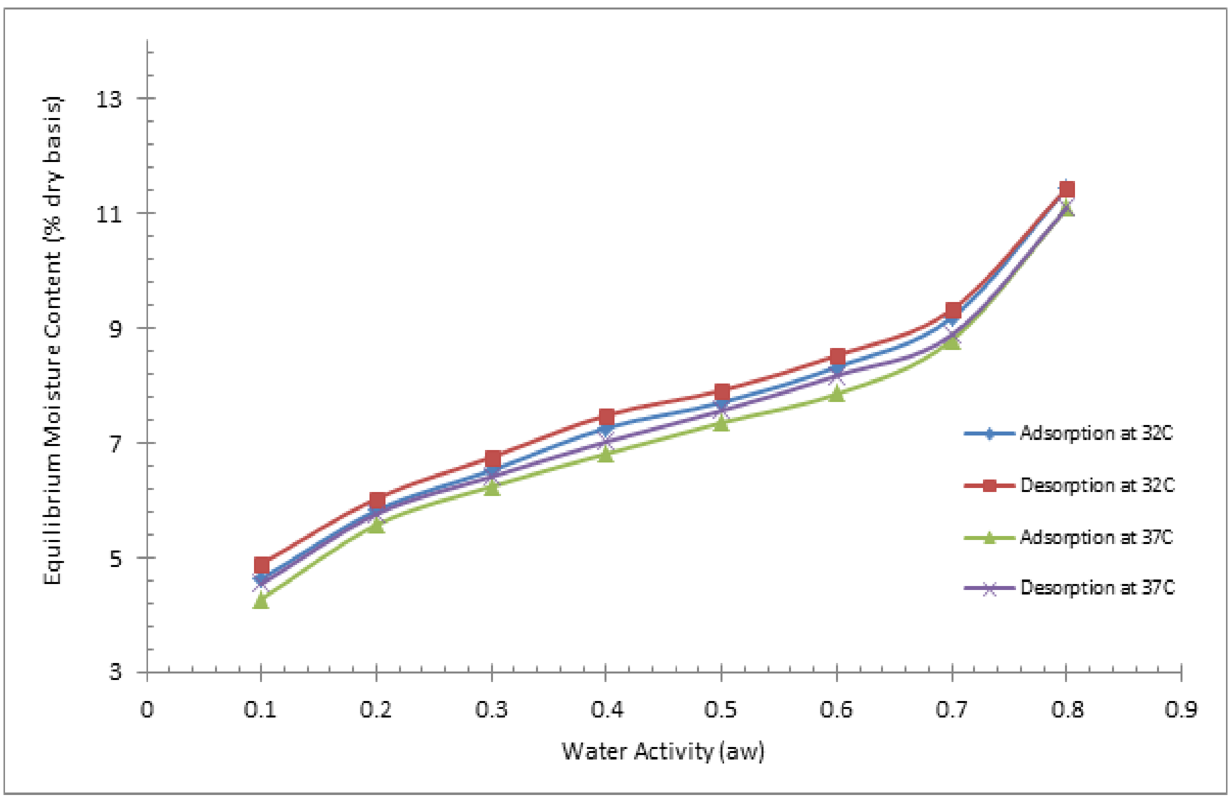

Figure 3: Isothermal curve of wheat-yam (25:75) noodles at 32 and 37ºC

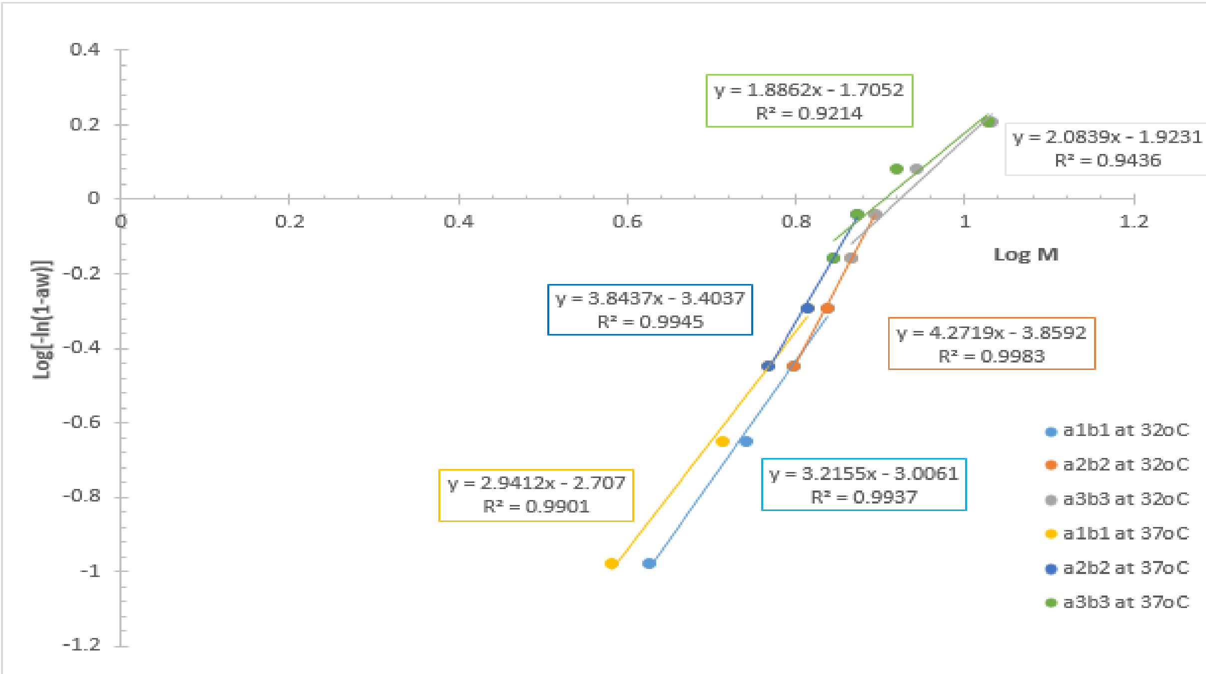

Figure 4: Henderson plot of wheat-yam (75:25) noodles at 32 and 37 ^oC
Where:

M = equilibrium moisture content
a_w = water activity
a1b1 - a3b3 = the values of water activity and the corresponding values of equilibrium moisture content

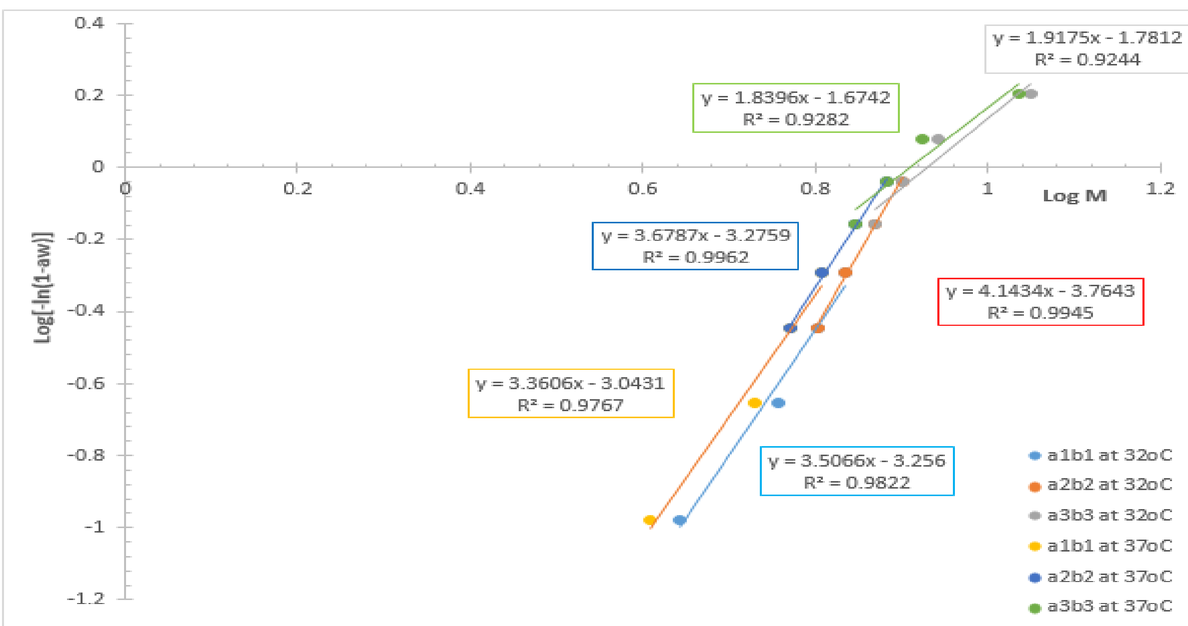

Figure 5: Henderson plot of wheat-yam (50:50) noodles at 32 and 37^oC
Where:

M = equilibrium moisture content
a_w = water activity
a1b1 - a3b3 = the values of water activity and the corresponding values of equilibrium moisture content

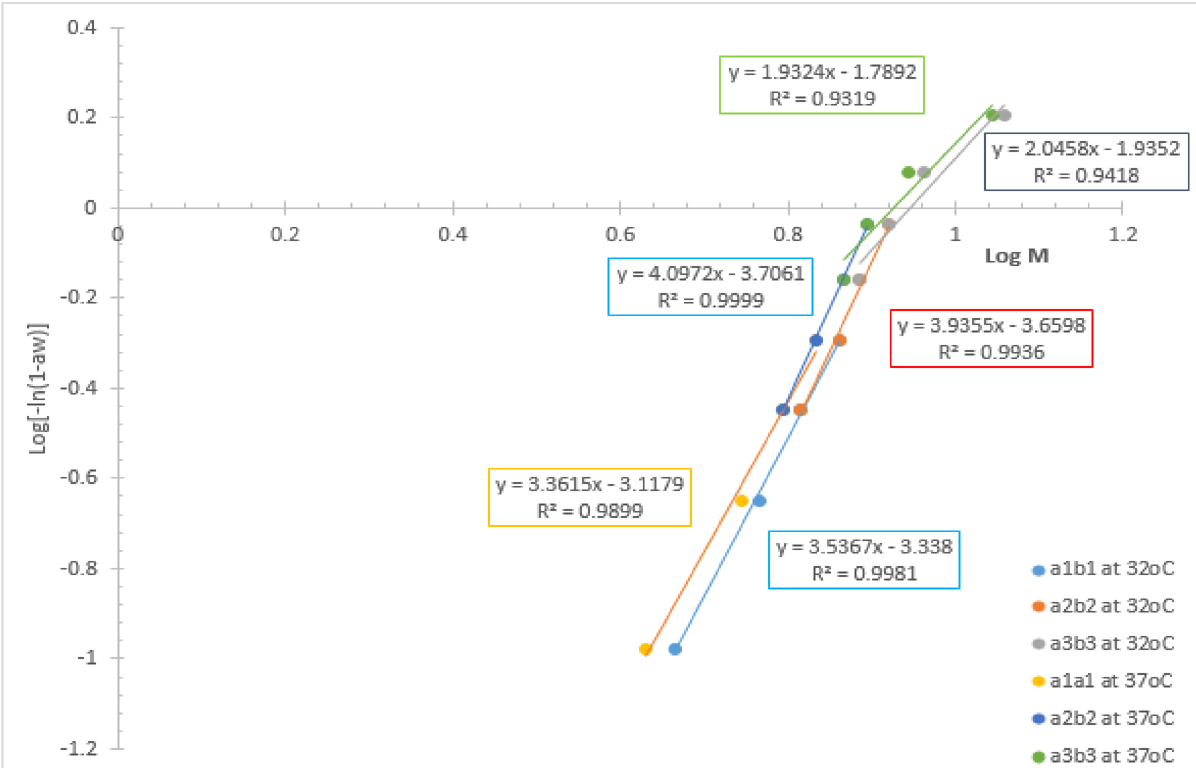

Figure 6: Henderson plot of wheat-yam (25:75) noodles at 32 and 37°C

Where:

M = equilibrium moisture content

a_w = water activity

a1b1 - a3b3 = the values of water activity and the corresponding values of equilibrium moisture content

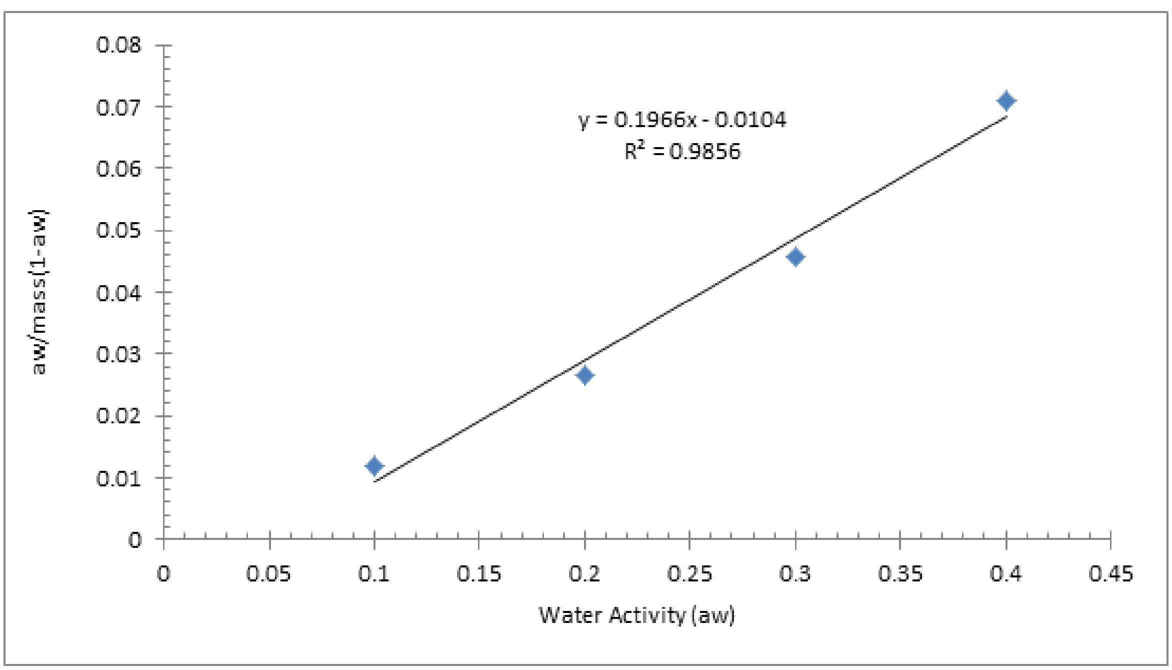

Figure 7: BET plot of wheat-yam (75:25) noodles at 32 and 37°C

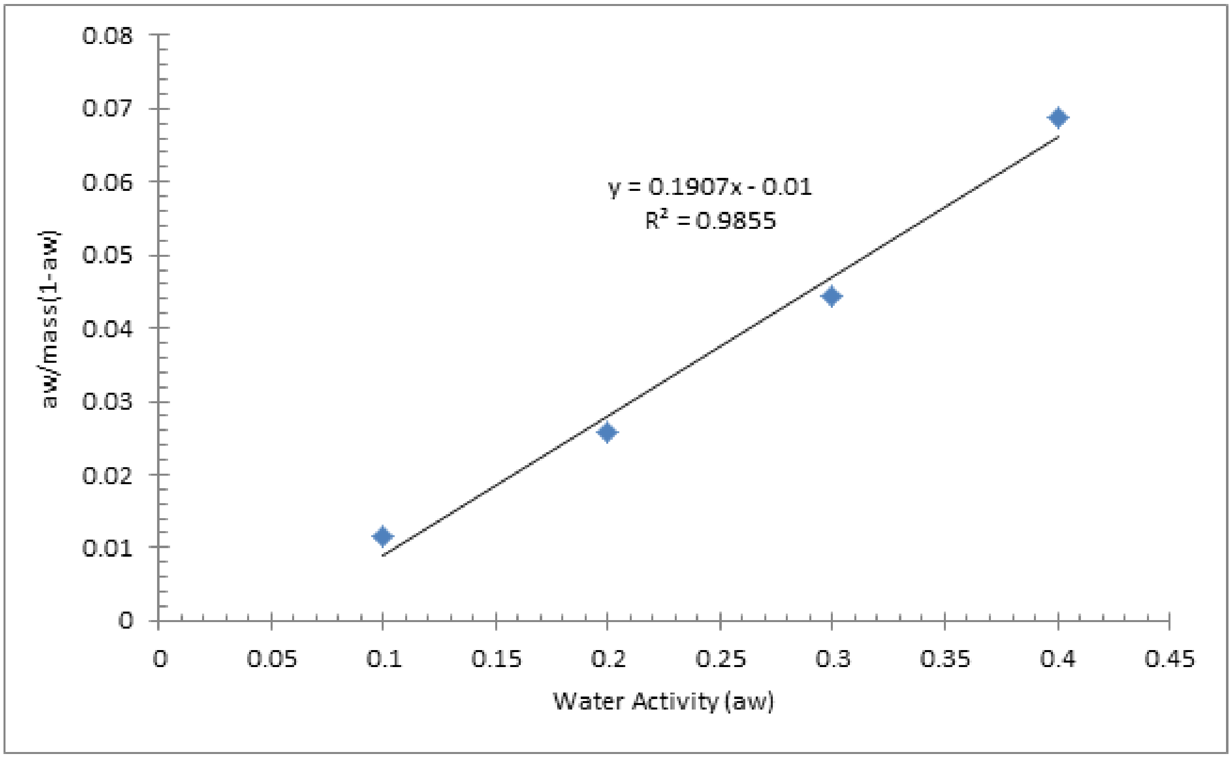

Figure 8: BET plot of wheat-yam (50:50) noodles at 32 and 37ºC

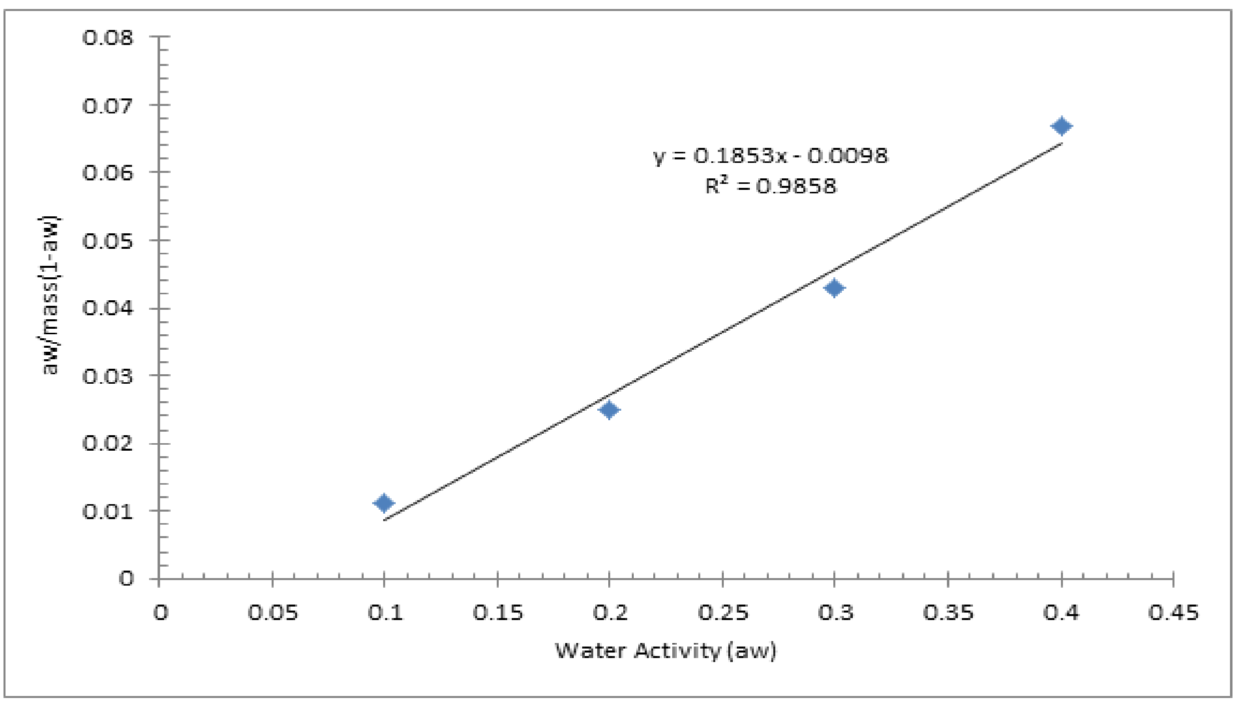

Figure 9: BET plot of wheat-yam (25:75) noodles at 32 and 37 ºC

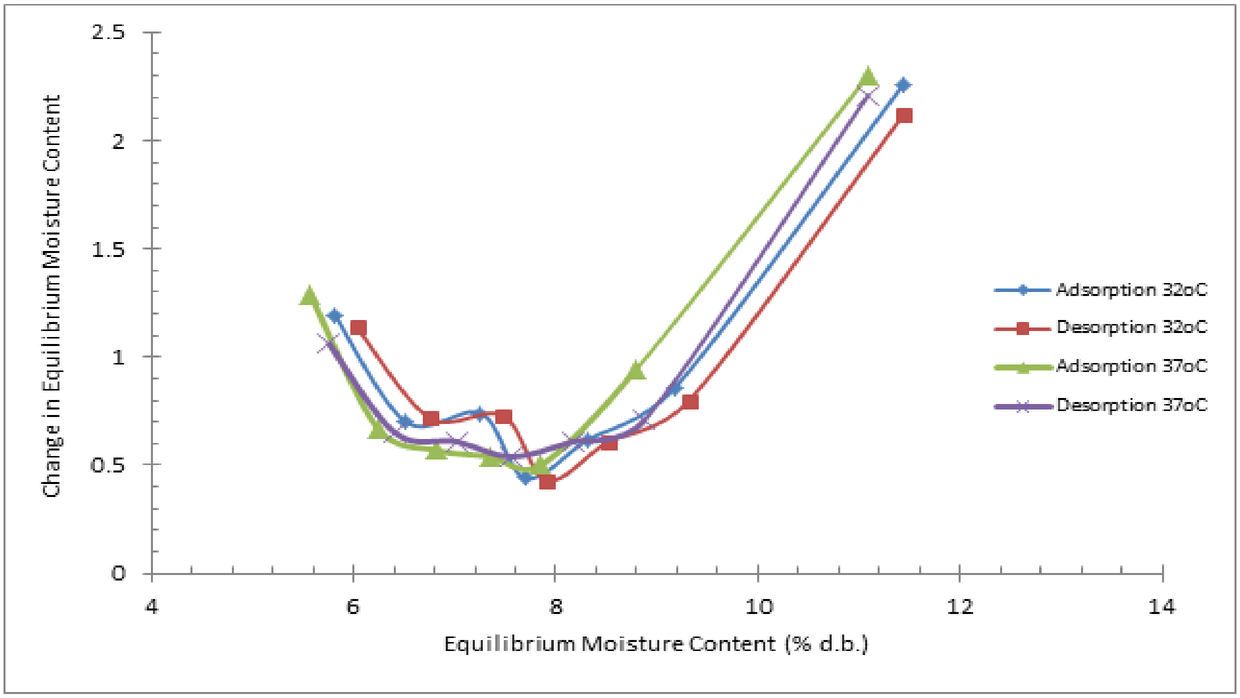

Figure 10: Moisture stability index curve of wheat-yam (75:25) noodles at 32 and 37^{o}C

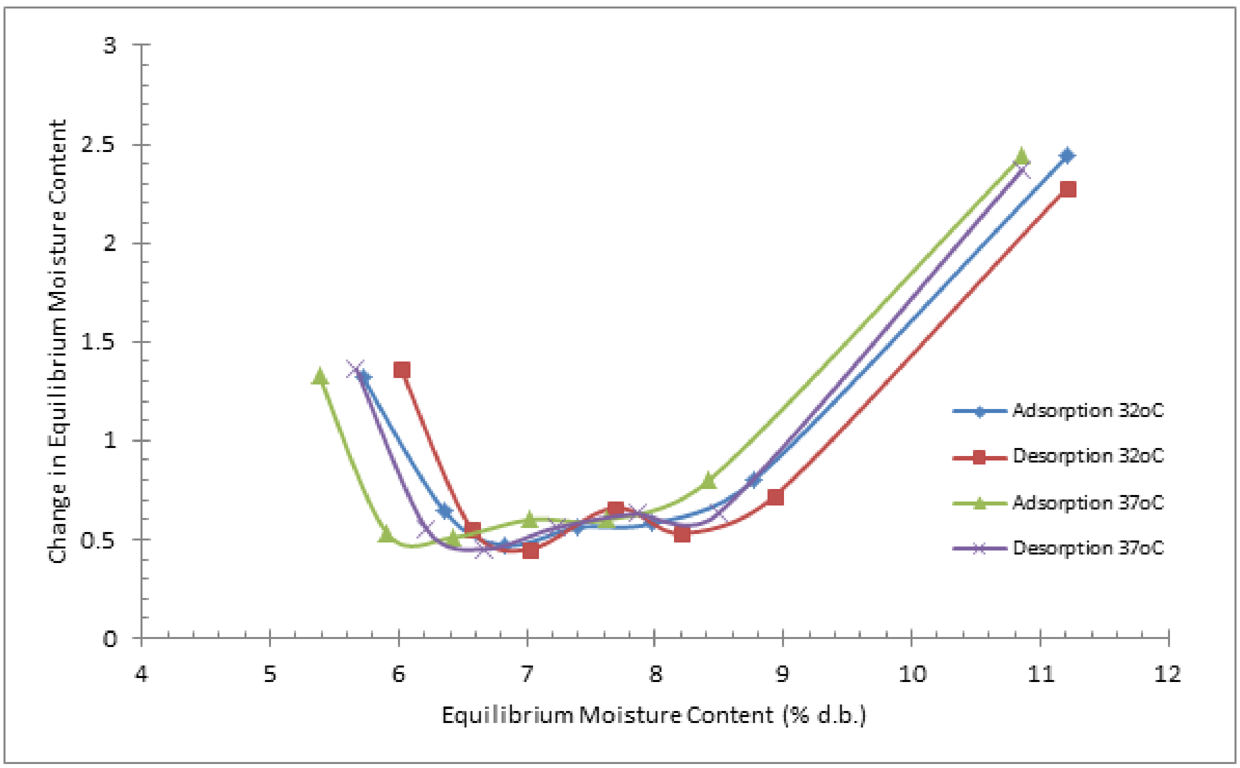

Figure 11: Moisture stability index curve of wheat-yam (50:50) noodles at 32 and 37^{o}C

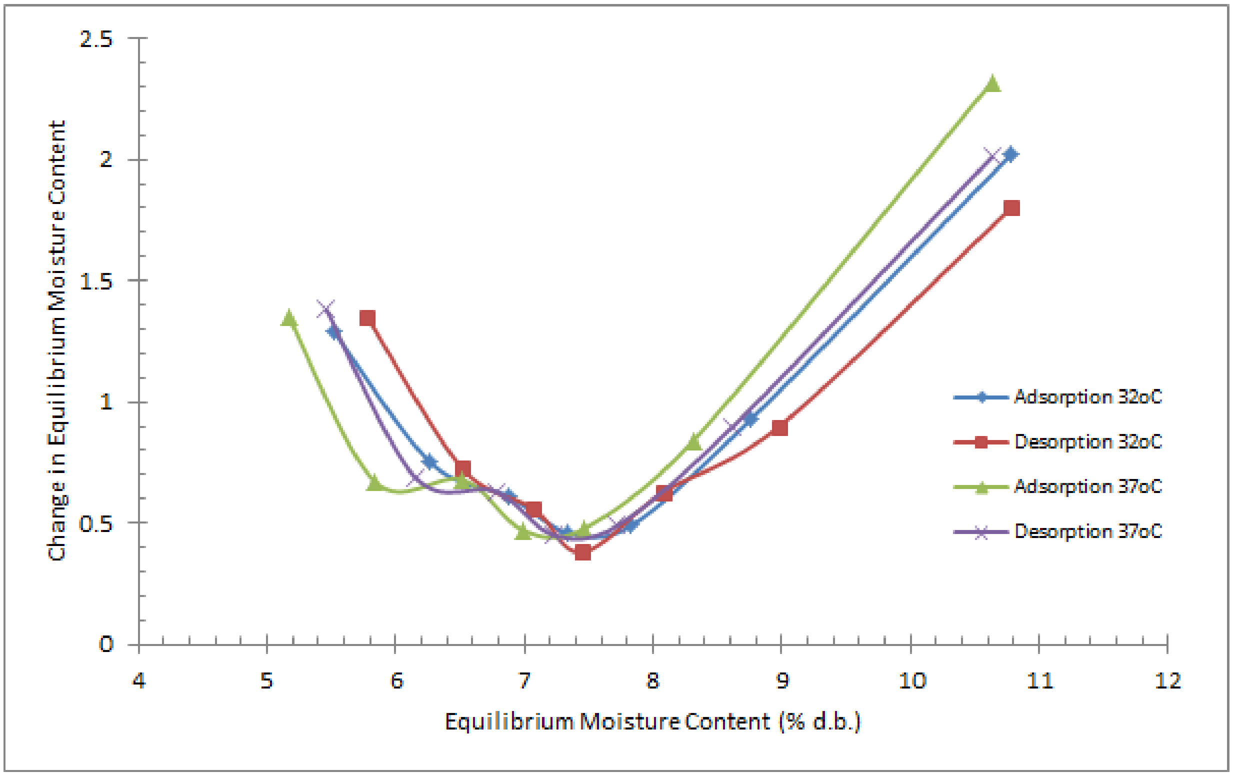

Figure 12: Moisture stability index curve of wheat-yam (25:75) noodles at 32 and 37^{o}C

The wheat-yam noodles isotherm predictive models

The isotherm predictive models of the wheat-yam noodles are shown in Table 3. From the table, it could be deduced that all the models adequately described the experimental adsorption and desorption isotherms of wheat-yam noodles as demonstrated by their high R^2 values (≥ 0.968). There are no differences in the R^2 values (0.968) displayed by the four models for adsorption and desorption at the storage temperatures of 32 and 37^{o}C. This indicated that all the models have the same degree of high prediction reliability with the equations in terms of their coefficient of fit. However, the use of R^2 alone does not mean that the models fitted the experimental data accurately. Therefore, the use of indices to calculate the errors associated with the models are the RSS, MSE, and SEE. Based on this, GAB and MGAB could be said to justifiably describe the experimental adsorption and desorption data of wheat-yam noodles at 32 and 37 ^{o}C.

The residual plots displayed systematic patterns for some of the models. These residual plots served as an index of assessing the closeness of fitted. The R^2 obtained in the plots measures the systematic departure from linearity that exploited the variability in the response variable explained by the predictors (Oyelade et al. 2008; Sobowale et al. 2017). This result is according to the type II isotherm shape previously observed for cereal and tuber products (Arslan and Togrul, 2005; Li et al. 2016; Okeleye et al. 2019). It showed that the widely recommended GAB, MGAB, OE, and MOE models are suitable for predicting the EMC of wheat-yam noodles under practical storage situations in the tropics.

Table 3: The performance of selected models for sorption isotherms

Model	Constants	Adsorption		Desorption	
		32ºC	37ºC	32ºC	37ºC
GAB	a	5.062	4.699	5.367	5.023
	b	83.380	76.866	86.247	79.955
	c	0.667	0.693	0.633	0.653
	R^2	0.968	0.972	0.969	0.966
	RSS	0.9567	0.8556	1.3471	0.9331
	MSE	0.1196	0.1070	0.1684	0.1166
	SEE	0.3458	0.3270	0.4104	0.3415
	Residual plot	Random	Random	Random	Random
MGAB	a	5.062	4.699	5.367	5.023
	b	0.667	0.693	0.633	0.653
	c	2.67E+03	2.84E+03	2.76E+03	2.96E+03
	R^2	0.968	0.972	0.969	0.966
	RSS	0.9567	0.8556	0.8462	0.9331
	MSE	0.1196	0.1070	0.1058	0.1166
	SEE	0.3458	0.3270	0.3252	0.3415
	Residual plot	Random	Random	Random	Random
OE	a	7.559	7.172	7.774	7.387
	b	-	-	-	-
	c	0.244	0.260	0.228	0.239
	R^2	0.968	0.970	0.971	0.967
	RSS	0.9723	0.9203	0.8185	0.9207
	MSE	0.1215	0.1150	0.1023	0.1151
	SEE	0.3486	0.3392	0.3199	0.3393
	Residual plot	Random	Random	Random	Random
MOE	a	3.46E+05	4.66E+04	6.42E+04	1.48E+05
	b	-1.08E+04	-1.26E+03	-2.01E+03	-4.00E+03
	c	0.244	0.260	0.228	0.239
	R^2	0.968	0.970	0.971	0.967
	RSS	0.9723	0.9203	0.8185	0.9207
	MSE	0.1215	0.1150	0.1023	0.1151
	SEE	0.3486	0.3392	0.3199	0.3393
	Residual plot	Random	Random	Random	Random

Where:

GAB = Guggenheim, Anderson and de Boer
MGAB = modified Guggenheim, Anderson and de Boer
OE = Oswin
MOE = modified Oswin
RSS = residual sum of squares
MSE = mean square error
SEE = standard error of estimate between experimental and calculated

Conclusion

The equilibrium moisture content for wheat-yam noodles decreased with increased temperature and showed an increasing pattern with elevated water activity. The sorption isotherms of the wheat-yam noodles followed similar trends of shape and temperature dependence. The moisture sorption curves of the wheat-yam noodles obtained at the two temperatures (32 and 37 °C) showed a sigmoid shape, similar to previous studies in the literature. The sorption isotherm models that were evaluated satisfactorily predicted the adsorption and desorption isotherms of wheat-yam noodles at the evaluated temperatures, with $R^2 \geq 0.968$. Thus, these models are suitable for predicting the EMC of wheat-yam noodles under the practical storage conditions studied.

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