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Study of Moisture Sorption Characteristics of White and Yellow Gari and Its Thermodynamics

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ABSTRACT

Evaluation of moisture sorption characteristics of gari sold in Ebonyi, Enugu, and Abia state were studied. Freshly produced gari samples were collected from primary gari producers that sells at various markets located in the three aforementioned states. The samples code were; Abia white gari sample (ABW), Abia yellow gari sample (ABY), Ebonyi white gari sample (EBW), Ebonyi yellow gari sample (EBY), Enugu white gari sample (ENW), and Enugu yellow gari sample (ENY). The equilibrium moisture content (EMC) was determined using a standard Gravimetric method with tetraoxosulphate (VI) salt and water mixtures providing equilibrium relative humidity (ERH) of 15, 25,35, 45, 55 and 65% respectively to yield a water activity (aw) range of 0.0972 - 0.9811 at 30, 40 and 50 ^{O}C for adsorption and desorption isotherm. Sorption data generated were fitted into the BET and Oswin models. A sigmoidal behaviour (type II) was observed.Equilibrium moisture content increased directly with water activity.There were significant (P<0.05) differences between the sorption behaviour of white and yellow gari samples. The equilibrium moisture content decreased with an increase in temperature at constant water activity. The goodness fit of the models was determined using four statistical parameters: coefficient of determination (r^2), root mean square error (RMSE), percentage mean relative deviation modulus (%p), and chi square (x^2). BET and OSWIN models appeared suitable for the water activity ranges. In this study, EBW and EBY gari samples exhibited good shelf stability.

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INTRODUCTION

Cassava (*Manihot esculanta Crantz*) is a well-known staple root crop for over 80 million people around the world, an annual crop mostly grown in the tropical countries of Africa, Asia and South America (Ajala et al., 2020; Okoronkwo et al., 2024). Cassava, a 21st-century crop, the "food of the poor," has become a multipurpose crop that responds to the priorities of developing countries, to trends in the global economy, and to the challenge of climate change. It plays a food security role in Africa where annual production feeds over 80 million people annually (Ibegbulem and Chikezie, 2018) and its production had to rise by more than 700% in the 21st century in West Africa and Central and East Africa. This root crop is to poor African farmers what wheat and potatoes are to European farmers and rice to Asian farmers (FAO, 2020).

The major product derived from cassava, which is primarily consumed across and beyond west and central Africa is Gari. Gari is a fermented gelatinized creamy white or yellow (due to addition of palm oil during its production) granular flour sourced from cassava tubers (Manihot esculenta Crantz) through various food processing unit operations such as harvesting, peeling, washing, grating and fermentation of the cassava tubers (Okoronkwo et al., 2024). It has a slightly fermented flavour and a slightly sour taste due to fermentation and gelatinization in its processing (FAO, 2020). It contains some essential vitamins and a high level of fibre. Gari consumption cuts across all socio-economic classes. The proliferation of microbes in foods, which is primarily associated with moisture availability, remains the major constraint on the shelf-stability of foods; hence, several preservation techniques are targeted at shelf-stable foods (Igbabul et al., 2013).

The relationship between the total moisture content and water activity of food over a range of values, under equilibrium conditions, yields a moisture sorption isotherm which gives information on the relation between the food and water (Olaoye et al., 2015). Understanding the moisture sorption behavior of dehydrated agricultural products is of great importance in solving food processing and engineering problems, such as the prediction of shelf life, the design and optimization of drying equipment, the determination of moisture changes during storage, ingredient mixing, the prediction of stability, and microbiological safety (Chikezie and Ojiako, 2013; Aguilera, 2020).

The application of moisture sorption knowledge to preserve various dehydrated foods has yielded good results over the years (Prette et al., 2013). Research has revealed that there is a gap in the information on the moisture sorption (adsorption and desorption) characteristics of both white and yellow gari, which is a useful handle for its shelf stability (Onimawo and Akubor, 2012). Therefore, actual determination of the moisture sorption characteristics of white and yellow gari is required in order to find the best-fit model for dehydrated food, which is a good handle for product and process development (Samuel and Ugwuanyi, 2014).

Furthermore, the information is required to predict the fundamental behavior during the handling, processing, and development of packaging material and storage of white and yellow gari. The research reported in this paper was designed to obtain adsorption and desorption equilibrium moisture properties for white and yellow gari at 30, 40, and 50 ^{O}C over a range of water activities of 0.09 – 0.92% and interpret these data using the BET and Oswin models.

MATERIAL AND METHODS

The various white and yellow gari samples were procured from direct gari producers/sellers at Enugu state (Ogige market, Nsukka), Abia state (Orie ndu market, Obim, Isikwuato) and Ebonyi state (Nkwor-agu-isu,Afikpo), all in the Eastern part of Nigeria and were coded as follows; Abia white gari sample (ABW), Abia yellow gari sample (ABY), Ebonyi white gari sample (EBW), Ebonyi yellow gari sample (EBY), Enugu white gari sample (ENW) and Enugu yellow gari sample (ENY), respectively. Airtight plastic containers with a diameter of 12.8 cm, a height of 9cm, and a volumetric space of 1158 cm^3 were also procured from Ogige Market in Nsukka, Enugu State, Nigeria. The saturated salt (H_2SO_4) used is of analytical grade (93%).

Experimental Procedure

The moisture sorption isotherms (adsorption and desorption) of the gari (white and yellow samples from Abia, Ebonyi and Enugu states, in south eastern part of Nigeria) samples were obtained using the gravimetric static method (Labuza, 1984). Each of the gari samples was placed under the required controlled environment (water activity and temperature) at the same time for adsorption and desorption processes, and weight loss or gain was measured simultaneously until constant weight (equilibrium moisture content) was reached. The gari samples for desorption were conditioned to constant weight by sprinkling distilled water on the samples and allowing the samples to stay in the refrigerator for twelve hours, while the samples for adsorption were left in the dried state. The initial moisture content of both samples for adsorption and desorption was determined. An oven was used as a temperature control chamber.

The eqsuilibrium moisture content (EMC) was calculated using a material balance equation from the initial moisture content using the formula;

M/100 (W1) + (W3-W2) = EMC/100 (W1 + (W3-W2)

Where M = initial moisture content of the sample, W1 = Weight of sample used during sorption experiment,

W2 = Initial weight of sample and crown cork,

W3 = Final weight of sample and crown cork at equilibrium,

EMC = Equilibrium moisture content

Results of each determination were unified by calculating the mean equilibrium moisture content values which was used for plotting moisture sorption isotherms graphs of the gari samples. The experimental sorption data (values obtained from for the equilibrium moisture contents, water activities, and temperatures) were fitted into two moisture sorption isotherm (MSI) models which includes, BET (Brauneur–Emmet-Teller) and OSWIN as shown in Table 1.

Table 1. Selected moisture isotherm models applied to the experimental data obtained

Model	**Equation**
BET	$MC = \dfrac{M_0 C a_W}{\left[(1-a_W) + (C-1)(1-a_W)a_W\right]}$
Oswin	$MC = C\left(\dfrac{a_W}{1-a_W}\right)^A$

These models were chosen because of their suitability for high carbohydrate foods, application over a wide range of water activities, simplicity and ease of evaluation. These chosen models also present the advantage of correctly describing sorption isotherms of agro-food products for water activity values between 0.0-0.95. Adequacy of each model used was examined using four statistical parameters; coefficient of determination (R^2), which provides information about the goodness of fit for each model, the Root Mean Square Error (RMSE%) between the experimental and predicted EMCs which determines the accuracy of fit of the models, percentage mean relative deviation modulus (%p) and the reduced Chi square (x^2) which shows the suitability of the models. These parameters were calculated using the standard equations. Graph-pad prism version 8.2.1 (441) was used in plotting of the sorption curves for accuracy and smoothness purposes.

RESULTS AND DISCUSSION

Moisture Isotherm

The moisture isotherm curve of equilibrium moisture content versus water activity of the moisture adsorption and desorption for the various white and yellow gari samples in accordance with range of temperatures analysed are given in Figures 1 and 2, respectively. The equilibrium moisture content of the various gari samples decreased with increasing temperature between 30 and 40 °C at constant water activity due to the vapour pressure of water present in samples decreased with the environment. Meanwhile at 50 °C, EMC was observed to increase with temperature at the adsorption and desorption arm. The sorption isotherms were sigmoid shaped (type II) which is predominant among hygroscopic products and food materials especially those rich in carbohydrates. This is in accordance with the report of Samuel and Ugwuanyi (2014) who studied sorption behaviour of white gari sold in Nsukka, Nigeria at temperatures of 20 and 30 °C. The type II curves of isotherms are slow at water activity less than 0.5 where relatively low moisture was absorbed for a high increase in water activity, while high amount of water was absorbed for a small rise in water activity above 0.5 water activity.

This behaviour is generally ascribed to reduction in the number of active sites due to chemical and physical changes induced by temperature; the extent of decrease, therefore, depends on the nature or constitution of the food. However, the increase in equilibrium moisture content observed at the adsorption and desorption arms of the gari samples at 50 °C is a rare behaviour in sorption studies and could be attributed to the effect of the high temperature on the components of the food product which leads to high exposure of more moisture binding sites of the food product through faster dissolution of the food sample. Although the white and yellow gari samples showed the expected type II sigmoidal behaviours, little difference was observed between the sorption behaviour of the yellow and the white gari sample. This slight variation could be attributed to the difference in the unit operations involved in their production (addition of palm oil) because, at every given temperature, the rate of change of moisture content with water activity of white gari was higher than that of the yellow gari samples slightly. Lipids play a significant role in the moisture sorption behavior of food materials, including gari. The presence of lipids can affect the moisture sorption isotherms (MSI) of gari by altering its surface properties and interactions with water (Aguilera, 2020). Studies have shown that lipids can reduce the moisture sorption capacity of food materials by occupying active sites on the surface, thereby reducing the availability of sites for water binding (Okoronkwo et al., 2024). Therefore, it could be said that the processing methods has an effect on the sorption characteristics of the gari samples, and the lipid content of yellow gari modified the moisture sorption behaviour of the food product.

Hysteresis is a phenomenon observed in moisture sorption isotherms, where the adsorption and desorption curves do not coincide. This phenomenon is attributed to the differences in the energy required for adsorption and desorption processes (Ricardo et al., 2011). In gari, hysteresis can occur due to the complex interactions between its components, including starch, protein, and lipids. It is mostly seen in most hygroscopic products (products that bind water when the vapour pressure is lowered). The hysteresis curve for the adsorption and desorption isotherm of the various white and yellow gari samples at selected temperatures (30, 40 and 50 °C) are shown in Figure 1 and 2. A marked intersection of the isotherms was observed for the various white gari samples at 40 and 50 °C, while the reverse was observed at 30 °C. The yellow gari samples showed a marked intersection at 30, 40 and 50 °C. The expected non-crossing over of the white gari sample at 30 °C could be ascribed to the fact that gari is a highly starchy food with a wide hysteresis values but, there is a very high tendency for 'crossing-over' at higher water activities. Recent studies have investigated the hysteresis phenomenon in gari. A study by Okoronkwo et al., (2024)observed hysteresis in the MSI of gari, with the desorption curve lying above the adsorption curve. The hysteresis loop in gari was affected by its moisture content and temperature. Hence, the hysteresis effect of the gari samples at 30, 40 and 50 °C showed that adsorption curve of both the white and yellow gari sample is greater than desorption curve, which is an interpretation of the equilibrium moisture content of the various gari samples, respectively.

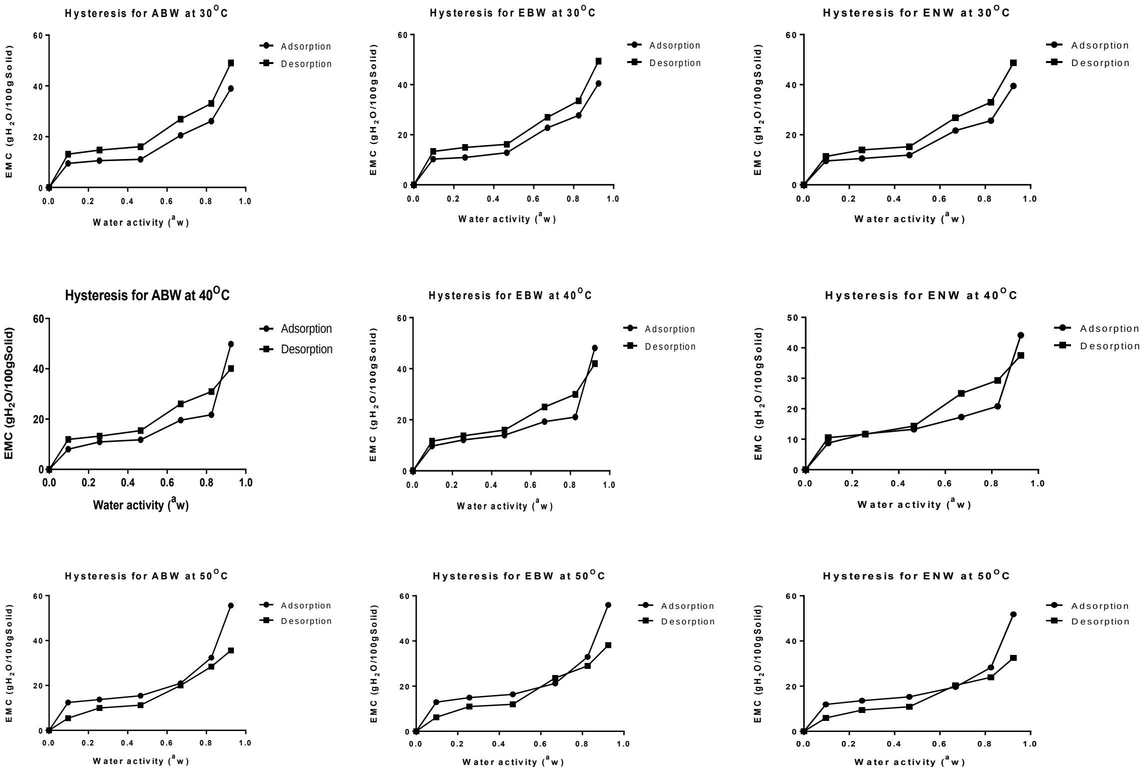

Figure 1. Moisture sorption isotherm of ABW, EBW and ENW gari samples showing HYSTERESIS behavior for adsorption and desorption isotherm of the various white gari samples at different water activities and temperatures selected

EMC= Equilibrium moisture content, ABW= Abia white gari, EBW= Ebonyi white gari and ENW = Enugu white gari. EMC= Equilibrium moisture content, ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY = Enugu yellow gari. Hysteresis behavior for adsorption and desorption isotherms of at 30, 40 and 50°C.

The thermodynamics of moisture sorption in gari is crucial for understanding the energy changes associated with moisture uptake or release. Recent studies have focused on calculating thermodynamic properties like Gibbs free energy, enthalpy, and entropy (labuza et al., 1968). These properties can provide valuable insights into the moisture sorption behavior of gari and its stability. Samuel and Ugwuanyi (2014) calculated the thermodynamic properties of moisture sorption in gari and found that the process was spontaneous and exothermic. The thermodynamic properties of gari were affected by its moisture content and temperature. Thus, the EMC (equilibruim moisture content) of the adsorption curve for the white gari samples is higher than the yellow gari, although at 40 °C, the EMC of the adsorption arm of the white and yellow gari samples are slightly close at water activity of 0.4 and below.

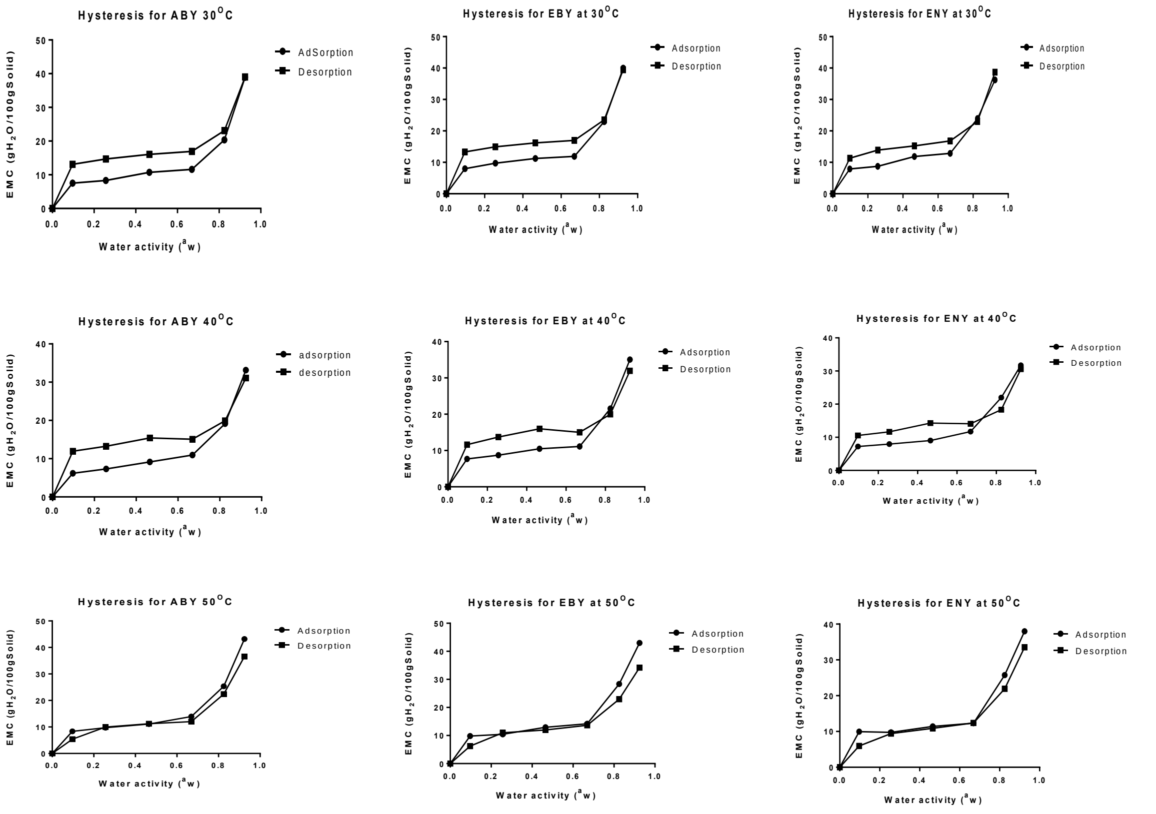

Figure 2. Moisture sorption isotherm of ABY, EBY and ENY gari samples showing HYSTERESIS behavior for adsorption and desorption isotherm of the various yellow gari samples at different water activities and temperatures selected

EMC= Equilibrium moisture content, ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY = Enugu yellow gari. EMC= Equilibrium moisture content, ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY = Enugu yellow gari. Hysteresis behavior for adsorption and desorption isotherms of at 30, 40 and 50°C.

Generally, the desorption EMC of the white gari samples is greater than that of yellow gari samples at the temperatures studied. This behaviour could be attributed to the fact that hysteresis curve of a food product is principally influenced by the components of the food product, structure of the material, temperature and equilibration method applied (Machhour et al., 2012). The lower adsorption curve at low water activity could be attributed to the fact that water may be absorbed only to the surface -OH sites of crystalline proteins, sugar and polysaccharides while at 50, low hysteresis was observed than 40 and 30 °C may be due to increase in the elasticity of the capillary walls and higher capacity to yield hydrogen bonds between the constituent of the food such as water, protein and carbohydrate in the structure of the food material (gari) (Labuza et al., 1985).

BET model Monolayer Moisture Content Values for the Gari Samples

BET monolayer moisture content (Mo) values for the ABW, EBW and ENW; and ABY, EBY and ENY gari samples at temperatures of 30, 40 and 50 °C were within the range of 5.4201 - 9.4787 for the adsorption arm and 4.2141 - 6.9735 g/H2O/100g solid for the desorption arm of ABW, EBW and ENW gari samples while those of ABY, EBY and ENY gari samples ranged from 5.0659 - 7.5586 g/H2O/100g solid (%, dry basis). The BET model values obtained agreed with monolayer moisture content values (within ranged of 4-11 %) reported by Alakali and Satimehin (2009) ; ajala et al., (2020) for foods that are rich in carbohydrate. The results indicate that within the temperature range studied, gari samples are best kept safe for storage at a moisture content of about 4 - 5 % (db).

Table 2. BET parameters and derivatives for the moisture sorption of the various white gari samples at 30, 40 and 50 °C

Temperature (°C)	Regression parameters	Adsorption			Desorption		
		ABW	ENW	EBW	ABW	ENW	EBW
30	Mo	5.71429	6.1614	6.6401	8.3195	7.9745	8.3682
	So	236.6747	218.378	231.7437	221.8238	199.3763	229.9837
	C	-18.4211	-22.8592	-24.2903	-21.5727	-21.1364	-20.3913
	r^2	0.9827	0.9908	0.9946	0.9869	0.9842	0.9863
40	Mo	6.0680	6.8823	7.1685	7.8247	7.2727	8.1699
	So	211.487	207.4845	220.8757	209.3423	193.3467	210.4764
	C	-17.9126	-16.9386	-21.5584	-17.7879	-20.6571	-19.9083
	r^2	0.9762	0.982	0.9879	0.9924	0.9744	0.9906
50	Mo	8.9127	8.8731	9.4787	7.5700	6.7568	7.5358
	So	201.873	183.3762	206.9944	199.8947	150.4468	176.3487
	C	-32.0571	-34.1515	-31.1029	-38.125	-31.92	-32.5909
	r^2	0.9953	0.9945	0.9925	0.9486	0.9744	0.9547

ABW= Abia white gari, EBW= Ebonyi white gari and ENW = Enugu white gari. ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY = Enugu yellow gari. MO = Monolayer moisture content (g/H2O/100g solid), C = BET constant. r^2 = coefficient of determination. SO = surface area of sorption for monolayer (m2/g solid).

It was also observed that monolayer moisture content decreased with increase in temperature from 30 to 40 °C and then increased at 50 °C for both ABY, EBY and ENY and ABW, EBW and ENW gari samples. Such decrease with temperature could be because of the fact that binding of water molecules become less stable at increased temperature, thus break away from water binding sites of the sample (Simal et al., 2007). While the increase in the monolayer (MO) values with temperature could be due to the effect of increase in temperature which led to opening of new binding sites, therefore encourages more water vapour molecules to bind. According to Sawhney et al. (2011) who defined monolayer moisture content of a food material as the moisture content of that food when its entire surface is covered with one molecular layer of water vapour molecules. This implies that the optimum amount of water strongly adsorbed to specific sites per gram of a dry substance is considered the optimum moisture value at which a food is highly stable (Labuza et al.; 1985). At a given temperature, the safest water activity level is the corresponding MO value or lesser MO value. MO values are very important in handling of a food material because below MO of a food, water is strongly bound and the rates of deteriorative reactions are lowered.

Table 3. BET parameters and derivatives for the moisture sorption of the various yellow gari samples at 30, 40 and 50 °C

Temperature (°C)	**Regression parameters**	**Adsorption**			**Desorption**		
		ABW	**ENW**	**EBW**	**ABW**	**ENW**	**EBW**
30	Mo	5.6306	6.2422	5.8893	8.3195	7.9745	8.3682
	So	220.7467	201.9628	180.6688	192.2762	188.7890	202.3278
	C	-25.9737	-22.5057	-20.6484	-25.8623	-21.8920	-22.0389
	r^2	0.9993	1	0.9898	0.9869	0.9842	0.9863
40	Mo	4.7015	4.5537	5.3390	7.8247	7.2727	8.1699
	So	207.3427	198.3873	172.3284	187.3768	164.7962	196.9523
	C	-18.9223	-18.6698	-18.019	-17.8943	-18.8929	-18.8279
	r^2	0.9961	0.9903	0.9943	0.9924	0.9964	0.9906
50	Mo	6.4893	6.5232	7.5586	7.1994	6.7568	7.5358
	So	200.3768	178.6321	198.9638	167.4643	132.4039	126.3145
	C	-24.5781	-23.6615	-52.92	-22.4674	-23.7929	-52.4983
	r^2	0.9945	0.9991	0.9995	0.9486	0.9744	0.9547

ABW= Abia white gari, EBW= Ebonyi white gari and ENW = Enugu white gari. ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY = Enugu yellow gari. MO = Monolayer moisture content (g/H2O/100g solid), C = BET constant. r^2 = coefficient of determination. SO = surface area of sorption for monolayer (m2/g solid).

BET CONSTANT C

BET model is one of the most popular models that have received greatest application to sorption studies on food applications. Thus, this model is referred to as the most useful for determining the optimum moisture condition for good storage stability for most dehydrated food products, such as gari (Yan *et al*., 2008; Samuel and Ugwuanyi, 2014). It is also applied in the determination of surface area of moisture sorption. The BET constant C for adsorption and desorption of the various gari samples did not exhibit a definite pattern across temperature and the dried food sample (gari) as reported by GAB model. The C values observed were negative, which could be attributed to the negative intercept obtained from BET plots. In the context of gari, a negative C value indicates that the food material's sorption behavior is more complex due to its composition, structure, or interactions between components. The BET model coefficient of determination (r^2) for ABW, EBW, and ENW gari samples ranged from 0.9762 - 0.9953 for adsorption and 0.9486 - 0.9964 for desorption, while that of ABY, EBY, and ENY gari samples ranged from 0.9898 - 1 for adsorption and 0.9486-0.9906 for desorption. The r^2 values were actually high, showing that the BET model is also a good fit for the adsorption and desorption of the various gari samples analyzed.

Apparent Sorbate Sorption Area For The Various Gari Samples

The results of the SO values for the white and yellow gari samples are presented in Tables 2 and 3. The SO values for ABW, and ENW gari samples ranged from 183.3762 - 236.6747 m^2/g solid for the adsorption arm and 150.4468 - 229.9837 m^2/g solid for the desorption arm of the sorption isotherm with EBW higher, followed by ABW and ENW, respectively. Also, the SO values for ABY, EBY, and ENY gari samples ranged from 172. 3284 - 220.7467 m^2/g solid and 126.3145 - 202.3278 m^2/g solid for the adsorption and desorption, respectively, with ABY having the highest value, followed by EBY and ENY. The So values derived from this research work are within the acceptable range of 100 - 250 m^2/g solid reported by Labuza (1968) and Tunc and Duman (2007.The SO decreased with increase in temperature from 30 - 40 oC over the range of the white (ABW, EBW and ENW) and yellow (ABY, EBY and ENY) gari samples except for adsorption sorption of EBY which showed decrease as temperature increased from 30 - 40 ^{o}C but increased on increase in temperature to 50 ^{o}C. The decrease in So of the samples with increase in temperature could be attributed to a reduction in the sorption capacity of the gari samples, while the increase in the So with the temperature may be ascribed to the dissolution of the soluble components of the gari sample at high temperature. According to Tunc and

Duman (2007), the apparent surface area of sorption is a very essential parameter in the determination of the water-binding properties of foods.

Oswin Model Parameters For The Various Gari Samples

The Oswin model parameters for ABW, EBW and ENW; and ABY, EBY and ENY gari samples are shown in Tables 4 and 5. Oswin model is one of the most applied sorption model because of its wide application of water activity range between 0 - 0.9 just like GAB and Henderson model.

Table 4. Oswin parameter and derivatives for the moisture sorption of the white Gari Samples at 30, 40 and 50 °C

Temperature (°C)	Regression parameters	Adsorption			Desorption		
		ABW	ENW	EBW	ABW	ENW	EBW
30	A	0.1453	0.1399	0.1395	0.1201	0.1196	0.1342
	C	12.3505	12.1901	13.2196	8.2763	8.4359	8.5883
	r^2	0.9083	0.9233	0.925	0.9269	0.9478	0.9425
40	A	0.1383	0.1374	2.4954	0.0968	0.1088	0.1185
	C	11.5779	11.1284	12.1266	8.5720	8.8490	9.0793
	r^2	0.9098	0.907	0.8836	0.9412	0.9305	0.966
50	A	0.1408	0.1351	0.1359	0.1364	0.1305	0.1240
	C	16.8525	16.2436	17.5140	11.6838	11.6116	12.6038
	r^2	0.9124	0.9013	0.9097	0.9703	0.8599	0.9595

ABW= Abia white gari, EBW= Ebonyi white gari and ENW = Enugu white gari. ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY = Enugu yellow gari. A and C = Oswin' constant. r^2 = coefficient of determination.

Table 5. Oswin' Parameters and Derivatives for Moisture Adsorption and Desorption of Yellow Gari Samples at 30, 40 and 50 °C

Temperature (°C)	Regression parameters	Adsorption			Desorption		
		ABW	ENW	EBW	ABW	ENW	EBW
30	A	0.1516	0.1293	0.1420	0.1134	0.1090	0.1250
	C	10.0775	10.2308	10.8082	8.0531	7.314	7.8060
	r^2	0.8679	0.9078	0.8604	0.8248	0.8847	0.8181
40	A	0.1021	0.1075	0.1120	0.1010	0.1052	0.1091
	C	10.2338	10.1859	10.7564	9.1861	9.1290	10.0245
	r^2	0.9138	0.8856	0.8619	0.8436	0.8538	0.8401
50	A	0.1487	0.1278	0.1542	0.1082	0.1007	0.1034
	C	12.7624	12.5925	13.4436	11.5490	11.2171	12.4294
	r^2	0.909	0.8328	0.8901	0.9295	0.952	0.9435

ABW= Abia white gari, EBW= Ebonyi white gari and ENW = Enugu white gari. ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY = Enugu yellow gari. A and C = Oswin constant. r^2 = coefficient of determination.

This empirical model consists of expansion series for sigmoid shaped curve. The co-efficient of determination (r^2) values derived from the analysis of ABW, EBW and ENW gari sample ranged from 0.8836 - 0.927 for adsorption arm and 0.8599 - 0.9703 for desorption arm, while the ABY, EBY and ENY gari samples has coefficient of determination value ranges from 0.8328 - 0.9138 for adsorption and 0.8181 - 0.998 for desorption arm, respectively. The coefficient of determination (r^2) values observed for the various gari samples in this study showed that Oswin model has better fit via the data derived from the various gari samples as well as BET model, respectively

Table 6. Suitability of the selected sorption models for moisture adsorption of ABW, EBW and ENW gari at 30, 40 and 50 °C

Temperature(°C)	Sample	Statistical parameter	Adsorption	
			Oswin	**BET**
30	ABW	RMSE	1.3243	2.9323
		X^2	0.7214	6.5480
		%P	0.1367	11.9800
		r^2	0.9083	0.9827
	ENW	RMSE	1.2358	1.8560
		X^2	0.5380	2.4619
		%P	0.1033	6.4549
		r^2	0.9233	0.9908
	EBW	RMSE	1.2493	1.5206
		X^2	0.4726	1.6750
		%P	0.8557	5.3264
		r^2	0.925	0.9946
40	ABW	RMSE	0.9372	2.2854
	S	X^2	0.2576	3.8385
		%P	0.0671	9.1396
		r^2	0.9098	0.9762
	ENW	RMSE	1.5270	2.63014
		X^2	0.7622	5.1494
		%P	0.1792	11.2461
		r^2	0.907	0.982
	EBW	RMSE	1.4082	1.3073
		X^2	0.7734	1.2236
		%P	0.1540	4.6412
		r^2	0.8836	0.9879
50	ABW	RMSE	0.9380	1.4468
		X^2	0.4236	1.4340
		%P	0.4628	2.38846
		r^2	0.9124	0.9953
	ENW	RMSE	0.4556	1.5250
		X^2	0.0845	1.5778
		%P	0.65	2.8678
		r^2	0.9013	0.9945
	EBW	RMSE	0.6286	2.0004
		X^2	0.1181	2.7285
		%P	0.1756	3.8075
		r^2	0.9097	0.9925

ABW= Abia white gari, EBW= Ebonyi white gari and ENW = Enugu white gari. r^2 = Coefficient of determination. RMSE= Root mean square error. x^2 = Reduced chi square. %P = percentage mean relative deviation modulus.

Table 7. Suitability of the selected sorption models for moisture desorption of ABW, EBW and ENW gari at 30, 40 and 50 °C

Temperature(°C)	**Sample**	**Statistical parameter**	**Adsorption**	
			Oswin	**BET**
30	ABW	RMSE	0.4487	2.0330
		X2	0.7285	2.9056
		%P	0.4669	11.2933
		r2	0.9269	0.9869
	ENW	RMSE	0.6387	2.1150
		X^2	0.1323	3.1584
		%P	0.0588	11.38
		r^2	0.9478	0.9842
	EBW	RMSE	0.7034	2.2347
		X^2	0.1724	3.5769
		%P	0.0738	12.5935
		r^2	0.9425	0.9863
40	ABW	RMSE	0.2398	2.0235
	S	X^2	0.1723	2.987
		%P	0.806	10.5565
		r^2	0.9412	0.9924
	ENW	RMSE	0.7458	2.2649
		X^2	0.2083	3.4667
		%P	0.1130	10.8336
		r^2	0.9305	0.9964
	EBW	RMSE	0.5850	2.3899
		X^2	0.1764	3.8926
		%P	0.0863	11.5806
		r^2	0.966	0.9906
50	ABW	RMSE	0.6358	1.2263
		X^2	0.1055	1.0066
		%P	0.3123	3.1935
		r^2	0.9703	0.9486
	ENW	RMSE	0.3390	0.7627
		X^2	0.0408	0.4024
		%P	0.1193	2.1201
		r^2	0.8599	0.9744
	EBW	RMSE	0.6362	1.5774
		X^2	0.1473	1.6808
		%P	0.3495	4.06552
		r^2	0.9595	0.9547

ABW= Abia white gari, EBW= Ebonyi white gari and ENW = Enugu white gari. r^2 = Coefficient of determination. RMSE= Root mean square error. x^2 = Reduced chi square. %P = percentage mean relative deviation modulus.

Suitability of the selected moisture sorption models on experimental data of ABW, EBW and ENW; ABY, EBY and ENY gari samples

The statistical parameters for the adsorption and desorption of the sorption models tested for ABW, EBW and ENW gari samples are shown in Tables 6, 7, 8, and 9, respectively.

Table 8. Suitability of the selected sorption models for moisture adsorption of ABY, EBY and ENY gari samples at 30, 40 and 50 °C

Temperature(°C)	Sample	Statistical parameter	Adsorption	
30	ABW	RMSE	0.8804	1.1606
		X2	0.2506	0.9487
		%P	0.7283	5.18253
		r2	0.8679	0.9993
	ENW	RMSE	0.6072	1.6022
		X^2	0.1103	1.8558
		%P	0.2990	7.0459
		r^2	0.9078	1
	EBW	RMSE	1.2042	2.5616
		X^2	0.4762	4.7292
		%P	0.1181	11.4825
		r^2	0.8604	0.9898
40	ABW	RMSE	0.8402	2.1085
	S	X^2	0.1098	3.19260
		%P	0.58	9.0311
		r^2	0.9138	0.9961
	ENW	RMSE	0.4003	1.9982
		X^2	0.0656	2.8918
		%P	0.1247	8.5637
		r^2	0.8856	0.9903
	EBW	RMSE	0.8700	2.3150
		X^2	0.2785	3.9200
		%P	0.598	9.67005
		r^2	0.8619	0.9943
50	ABW	RMSE	1.0346	1.8532
		X^2	0.3556	2.3977
		%P	0.7617	4.7984
		r^2	0.909	0.9945
	ENW	RMSE	1.54494	1.6327
		X^2	0.8273	1.9168
		%P	0.1428	4.7280
		r^2	0.8328	0.9991
	EBW	RMSE	0.6965	0.3238
		X^2	0.1319	0.7000
		%P	0.3303	0.5702
		r^2	0.8901	0.9995

ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY= Enugu yellow gari. r^2 = Coefficient of determination. RMSE= Root mean square error. x^2 = Reduced chi square. %P = percentage mean relative deviation modulus.

The goodness-fit of a moisture sorption model for ABW, EBW, and ENW gari samples was derived based on the model with the highest r^2 value, least RMSE, X^2, and %P value. Tables 6, 7, 8, and 9 revealed that Oswin model has good description for the data obtained from the experiment on the moisture adsorption and desorption of ABW, EBW and ENW gari samples within the water activity range analyzed. BET model fits best to the adsorption and desorption data of the white gari sample within the water activity range of 0 - 0.5 as expected.

Table 9. Suitability of the selected sorption models for moisture desorption of ABY, EBY and ENY gari at 30, 40 and 50 °C

Temperature(°C)	**Sample**	**Statistical parameter**	**Adsorption**	
30	ABW	RMSE	0.7436	1.3901
		X2	0.2154	0.9926
		%P	0.0238	5.3829
		r2	0.8248	0.9869
	ENW	RMSE	0.6041	1.6712
		X^2	0.1138	1.8358
		%P	0.0293	7.0522
		r^2	0.8847	0.9842
	EBW	RMSE	1.2032	2.6154
		X^2	0.6614	4.7292
		%P	0.1137	11.4291
		r^2	0.8181	0.9863
40	ABW S	RMSE	0.96270	2.0950
		X^2	1.9803	3.32597
		%P	0.5782	9.1359
		r^2	0.8436	0.9924
	ENW	RMSE	1.0063	1.9982
		X^2	0.6173	2.9542
		%P	0.9047	8.5637
		r^2	0.8538	0.9744
	EBW	RMSE	0.8332	2.3141
		X^2	0.7943	2.9118
		%P	0.998	9.6701
		r^2	0.8401	0.9906
50	ABW	RMSE	1.4635	1.9343
		X^2	0.4763	2.2397
		%P	0.1762	4.9357
		r^2	0.9295	0.9486
	ENW	RMSE	1.4862	1.7163
		X^2	0.8525	1.8036
		%P	0.5812	4.8352
		r^2	0.952	0.9744
	EBW	RMSE	0.7361	0.4733
		X^2	0.3152	0.7241
		%P	0.8503	0.5702
		r^2	0.9435	0.9547

ABY= Abia yellow gari, EBY= Ebonyi yellow gari and ENY= Enugu yellow gari. r^2 = Coefficient of determination. RMSE= Root mean square error. x^2 = Reduced chi square. %P = percentage mean relative deviation modulus.

The primary principles applied in choosing the adequate model fit for determining the sorption isotherm behaviour of ABW, EBW and ENW; and ABY, EBY and ENY gari samples is the statistical principle of coefficient of determination (r^2), followed by reduced chi square (x^2), average percentage difference (% P) and root mean square error (RMSE).

CONCLUSION

The moisture sorption isotherms data of the gari samples (ABW, EBW and ENW; and ABY, EBY and ENY) were analyzed properly using two models (BET and OSWIN). BET gave good fit for water activity range of 0 – 0.45 of the gari samples. The monolayer water content values are not a particular function of temperature but were dependent on the particular model used for its estimation. Of all the gari samples, EBW and EBY gari has high moisture adsorbing capacity and long safe storage period, followed by other gari samples. This could be attributed to prolonged heat treatment process (toasting) that results to a hard, crisp and hygroscopic gari.

Lipids play a significant role in the moisture sorption characteristics of gari, and hysteresis is a phenomenon that can occur due to the complex interactions between its components. Understanding the thermodynamics of moisture sorption in gari is crucial for predicting its behavior and stability. Further research is needed to investigate the effects of lipids and hysteresis on the moisture sorption characteristics of gari and its thermodynamics.

Generally, the two models had high regression coefficients; hence could be said to be good for determination of moisture sorption characteristics (adsorption and desorption isotherm) of ABW, EBW and ENW; ABY, EBY and ENY gari samples. Based on the highest regression coefficient (R^2), the root mean square error (RMSE) and the reduced chi square (X^2) values, Oswin model is suitable for the sorption studies of gari or dried foods.

For a quality shelf-stable gari to be produced; a very low moisture content (4 – 5 %), low water activity (low relative humidity, below 0.5 aw created within the packaging material), temperature range of 27–30 ^{o}C, good agricultural practices and good manufacturing practices (hygienic handling) from the farm to the point of consumption, and a moisture - proof packaging material (air - tight high density polyethylene and plastic containers) should be implored.

Conflict of interest statement:

The authors declared no conflict of interest of any sort on the research work.

Author's contribution

TON executed the research study, discussed the results and compiled the work and AC read the manuscript and IN supervised the experimental research thoroughly.

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