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Determination of Moisture Sorption Isotherm of *Ighu* from Different Cassava Varieties and Accelerated Shelf Life Storage in Different Packaging Materials

[1]Adindu Linus-Chibuezeh, [1]Chidiamara Onyinyechi Adindu-Linus, [2]Kelechi Ikwuakolam Chibuezeh-Linus, [1]Amarachcukwu Margaret Chimenta, [1]Glory Chiamaka Anwuacha, [1]Maduebibisi Ofo Iwe, [1]Titus Ugochukwu Nwabueze

[1]Department of Food Science and Technology, Michael Okpara University of Agriculture, Umudike (440101), Nigeria
[2]Department of Chemistry, Imo State University, Owerri, Imo State, Nigeria

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Corresponding author:
Adindu Linus-Chibuezeh
Department of Food Science and Technology, Michael Okpara University of Agriculture, Umudike (440101), Nigeria

ABSTRACT

Objective: This study was designed to investigate how different indigenous processing methods of Isuochi and Udi, along with relative humidity and packaging type, affected the moisture sorption behavior and shelf life of *Ighu* made from improved cassava varieties from TME 419 and TMS 070072.

Materials and Methods: Shelf life of *Ighu* was also studied in Low Densities Polyethylene (LDPE), High Densities Polyethylene (HDPE) and laminated nylon packaging materials using the accelerated shelf life prediction method. The influence of storage temperature and relative humidity on the product's Equilibrium Moisture Content (EMC) was evaluated using the static gravimetric method at water activity levels of 0.08 to 0.01. Equilibrium moisture content was determined by static gravimetric method at water activity levels of 0.08 to 0.1 in an airtight container. The experimental data were fitted to four common isotherm models of Brunauer-Emmet-Teller (BET), Guggenheim-Anderson-de Boer (GAB), Oswin, and Halsey. Additionally, water vapor transmission rate and permeability coefficients for each packaging type were measured at 30°C and varying relative humidity levels of 20.16 to 90.70.

Results: Results showed a direct relationship between EMC and increasing water activity, with sorption curves exhibiting typical sigmoid (Type II) shapes. BET provided the best fit among the models. Laminated nylon demonstrated the lowest WVTR values of 0.048 to 2.250 g H_2O/day/m^2 compared to 1.201 to 4.011 g H_2O/day/m^2 (LDPE) and 0.240 to 2.391 g H_2O/day/m^2 (HDPE) for other materials. Results of moisture sorption isotherm study also showed that EMCs of *Ighu* directly increased with water activity (a_w) at specific temperatures for both methods. The results also revealed that *Ighu* exhibited an isotherm with a sigmoid (type II) shape, while BET model showed more goodness of fit than other models to clarify adsorption isotherm behaviour of *Ighu*.

Conclusion: Processing methods and varietal differences had significant effect on equilibrium moisture content of the products studied and storing *Ighu* in

INTRODUCTION

Moisture sorption isotherms, which represent the equilibrium relationship between water activity and moisture content at constant temperature, are crucial tools in food preservation, packaging design, and quality assessment. Temperature, moisture, and surrounding relative humidity are known to impact the stability and quality of food products due to their influence on water activity (a_w)[1,2]. These isotherms vary with food type, processing technique, and temperature[2], and can be described by a variety of mathematical models-some mechanistic, others empirical or semi-empirical[3-5].

Since no universal model captures the sorption behavior of all food products, selecting an appropriate model depends on the specific characteristics of the food matrix[6]. For hygroscopic foods, moisture sorption data also reveal critical structural parameters such as surface area, porosity, and crystallinity[7], which are important for understanding deterioration mechanisms and optimizing storage conditions[8-11].

Ighu is one of the various edible products made from cassava tubers[12]. *Ighu* is processed by boiling unpeeled cassava tubers for about 30-40 min depending on the quantity and rate of heat supply, cooling, peeling and shredding with a metallic shredder (*nko*) having many openings on it[13]. The thinly sliced shreds are sometimes spread in a rectangular shaped wooden basket for several hours to further reduce the cyanogenic glycoside in the tuber by washing and drying in the wooden baskets on elevated platform referred to as "*nlugbu*". This study aimed to explore how these indigenous methods, along with relative humidity and packaging type, affect the moisture sorption behavior and shelf life of *Ighu* made from improved cassava varieties.

MATERIALS AND METHODS

Material: Ighu was processed from two improved cassava varieties of TME 419 and TMS 070072 (Plate 1) planted and monitored for a period of eight months in a demonstration farm at the National Root Crop Research Institute, Umudike Abia State Nigeria. The production of *Ighu* (Plate 2) followed the methods of Nwagbara and Iwe[12] described by Linus-Chibuezeh *et al.*[14] is shown in Figure 1. Analytical grades reagents for moisture sorption determination and shelf life prediction were obtained from the Food analysis laboratory of Department of Food Science and Technology, Michael Okpara University of Agriculture, Umudike, Abia State.

Methods

Experimental design for moisture sorption isotherm studies: A General Factorial Design (GFD) was employed in this work, where each factor can have a different number of levels. The factors considered were two varieties of cassava (2 levels), shredder diameter (2 levels), and three sorption temperatures (3-levels). The total of twelve experimental runs tested at eight different water activity levels were generated, while the analysis was conducted in duplicates. Experimental variables for processing of *Ighu* and actual variables of experimental data are presented in Table 1 and 2.

Plate 1: Some improved cassava varieties

Plate 2: *Ighu* samples

Table 1: Process variable of experimental design

Independent variables	K=3	Variable levels		
		i	ii	iii
Cassava variety	X_1	A	B	
Shred diameter	X_2	Isu-3 mm	Udi-5 mm	-
Sorption temperature	X_3	20	30	40

A and B represents cassava varieties TME 419 and TMS 070072

Table 2: Actual variables of experimental design

Cassava variety	Processing method Shred diameter	Sorption temperature
TMS 070072	Isu-3 mm	40°C
TMS 070072	Udi-5 mm	30°C
TME 419	Udi-5 mm	40°C
TMS 070072	Isu-3 mm	30°C
TME 419	Isu-3 mm	20°C
TMS 070072	Isu-3 mm	20°C
TMS 070072	Udi-5 mm	20°C
TME 419	Udi-5 mm	20°C
TME 419	Isu-3 mm	40°C
TME 419	Udi-5 mm	30°C
TME 419	Isu-3 mm	30°C
TMS 070072	Udi-5 mm	40°C

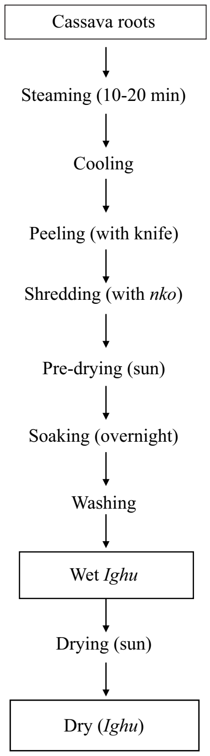

Fig. 1: Processing of *Ighu* from cassava roots

Moisture sorption isotherm experiment: Moisture interaction with the samples was assessed under controlled humidity using a static gravimetric technique. To simulate various humidity conditions, sulfuric acid solutions (15-65%) corresponding to water activities ranging from 0.10 to 0.90 were used. Experiments were conducted at three distinct temperatures 20°C, 30°C, and 40°C, while the *Ighu* samples (0.5 g each) were placed in tightly covered containers above the solutions and in a thermostatically controlled incubator. Sample weights were monitored every 12 hrs until readings stabilized (less than 0.5% difference). The final moisture content of samples was calculated on a dry-weight basis (Equation 1) after oven-drying at 105°C for 4 hrs and cooling in a desiccator. The total time for removal and putting back in the airtight containers was about 1-2 min to reduced atmospheric adsorption occurring as recommended by the co- operative project cost 90 as reported by Ojike et al.[15].

$$EMC = \frac{MW_1 + 100(W_3 - W_2)}{W_1 + (W_3 - W_2)} \quad (1)$$

EMC = Equilibrium moisture content
M = Initial moisture content of the sample
W_1 = Weight of sample used during sorption
W_2 = Initial weight of sample plus crown cork
W_3 = Final weight of sample plus crown cork at equilibrium

Modelling of sorption data: Experimental EMC and a_w values were fitted to four established isotherm models of BET, GAB, Halsey and Oswin. These models were selected due to their proven application to carbohydrate-rich food matrices. The GAB as well as Oswin and Halsey models have been used to describe sorption isotherms of agro-foods within the water activity range of 0.00-0.95 as noted by Iguedjtal et al.[16], while BET has been used for water activities levels below 0.5 (a_w<0.5). Model parameters were derived using nonlinear regression analysis[17]. Goodness of fit between the experimental and predicted EMCs was assessed using coefficient of determination (R^2) and Root Mean Square Error (RMSE) using equations 2-5:

BET: $$\frac{M}{M_O} = \frac{Ca_W}{(1-a_W)[1+(C-1)a_W]} \quad (2)$$

Or : $$\frac{a_W}{1-a_w} = \frac{1}{M_oC} + \frac{C-1}{M_oC}a_w \quad (2b)$$

GAB: $$\frac{CKa_w}{(1-Ka_w)(1-Ka_w+CKa_w)} \quad (3)$$

HALSEY: $$M = \left[\frac{\exp AT + B}{-In(a_w)}\right]^C \quad (4)$$

OSWIN: $$M = A\left[\frac{a_w}{1-a_w}\right]^B \quad (5)$$

Source: Basu et al.[18]
Where:
a_w : Water activity
M_o : Monolayer moisture content
A, B, C : Model constants

Determination of apparent surface area of solvent: Monolayer moisture content (Mo) from BET equation was used to estimate the adsorption surface area (So) using equation 6 as reported by Linus-Chibuezeh et al.[14]. The derived surface area offers insight into the food's moisture-binding potential.

$$S_o = \frac{A_oXN_oXM_o}{M_s} = 3530M_o \quad (6)$$

Constants include: Avogadro's number ($N_o = 6.023\times10^{23}$ molecules/mole)
M_s : Molar mass of water (18 g/mol)
A : Apparent surface area of one water molecule ($1.05\times10^{-19}m^2$)
M_o : Monolayer moisture content (g H_2O/100g solid)
S_o : The apparent area of sorption.

Plate 4: Accelerated shelf life testing set-up according to ASTM[19]

Assessment of water vapour permeability coefficient of the packaging material: This was determined for packaging materials used in this study including LDPE, HDPE and laminated polyethylene/nylon at various storage conditions using the protocol of ASTM[19]. Salts of known saturation were used to maintain different ranges of relative humidity of 20.16 to 90.70. About 5 samples of the packaging materials were prepared with the addition of 10 g of desiccant or silica gels into three of the five samples, the other two packages without silica gel was used as controls (Plate 4) and were sealed using a band-sealer. The thickness and surface area of the materials were measured using a micro-metre screw gauge and meter rule, respectively. The experiment was carried out in a controlled system which maintained temperature of 30°C and varying range of relative humidity 20.16 to 90.70%. At day two intervals, the materials were reweighed until a constant weight was achieved. The weight gains by the packaging materials during the experiment were subtracted from the weight gain of the control samples, and were plotted in a graph. The slope (weight gain vs time in days) of the graph was used to determine the Water Vapor Transmission Rate (WVTR) and permeability coefficient (P) of the packaging material.

The following equations were used to calculate the WVTR:

$$WVTR = \frac{W}{tA} \quad (7)$$

$$P = \frac{W}{tA}\frac{X}{\Delta P} \text{ or } P = \frac{WVTR}{\Delta P} \quad (8)$$

Source: ASTM[19]

Where:

Q/t : Slope
A : Total surface area of both sodes of package
X : Thickness
Δp : Partial pressure change
Po : Saturated vapor pressure of pure water (30°C)
RH : Storage relative humidity

Accelerated Shelf life prediction of *Ighu*: The prediction and simulation of the shelf life of packaged *Ighu* will follow the method stated by Kulchan et al.[20] given in equation 9:

$$t = \frac{GL}{AP\Delta P} \quad (9)$$

Where:

G : d (M_C - M_0)
d : Mass of dry product (g)
M_C : Critical moisture content (%)
M_O : Initial moisture content (%)

Therefore:

$$t\ (days) = \frac{d(M_o - M_C)}{AP\Delta P}L \quad (10)$$

Where:

t : Shelf life (days)
d : Weight of dry product (g)
M_C : Critical moisture content (%)
M_O : Initial moisture content (%)
L : Thickness of the packaging materials (mm)
A : Area (m^2)
P : Permeability coefficient ($gmmd^{-1}m^{-2}mmHg^{-1}$)
ΔP : Vapour pressure difference (mmHg)

RESULTS AND DISCUSSION

Effect of processing methods of *Ighu* on water activity and equilibrium moisture content (EMC) at different temperatures: Two indigenous methods of processing *Ighu* at various temperatures were used to study the effect of water activity on Equilibrium Moisture Content (EMC) (Fig. 2-5).

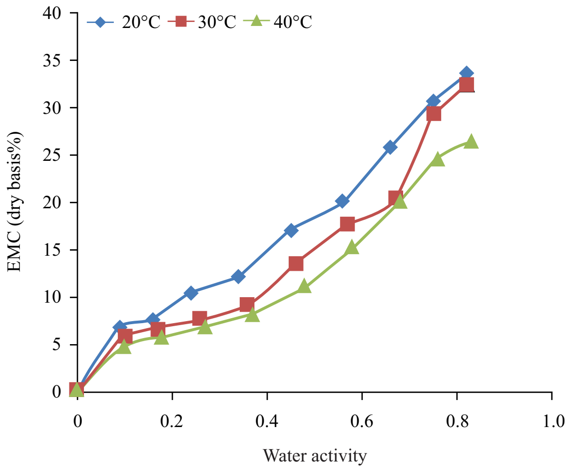

Fig. 2: Effect of water activity on EMC of *ighu* from TME419 (Isuochi method)

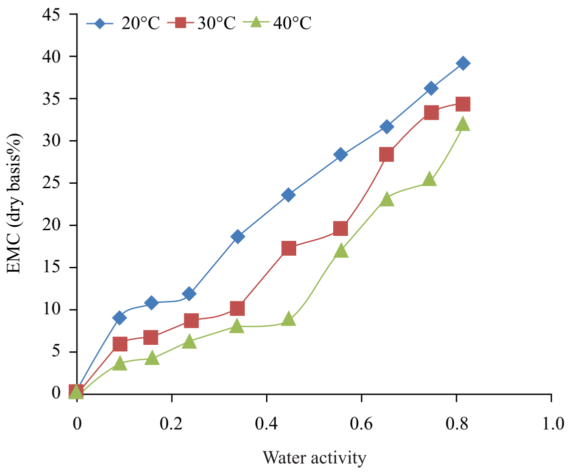

Fig. 3: Effect of water activity on EMC of *ighu* from TME419 (Udi method)

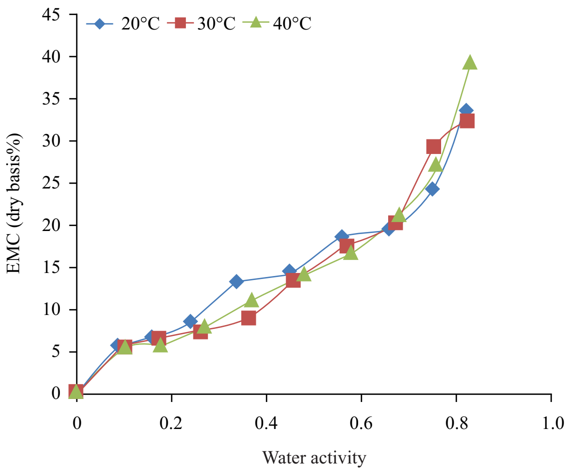

Fig. 4: Effect of water activity on EMC of *ighu* from TMS 070072 (Isuochi method)

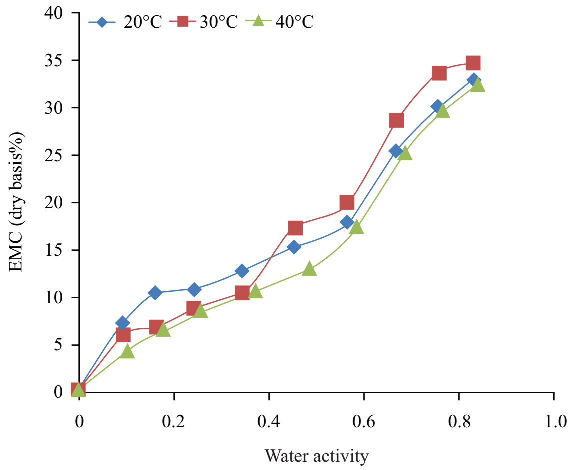

Fig. 5: Effect of water activity on EMC of *ighu* from TMS 070072 (Udi method)

The results clearly showed that in the *Ighu* samples, the adsorption isotherm behavior was clearly affected by changes in the level of water activity and storage temperature. An increasing EMC was observed with increasing water activity levels for the samples irrespective of the processing method adopted. Using the Udi method, higher equilibrium moisture contents were recorded for *Ighu* samples, this being due to the larger shred diameter (average of 5 mm) of both *Ighu* strands and the shredding aperture of the metallic device (*nko*) used. The larger strands of *Ighu* samples absorbed more moisture at the temperatures observed for storage (20, 30 and 40°C). It could also be observed (as shown in Fig 3 and 5) that at water activity level above 0.5, there was increase in water adsorption for every small rise in a_W. This could be attributed to low water activities as physical sorption occurs on strongly active binding sites of substrate, present on the surface film. In the intermediate range of water activity (a_w), adsorption of moisture occurred at less active sites, which is an indication that the region could be a zone more susceptible to spoilage. This result is supported by Ariahu et al.[7] for behavior of different hygroscopic foods. The displayed moisture adsorption isotherm curves (Fig 2 and 3) are typically a sigmoid shape and Type II isotherms[15,20]. This type of isotherm curve (Type II) usually leads to the formation of multiple layers of adsorbate molecules at the internal surface of food solid, a character specific to most organic tissues and especially in hygroscopic food products[21]. However, Shivhare et al.[22] reported a different kind of moisture adsorption for *Awara* which was attributed to high protein content of the product.

Furthermore, Figure 2 (*Ighu* processed using Isuochi method) shows an overlapping isotherm at temperature of 20°C and 30°C while a clear line was observed at higher temperature (40°C). As a result of an increase in water

Table 3: Moisture adsorption parameters for *Ighu* processed from TME419 and TMS 070072

Models/temp	*Ighu* from Isuochi method 20 °C	30 °C	40 °C	*Ighu* from Udi method 20 °C	30 °C	40 °c
			Ighu from TME 419			
BET Model						
M_o (g H_20/100 g solid)	9.9900	7.2800	5.9500	14.3400	9.6600	5.6000
S_o (m^2/g solid)	351.0900	255.8500	209.1100	503.9700	339.4900	198.9200
C	11.7500	15.1300	19.5000	9.3300	8.4700	14.4300
R^2	0.9773	0.9431	0.9903	0.9295	0.8727	0.9718
RMSE	0.6440	0.6770	0.7000	0.6420	0.6460	0.6530
GAB Model						
M_o (g H_20/100 g solid)	11.8600	7.6000	6.7700	19.8500	10.9100	6.0800
K	0.9658	0.8707	0.9029	0.7151	0.8907	0.8692
C	9.7500	10.9700	12.8700	8.2730	7.7430	7.1800
R^2	0.8864	0.8230	0.8262	0.7858	0.6046	0.6685
RMSE	1.5490	1.5700	1.6000	1.5480	1.5490	1.5510
Oswin Model						
A	2.8820	2.6970	2.5330	3.2890	3.0160	2.7380
B	0.4580	0.5030	0.4990	0.3720	0.4940	0.5830
R^2	0.9899	0.9694	0.9746	0.9376	0.9514	0.9608
RMSE	6.9000	6.7000	6.8400	7.4700	7.2500	6.9900
Halsey Model						
A	2.5580	2.3450	2.1860	2.8440	2.4590	2.0720
B	-0.6890	-0.7570	-0.7410	-0.6270	-0.8000	-0.9230
R^2	0.9881	0.9844	0.9826	0.9378	0.9650	0.9719
RMSE	8.8200	8.3700	8.0100	9.5600	8.7500	7.9900
			Ighu from TMS 070072			
BET Model						
M_o (g H_20/100 g solid)	9.1400	7.2800	8.6400	8.6000	10.1200	7.6000
S_o (m^2/g solid)	321.2200	255.8500	303.6500	302.3400	355.6600	269.1000
C	11.0500	15.1300	9.6400	63.9300	14.6700	10.9800
R^2	0.9456	0.9431	0.9609	0.9953	0.9962	0.9940
RMSE	0.6450	0.6770	0.7220	0.6440	0.6730	0.7030
GAB Model						
M_o (g H_20/100 g solid)	10.5700	7.6000	8.0700	9.8300	10.7100	9.1000
K	0.9658	0.9569	0.9497	0.8600	0.9280	0.8692
C	8.4300	10.9700	10.8200	30.7200	7.7400	9.0000
R^2	0.8093	0.8230	0.8743	0.9454	0.6046	0.8529
RMSE	1.5490	1.5700	1.5990	1.5450	1.5490	1.5990
Oswin Model						
A	2.7610	2.6970	2.7090	3.0180	3.0160	2.8930
B	0.4590	0.5030	0.5260	0.3980	0.4940	0.4800
R^2	0.9038	0.9694	0.9786	0.9563	0.9514	0.9694
RMSE	6.6400	6.7000	6.8100	6.2900	6.4300	6.3200
Halsey Model						
A	2.4370	2.3450	2.3420	2.5980	2.4590	2.3110
B	-0.6870	-0.7570	-0.7930	-0.5970	-0.8000	-0.8040
R^2	0.9655	0.9844	0.9902	0.9813	0.9650	0.9887
RMSE	8.4800	8.3700	8.5100	8.8200	8.7500	8.4500

vapor pressure present in food compared to the surrounding air, the EMC of cassava shreds increases with increasing a_W at selected temperatures, regardless of processing method. This result corresponds with the findings of Shivhare et al.[22] who studied the adsorption using mushroom, Ojike et al.[15] for *Gongronema latifolium* leaf grits and Shivhare et al.[22] for *awara* (tofu-like product from soybean). It has been reported that this trend is common to all food materials and it is an indication that *Ighu* samples would adsorb more water at higher relative humidity/water activity. However, if relative humidity of the storage environment is kept constant, *Ighu* may absorb more moisture at lower temperature than at higher temperatures. Whereas at constant moisture content, as temperature rise, isotherm curves will be lowered, resulting in an increase in A_W, this will make *Ighu* shreds more susceptible to microbe spoilage.

Moisture sorption models and derivatives: Table 3 presents the results of different moisture sorption equations used to fit generated data.

Monolayer moisture content: Monolayer moisture content (Mo) of *Ighu* samples was determined using the BET and GAB models. A significantly lower BET monolayer moisture contents [5.95 to 9.99 gH_2O/100 g (Isuochi method) and 5.60 to 14.34 gH_2O/100 g (Udi method) for TME 419, while 7.28 to 9.14 gH_2O/100 g (Isuochi method) and 7.60 to 10.12 gH_2O/100 g (Udi method) was recorded for TMS 070072] were obtained for the *Ighu* samples; compared with GAB monolayer moisture content 6.77 to 11.86 gH_2O/100 g (Isuochi method) and 5.60 to 14.34 gH_2O/100 g (Udi method) for TME 419, and 7.60 to 10.57 gH_2O/100 g (Isuochi method) and 7.60 to 10.12 gH_2O/100 g (Udi method) recorded for TMS 070072. The variation in monolayer moisture content of the models could be attributed to the fact that GAB model is a specialized or improved form of BET model. The Monolayer moisture content revealed the highest amount of water that is strongly adsorbed to specific sites of dry substance per gram and an indication of favourable value at which a food is more stable[23,24]. In food, Mo represents the level of water at which biochemical, enzymatic, and microbial reactions are negligible due to strong binding of water to the surface[25]. It is therefore, a crucial parameter for selecting suitable storage conditions for hygroscopic food products. As the temperature increased from 20 to 30°C, the monolayer values of the samples showed an inverse trend; however, regardless of the varietal effect or the processing method, the monolayer values increased at 40°C. As a result of the physical and chemical changes due to temperature, there might be lower number of active sites for water binding[15]. Also, because of the increase in energy levels, high temperatures could activate the water molecules of food, causing less stability and breaking away from the water binding sites. Thus, the monolayer moisture content of the food reduced. This result is supported by Ariahu *et al.*[7] who evaluated adsorption isotherm of tropical water crayfish. However, increasing monolayer moisture content and temperature might also be due to more opening of new binding sites or some of its components becoming increasingly hydrophilic as the temperature increases. This can allow greater water vapor molecules to bind, resulting in increase in M_o[15].

Apparent surface area of sorption: Apparent surface area of sorption ranged from 209.11 to 351.09 m^2/g solid (Isuochi method) and 198.92 to 503.97 m^2/g solid (Udi method) for TME 419 while the range of 255.85 to 321.22 m^2/g solid (Isuochi method) and 269.10 to 355.66 m^2/g solid (Udi method) were recorded for TMS 070072. Higher apparent area of sorption was recorded at the lower storage temperatures and reduced with increasing temperature. This was as a result of the quantity of sorbed moisture at that level. The S_o values reported in this study were higher than 179.2545 to 249.1489 m^2/g solid reported by Ojike et al.[15] for *Gongronema latifolium* leaves dried using oven and sun, while Linus-Chibuezeh[13] reported comparable apparent area of sorption values of 290.13 to 333.80 and 470.80 to 642.96 m^2/g solid for *Ighu* from Sandpaper variety processed using the same processing methods of Isuochi and Udi communities. The large disparity between the reported values and the values obtained in this research could be attributed to the nature of the products and higher starch content in cassava. Apparent surface area of sorption is used to estimate the water-binding properties of foods[15]. According to Yogendrarajah *et al.*[25] water adsorption could be influenced by surface area, porosity, composition, and the quantity of binding sites. The amount of water adsorbed by a food material is as a result of the affinity between the surface and the water molecules, water vapor concentration, temperature, and the absolute amount of surface area revealed, larger surface area means greater adsorption capacity which gives rise to faster deterioration of food[25]. This statement is in line with the findings of the current research indicating the difference in S_o of the samples with respect to processing method.

Effect of processing on moisture sorption models: The Guggenheim–Anderson–de Boer (GAB) constants (C and K) varied with temperature across the adsorption isotherms of *Ighu* produced using different processing methods (Table 3). Notably, the C-values showed a greater dependence on temperature than K-values, decreasing with increasing temperature. In contrast, K-values exhibited no consistent trend across temperature ranges but were generally higher in samples processed using the Isuochi method. Lower K-values suggest a less structured multilayer sorbate state, approaching that of the pure liquid phase. As Timmermann[26] emphasized, practical K-values are typically less than unity; when K = 1, multilayer water behaves like bulk water and the BET equation becomes applicable[24]. All K-values in this study remained below one, supporting the assumption that the multilayer moisture state falls between monolayer and bulk water properties-thus validating the GAB model for *Ighu* regardless of processing method. Comparable K-values have been previously reported for wheat, rice, corn flours, and *Gongronema latifolium* leaf grits[15,27,28]. The GAB constant C, reflecting enthalpy-related interactions, decreased with rising temperature. This inverse correlation suggests sensitivity to the difference in chemical potentials between monolayer and multilayer water molecules[15]. According to Blahovec and Vanniotis[29], a C-value above 2 yields Type II sigmoid isotherms with an inflection point, while values between 0 and 2 result in Type III isotherms lacking inflection. All C-values in this study exceeded 2 across processing methods and temperature conditions, affirming the presence of Type II sigmoid isotherms. These findings align with a prior study conducted by Ojike *et al.*[15] who reported comparable C-value ranges.

The Brunauer-Emmett-Teller (BET) model, known to perform well at water activity (a_w) levels below 0.5, was also evaluated. Agurre[30] and Owoicho et al.[28] highlighted its limitation in assuming liquid-like behavior for multilayer

Table 4: Effect of different relative humidity on WVTR and permeability coefficients of different packaging materials

			Q/t (g H_2O/ day)			WVTR (g H_2O/ day/ m^2)			*P* (g mm/m^2 day mmHg)		
Salt	RH	Δp [(30°C) mmHg]	LDPE	HDPE	Laminated nylon	LDPE	HDPE	Laminated nylon	LDPE	HDPE	Laminated nylon
CH_3COOK	20.16	6.415	0.01884	0.0046	0.0014	1.201	0.240	0.048	0.028082619	0.007482463	0.002618862
$MgCl_2$	32.40	10.310	0.0298	0.0076	0.0026	1.592	0.400	0.090	0.023161979	0.007759457	0.003055286
K_2CO_3	43.20	13.746	0.025	0.0110	0.0244	2.122	0.579	0.840	0.023155827	0.008424269	0.02138804
$NaNO_2$	63.50	20.206	0.0446	0.0201	0.0299	2.840	1.060	1.030	0.021082847	0.010491933	0.017841235
NaCl	75.50	24.024	0.0491	0.0327	0.0467	3.131	1.722	1.610	0.019549201	0.014335664	0.023455711
KCl	83.34	26.519	0.0502	0.0399	0.0597	3.202	2.100	2.060	0.018111543	0.015837701	0.027188054
KNO_3	90.70	28.861	0.0630	0.0454	0.0653	4.011	2.391	2.250	0.020846471	0.016569072	0.027285957
Surface area (m^2)			0.557	0.557	0.459						
Thickness (mm)			0.15	0.20	0.35						

RH: Relative humidity, p: Difference in saturated vapour pressure of pure water and RH, Q/t: Slope of isotherm curve, WVTR: Water-vapour transmission rate, P: Permeability coefficient, LDPE and HDPE: Low and high densities polyethylene

sorbate molecules. For the Oswin model, parameters A and B were derived via linear regression. Results were consistent with previous studies[27,31,32]. The Oswin parameters were inversely related to temperature: A decreased as temperature increased while B increased, indicating strong temperature dependence over processing method dependence. These trends are in line with previous studies[15,33,34] on starchy and non-proteinaceous food systems. The Halsey model, modified by Chirife and Iglesias[35] was applied to derive parameters via linearization. The A-values ranged from 2.186 to 2.558 (Isuochi method) and 2.072 to 2.844 (Udi method) for TME 419, while the range of 2.342 to 2.437 (Isuochi method) and 2.311 to 2.598 (Udi method) was reported for TMS 070072. The Halsey model demonstrated high fit quality, as reflected in strong coefficients of determination, consistent with prior applications to starchy[36], and lipid-rich food systems[37].

Goodness of fit of chosen models: Model performance was evaluated using coefficient of determination (R^2) and Root Mean Square Error (RMSE), both commonly adopted indicators in food sorption studies[38-40]. All models showed high R^2, but only BET and GAB achieved RMSE values below 2.0, indicating superior prediction accuracy. The BET model provided the best overall fit in terms of both R^2 and RMSE, followed by the GAB model. Despite its lower RMSE, GAB's R^2 was slightly inferior to that of the Oswin and Halsey models. These outcomes corroborate recent findings involving food sorption isotherms[15,27,28]. Model performance was not significantly influenced by temperature or cassava variety, but rather by the specific variation in Equilibrium Moisture Content (EMC) and water activity. Given the challenge in formulating a universal model applicable across the full a_w range for diverse food systems[41], empirical fitting remains essential. Similar chemical compositions may still exhibit different sorption behaviours due to differences in physical structure, reinforcing the necessity of experimental model calibration[42].

Effect of relative humidity on Water Vapour Transmission Rate (WVTR) and permeability coefficient (p) of packaging materials: The result of water-vapour transmission rate (WVTR) and coefficient of permeability (P) of the three different packaging materials used for packaging *Ighu* is presented in Table 4.

The WVTR values for low-density polyethylene (LDPE), High-density Polyethylene (HDPE) and laminated nylon were 1.201-4.011, 0.240-2.391 and 0.048-2.250 g H O/day·m^2, respectively. Corresponding permeability coefficients ranged from 0.037-0.0278 g·mm/m^2·day·mmHg (LDPE), 0.00561-0.01242 (HDPE), and 0.000599–0.006237 (laminated nylon). WVTR and permeability decreased with increasing relative humidity at a constant temperature of 30 °C (saturated vapor pressure: 31.82 mmHg). This behavior suggests that elevated RH compromises the moisture barrier properties of packaging films. LDPE exhibited the highest WVTR and permeability, followed by HDPE, while laminated nylon had the lowest values, confirming its superior barrier performance compared to other materials.

These findings confirm that packaging composition significantly affects moisture uptake and transmission. Permeability is quantified via transmission rate, permeance, and permeability coefficient, each accounting for area, pressure gradient, and material thickness[42-44]. Previous studies have consistently reported higher WVTR for LDPE compared to other packaging materials[45,46]. Moyls[47] and Yaptenco et al.[48] further demonstrated the effect of temperature at constant RH on WVTR, with values for polyethylene ranging between 1.47 and 5.22 g H O/day·m^2.

Estimated shelf-life of *Ighu* in different packaging materials and relative humidity: The result of shelf life simulation using the accelerated shelf life methods is presented in Table 5.

It was observed that the shelf life of a product is directly related to the permeability coefficient (P) of the packaging material. A lower material permeance to water, oxygen or other storage environmental factors, the higher it can keep and protect what is packaged in it.

Table 5: Predicted shelf life (days) of *Ighu* in different packaging materials at 30°C and different relation humidity

		ISUOCHI			UDI		
Sample	RH	LDPE	HDPE	Laminated nylon	LDPE	HDPE	Laminated nylon
TME 419	20.16	124	620	3761	140	700	4246
	32.40	150	598	3224	170	675	3639
	43.20	150	550	460	170	622	520
	63.50	165	442	552	186	499	623
	75.50	178	324	420	201	365	474
	83.34	192	293	362	217	331	409
	90.70	167	280	361	188	316	408
TMS 070072	20.16	151	754	4575	146	730	4429
	32.40	183	727	3922	177	704	3796
	43.20	183	670	560	177	648	542
	63.50	201	538	672	194	521	650
	75.50	216	394	511	210	381	494
	83.34	234	356	441	226	345	427
	90.70	203	341	439	196	330	425

RH: Relative humidity, LDPE: Low density polyethylene and HDPE: High density polyethylene

It was also observed that shelf life of *Ighu* increased with increasing RH in LDPE material up to 83.34%, then decreased remarkably. This trend was also observed for HDPE and laminated nylon material up to 75.50% RH. Processing of *Ighu* using shredder (*nko*) from Isuochi resulted to higher shelf life compared to those processed using Udi method. This is due to the lower initial moisture and critical moisture contents of the former reported by Linus-Chibuezeh *et al.*[49], as well as thickness variations among the products. Shelf life of *Ighu* was highest in laminated nylon especially at lower relative humidity of 20.16 and 32.40%, which recorded shelf life values above ten years. The higher shelf life values in laminated nylon showed that the packaging material was almost impermeable to moisture which accounted to higher storability of the products under this condition. Results of the present study are supported by previous researches. Yaptenco *et al.*[48] reported decreased shelf life of whole dried sandfish with change in relative humidity while Patindol and Norio[46] reported low shelf life of blue butterfly pea power stored in nylon/PE material.

CONCLUSION

The results of moisture sorption isotherms of *Ighu* from TME 419 and TMS 070072 cassava varieties, studied at 20°C, 30°C and 40°C and various water activities, showed greater moisture uptake at lower temperatures, exhibiting a typical Type II sigmoid curves. Equilibrium Moisture Content (EMC) increased with water activity, and both processing methods and cassava variety significantly affected EMC. *Ighu* processed with *nko* from Udi community had higher moisture adsorption than the Isuochi method which was attributed to resultant shred thickness of the products. There was no single sorption model fully captured sorption behavior of *Ighu* across all conditions, though the BET model best described sorption below water activity 0.50, outperforming GAB, Oswin, and Halsey models. Packaging studies showed laminated nylon offered the lowest water vapor transmission rate and permeability at low relative humidity, allowing *Ighu* to remain shelf-stable for up to 10 years under low RH (20.16-32.40%), with shelf life decreased as RH exceeded 43%. Therefore, converting cassava roots to *Ighu* and storing the product in laminated nylon under low humidity is recommended to ensure extended shelf life.

REFERENCES

1. Iglesias HA, Chirife J. Prediction of the effect of temperature on water sorption isotherms of food material. Int J Food Sci Technol. 1976;11(2):109-116.
2. Abraham SI, Charles AC, Oneh AJ, Iorwuese GD. Moisture Adsorption and Thermodynamic Properties of Sorghum-Based Complementary Foods. Int J Food Eng Technol. 2016;1(1):1-8.
3. Duckworth RB. Physical Properties of Foods. In: Jowitt R, Escher F, Hallstrom B, Mefert H, Spiess W, Vos G editors. Future needs in water sorption in food stuffs. London, UK: Elsevier Applied Science; 1983. p. 93-102.
4. Rizvi SSH. Engineering Properties of Foods. In: Rao MA, Rizvi SSH editors. Thermodynamic Properties of Foods in Dehydration. New York: Marcel Dekker Inc.; 1986. p. 133-214.
5. Saberi B, Vuong Q, Chockchaisawasdee S, Golding J, Scarlett C, Stathopoulos C. Water sorption isotherm of pea starch edible films and prediction models. Foods [Internet]. 2015;5. Available from: https://www.mdpi.com/2304-8158/5/1/1
6. Sebti I, Delves-Broughton J, Coma V. Physicochemical properties and bioactivity of nisin-containing cross-linked hydroxypropylmethylcellulose films. J Agric Food Chem. 2003;51(22):6468-6474.
7. Ariahu C, Kaze S, Achem C. Moisture sorption characteristics of tropical fresh water crayfish (Procambarus clarkii). J Food Eng. 2006;75(3):355-363.
8. Eke M, Ariahu C, Okonkwo T. Moisture Sorption Characteristics of Dambu-nama – A Nigerian Dried Meat Product. [Internet]. 201129(2). Available from: https://www.ajol.info/index.php/nifoj/article/view/80638

9. Arogba SS. Effect of temperature on the moisture sorption isotherm of a biscuit containing processed mango (Mangifera indica) kernel flour. J Food Eng. 2001;48(2):121-125.
10. Akubor PI, Egbekun MK. Browning, Viscosity and Moisture Sorption Characteristics of Fresh and Stored African Breadfruit Kernel Flour. Chem Res J. 2017;2(4):139-145.
11. Palou E, López-Malo A, Argaiz A. Effect of temperature on the moisture sorption isotherms of some cookies and corn snacks. J Food Eng. 1997;31(1):85-93.
12. Nwagbara L, Iwe M. Critical control points in the processing of cassava tuber for ighu production. Niger Food J [Internet]. 200826(2). Available from:http://dx.doi.org/10.4314/nifoj.v26i2.47445
13. Linus-Chibuezeh A. Effects of High Quality Cassava Flour (HQCF) from different Cassava Varieties on the Nutritional Quality of Wheat-Cassava Bread – A Response Surface Analysis [Master's Thesis]. Michael Okpara University of Agriculture, Umudike, Abia State; 2016.
14. Linus-Chibuezeh A, Adindu-Linus CO, Iwe MO, Nwabueze TU, Tasie UO, Sopuru-Udogu CJ. Moisture Sorption Isotherm of Ighu (A Shredded Cassava Product) From Sandpaper Cassava Variety at Different Temperature. Int J Nutr Res Health [Internet]. 2024;3(1). https://bioresscientia.com/article/moisture-sorption-isotherm-of-ighu-a-shredded-cassava-product-from-sandpaper-cassava-variety-at-different-temperature
15. Ojike O, Uzodinma EO, Ali EO, Nweze BC, Okoyeuzu CF, Eze CR. Moisture adsorption potentials and energy models of Gongronema latifolium leaves dried in separate environments. Food Sci Nutr. 2021;10(2):388-401.
16. Iguedjtal T, Louka N, Allaf K. Sorption isotherms of potato slices dried and texturized by controlled sudden decompression. J Food Eng. 2008;85(2):180-190.
17. IBM Corp. (2015). IBM SPSS Statistics for Windows (Version 23.0). https://www.ibm.com/support/pages/release-notes-ibm-spss-statistics-23
18. Basu S, Shivhare US, Mujumdar AS. Models for sorption isotherms for foods: A review. Drying Technol. 2006;24(8):917-930.
19. ASTM International. ASTM E96 00: Standard Test Methods for Water Vapor Transmission of Materials. West Conshohocken, PA: ASTM International; 2000. https://store.astm.org/e0096-00.html
20. Kulchan R, Boonsupthip W, Suppakul P. Shelf life prediction of packaged cassava-flour-based baked product by using empirical models and activation energy for water vapor permeability of polyolefin films. J Food Eng. 2010;100(3):461-467.
21. Rodríguez-Bernal J, Flores-Andrade E, Lizarazo-Morales C, Bonilla E, Pascual-Pineda L, Gutierréz-López G et al. Moisture adsorption isotherms of the borojó fruit (Borojoa patinoi. Cuatrecasas) and gum arabic powders. Food And BioProd. Process. 2015;94:187-198.
22. Shivhare U, Arora S, Ahmed J, Raghavan G. Moisture adsorption isotherms for mushroom. Lwt - Food Sci Technol. 2004;37:133-137.
23. Cassini A, Marczak L, Noreña C. Water adsorption isotherms of texturized soy protein. J Food Eng. 2006;77(1):194-199.
24. Pérez-Alonso C, Beristain C, Lobato-Calleros C, Rodríguez-Huezo M, Vernon-Carter E. Thermodynamic analysis of the sorption isotherms of pure and blended carbohydrate polymers. J Food Eng. 2006;77(4):753-760.
25. Yogendrarajah P, Samapundo S, Devlieghere F, Saeger SD, Meulenaer BD. Moisture sorption isotherms and thermodynamic properties of whole black peppercorns (Piper nigrum L.). Lwt - Food Sci Technol. 2015;64(1):177-188.
26. Timmermann EO, Chirife J. The physical state of water sorbed at high activities in starch in terms of the GAB sorption equation. J Food Eng. 1991;13(3):171-179.
27. Ahmed MW, Aziz MG, Islam MN. Modeling of moisture adsorption isotherm of selected commercial flours of bangladesh. Agriculturists. 2018;16(2):35-42.
28. Owoicho MC, Idoko FAO, G. ZGN, Zainab A. Moisture sorption characteristics of wheat-mango flake. J FoodNutr [Internet]. 2023;2(1). Available from: https://www.mediresonline.org/article/moisture-sorption-characteristics-of-wheat-mango-flake
29. Blahovec J, Yanniotis S. 'GAB' generalised equation as a basis for sorption spectral analysis. Czech J Food Sci. 2010;28(5):345-354.
30. L.W A. Fruits and Vegetable production in Africa. South Africa: Hafner Publication Company; 1989.
31. Al-Muhtaseb A, Magee WMT. Moisture sorption isotherm characteristics of food products: A review. FoodBioProd. Process. 2002;80(2):118-128.
32. D. APR, M. L, Roberto, E PCC. Models of sorption isotherms for food: Uses and limitations. Vitae. 2011;18(3):325-334.
33. Oswin CR. The kinetics of package life. III. The isotherm. J Society Chemical Industry. 1946;65(12):419-421.
34. Mok C, Hettiarachchy NS. Moisture sorption characteristics of ground sunflower nutmeat and its products. J Food Sci. 1990;55(3):786-789.
35. Chirife J, Iglesisa HA. Equations for fitting water sorption isotherms of foods: Part 1 — a review. Int J Food Sci Technol. 1978;13(3):159-174.
36. Crapiste GH, Rotstein E. Prediction of sorptional equilibrium data for starch containing foodstuffs. J Food Sci. 1982;47(5):1501-1507.
37. Lomauro CJ, Bakshi AS, Labuza TP. Evaluation of food moisture sorption isotherm equations part II: Milk, coffee, tea, nuts, oilseeds, spices and starchy foods. LWT - Food Sci Technol. 1985;18(2):118-124.
38. Arslan N, Toğrul H. Moisture sorption isotherms for crushed chillies. Biosyst Eng. 2005;90(1):47-61.
39. Rakshit M, Moktan B, Hossain SA, Sarkar PK. Moisture sorption characteristics of wadi, a legume-based traditional condiment. J Food Sci Technol. 2011;51:301-307.

40. Martinez-Monteagudo SI, Salais-Fierro F. Moisture sorption isotherms and thermodynamic properties of mexican mennonite-style cheese. J Food Sci Technol. 2012;51:2393-2403.
41. Chen C. A rapid method to determine the sorption isotherms of peanuts. J Agric. Eng. Res. 2000;75(4):401-408.
42. Vullioud M, Márquez CA, Michelis AD. Desorption isotherms for sweet and sour cherry. J Food Eng. 2004;63(1):15-19.
43. Valentas KJ, Rotstein E, Singh RP. Handbook of Food Engineering Practice. 1st ed. Boca Raton, Florida, USA: CRC Press; 1997.
44. Macedo I, Sousa-Gallagher M, Oliveira J, Byrne E. Quality by design for packaging of granola breakfast product. Food Control. 2013;29(2):438-443.
45. Zaghloul MM, Iskander MH, Kenawi MA, A SM. Minia international conference for agriculture and irrigation in the nile basin countries. In: editor. Minia International Conference For Agriculture and Irrigation In The Nile Basin Countries. 2012, Mar 26; El-Minia, Egypt. Minia University; 2012. p. 653-662.
46. C PJ, C NR. Moisture sorption isotherm and shelf-life estimation of blue butterfly pea (Clitoria ternatea linn.) Powder using GAB model. Int J Multidiscip Res Dev. 2022;9(4):80-90.
47. Moyls AL. Whole-bag (water) method for determining water vapor transmission rate of polyethylene films. Applied Eng. in Agriculture. 1998;41(5):1447-1451.
48. Yaptenco KF, Pardua SN, Duque JAC, Pangan RS. Moisture Sorption Isotherms and Mathematical Model Selection for Dried Sandfish (Holothuria scabra). Agric Eng Int: CIGR J. 2017;19(2):176-186.
49. Linus-Chibuezeh A, Adindu-Linus CO, Tasie UO, Sopuru-Udogu CJ, Nwabueze TU, Iwe MO. Physicochemical properties of Ighu from different cassava varieties using methods of two different localities. In: Proceedings of MOUAU Research & Innovation Fair & Conference 2024; Apr 24; Umuahia, Nigeria. Michael Okpara University of Agriculture Umudike; 2024. p 936-942.