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Research Article

Equilibrium Moisture Content and Thermodynamic Properties of Garri

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Abstract

Gari, a widely consumed cassava product in West Africa, plays a vital role in the dietary needs of millions of people. Moisture content is a critical factor affecting its quality, texture, shelf life, and susceptibility to microbial contamination. This study investigates the equilibrium moisture content (EMC) of gari at varying temperatures (40°C, 45°C, 50°C, and 55°C) across different relative humidity (RH) levels. The static gravimetric method was employed to measure EMC, with data fitted to four sorption models: GAB, Modified Henderson, Modified Oswin, and Modified BET. The results demonstrated that EMC decreased as temperature increased, with the Modified Oswin model providing the best fit (R^2 = 0.968–0.983). The GAB model revealed a reduction in the monolayer moisture content (M_0) from 3.988 to 3.640 as temperature rose, indicating a reduced water-binding capacity of the gari. Thermodynamic analysis showed exothermic enthalpy values ranging from -25.1 to -21.3 kJ/mol, and negative entropy values from -80.1 to -66.7 J/mol·K, suggesting strong interactions between water and starch molecules. These findings underscore the importance of controlling drying and storage conditions to maintain the quality and shelf life of gari, offering valuable insights for food processing, packaging, and storage solutsions.

Keywords

Equilibrium Moisture Content, Thermodynamic Properties, Monolayer Moisture Content, Gari, Cassava, Sorption Models

1. Introduction

Cassava (*Manihot esculenta Crantz*) is a versatile crop that has played a pivotal role in global food security for centuries. This perennial woody shrub, native to South America, has become a staple food for over 800 million people worldwide, particularly in Africa, Asia, and Latin America. Cassava's resilience and adaptability to poor soil quality and drought make it an invaluable resource in regions with challenging environmental conditions. Its significance extends beyond its role as a food source, contributing to various industrial applications and economic development [19].

In recent years, global cassava production has steadily increased, with Nigeria leading as the largest producer. In 2021, Nigeria produced approximately 63 million tonnes of cassava, accounting for 20% of global production [19]. Cassava's high carbohydrate content makes it an excellent energy source, providing essential sustenance to millions in developing regions. Beyond direct consumption, cassava is transformed into various products, such as tapioca, cassava flour, and notably in West Africa, gari. Gari is one of the most widely consumed products derived from cassava in West Africa. It is

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a dry, crispy, granular flour that is versatile in its preparation and serves as a staple in numerous households. The production of gari involves several critical steps, including peeling, washing, grating, fermentation, dewatering, roasting, and sieving, each influencing the final quality of the product [6].

Among the many factors that determine gari's quality, moisture content plays a significant role in its texture, shelf life and resistance to microbial contamination. The Equilibrium Moisture Content (EMC) of gari is particularly important for ensuring its storage stability. EMC refers to the moisture level at which gari neither gains nor loses moisture when exposed to specific environmental conditions (temperature and relative humidity). Understanding gari's EMC is essential for optimizing its storage conditions, maintaining its quality during distribution and extending its shelf life. Improper moisture levels can lead to spoilage, reduced nutritional value and economic losses for producers [6]. Gari's moisture content can vary significantly during production and storage depending on environmental conditions and such increases in moisture can make gari more prone to spoilage and microbial contamination, emphasizing the need for careful analysis of its equilibrium moisture properties [5].

This study focuses on investigating the equilibrium moisture content of gari at four different temperatures, fitting the data to four different models to estimate key parameters, including the monolayer moisture content, as well as the differential enthalpy and entropy derived from the data [5].

2. Methodology

2.1. Sample Collection and Preparation

Cassava tubers (TMS 419) used for the studies was collected from Teaching and Research Farm Ekiti State Polytechnic Isan-Ekiti. Care was taken to harvest tubers from cassava stands that were of the same varieties. The cassava mash used was produced by uprooting certain number of cassavas stands from the farm and processing them using the popular traditional method according to [17]. The harvested cassava tubers were washed, peeled and washed again to remove any form of dirt or impurity, then grated immediately after peeling. The peeled roots were grated using the conventional grater and the grated mash was collected in perforated propylene bags and allowed to ferment for four days. Thereafter, bags were tied and placed under the press for dewatering the pulp into a cake devoid of free liquid. The pressed cassava cake was then pulverized and sifted using the conventional raffia sieve of 2.5 mm aperture to produce a wet cassava mash. Fermented cassava mash was roasted using traditional fryer to produce *gari.* During the roasting process, carved wood turners with suitable handles are occasionally employed to turn or stir the gari in the pan, preventing uneven gelatinization allowed to cool to ambient temperature.

2.2. Equilibrium Moisture Content Determination (EMC)

The static gravimetric method was employed to determine the equilibrium moisture content (EMC) of HQCF samples, with saturated salt solutions used to create various relative humidity levels (Table 1). The HQCF samples were placed in stainless steel wire mesh baskets, which were then positioned inside desiccators containing carefully prepared saturated salt solutions [15]. These solutions were formulated to allow undissolved salt to settle at the bottom of the desiccators. The desiccators, holding both the samples and the salt solutions, were placed in ovens set to specific temperature values (40, 45, 50, and 55°C), with each sample tested in triplicate. Every 24 hours, the weight of the samples was measured until a consistent weight was observed over three consecutive readings, signifying equilibrium [10]. Once equilibrium was achieved, the moisture content of the HQCF samples was determined by oven drying at 105°C for 6 hours [3].

Table 1. *Values of relative humidity (%) of saturated salt solutions used at various temperatures.*

Salts	Temperatures (°C)			
	40	45	50	55
NaOH	6.26	5.60	4.94	4.27
LiCl	11.21	11.16	11.10	11.03
KF	22.68	21.46	20.80	20.60
$MgCl_2$	31.60	31.10	30.54	29.93
K_2CO_3	43.38	42.34	41.22	40.65
NaBr	53.17	51.95	50.93	50.15
$NaNo_2$	71.00	69.99	69.04	68.15
KCl	82.32	81.74	81.20	80.70
K_2SO_4	96.41	96.12	95.82	95.53

2.3. Modeling of the Sorption Isotherms

Data obtained from these experiments were fitted to four equilibrium moisture content equations (Table 2).

Table 2. Models for fitting equilibrium moisture content data.

S/No	Model name	Equation	Reference
1	GAB	$M = \frac{C_1 K M_0 aw}{(1-Kaw)(1-Kaw+C_1 Kaw)}$	Falade *et al*. (2003)
2	Modified BET	$M = \frac{(A+BT)\,C(aw)}{(1-aw)\,(1-aw)+(Caw)}$	Jamali *et al*.(2006)
3	Modified Henderson	$Aw = 1 - exp[-A(T+B)M^C]$	Jamali *et al*.(2006)
4	Modified Oswin	$Aw = \frac{1}{\left[{(A+BT)}/{M}\right]^C + 1}$	Jamali *et al*.(2006)

where A, B, C, C_1, K are equation coefficients; M = equilibrium moisture content, %; M_o = monolayer moisture content; Aw = water activity (decimal) and T= temperature (Kelvin)

2.4. Determination of the Thermodynamic Properties

Differential Enthalpy of Sorption

The differential enthalpy of sorption is also called the isosteric heat of sorption and is determined from experimental values using the Clausius-Clapeyron equation one relating the water activity and temperatures at a fixed moisture.

$$\frac{\partial \ln\ (RH)}{\partial (T)} = \frac{(\Delta H)}{RT^2} \quad (1)$$

where RH is the relative humidity, T is the temperature (K), ΔH is the isosteric heat of sorption (kJ/mol), R the universal gas constant (8.314 kJ/kmol K).

Integrating Equation (1) and assuming that the isosteric heat of sorption (ΔH) is temperature independent gives the following equation

$$\ln(RH) = -\left(\frac{\Delta H}{R}\right)\frac{1}{T} + C \quad (2)$$

where C is the arbitrary constant of the equation (2) which is the intercept value of graph plotting relationship between ln(RH) and inverse of temperature.

Thus, the slope of graph plot between at constant moisture content implies the differential enthalpy of sorption value and the intercept of the graph is the differential entropy [22].

3. Result and Discussion

3.1. Equilibrium Moisture Content

The experimental results of the equilibrium moisture content (EMC) of garri at temperatures of 40, 45, 50, and 55°C across ten different relative humidities (RH) are presented in Figure 1. A clear trend was observed: at each constant RH level, the EMC increased as temperature decreased. This inverse relationship between temperature and EMC is consistent with established theories of moisture sorption in food materials. The decrease in EMC with increasing temperature can be attributed to the higher kinetic energy of water molecules at elevated temperatures, which reduces their binding affinity to the garri matrix [21]. As temperature rises, water molecules become more mobile and are more likely to escape from the product into the surrounding air, leading to lower moisture retention. Conversely, at lower temperatures, water molecules are less energetic and remain more tightly bound within the garri, resulting in higher EMC values. Similar trends have been reported in other hygroscopic food products, such as cassava flour and maize [4], reinforcing the generalizability of these findings. The sorption isotherms generated from the experimental results exhibit a Type III sigmoidal curve, according to Brunauer's classification. This type of isotherm is typical for high-carbohydrate foods and indicates a weak interaction between water molecules and the primary binding sites of the food material at low relative humidity levels [16]. As the RH increases, water sorption rises sharply due to the clustering of water molecules, leading to multilayer formation and eventual capillary condensation. This phenomenon is particularly evident in garri, which is a granular, porous, and partially gelatinized starchy product.

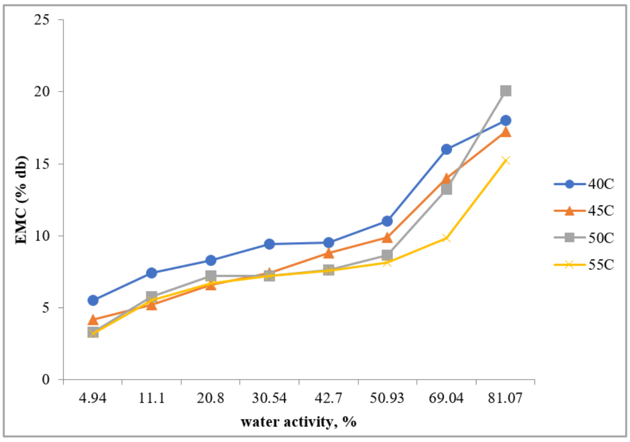

Figure 1. Equilibrium moisture content at different temperature and water activity ranges.

3.2. Fitting Sorption Models to Equilibrium Moisture Content

The equilibrium moisture content (EMC) data of garri were analyzed using four sorption models: GAB (Guggenheim-Anderson-de Boer), Modified Henderson, Modified Oswin, and Modified BET (Table 3). Statistical evaluation using R^2, SEE and MSE revealed distinct performance characteristics for each model. However, the Modified Oswin model demonstrated superior predictive capability with R^2 values ranging from 0.968 to 0.983 across all temperatures (40-55°C), consistent with findings by [5] in similar starchy food matrices. This model's excellent fit, coupled with the lowest standard errors, establishes it as the most reliable for garri moisture prediction. The GAB model also performed exceptionally well (R^2 = 0.948-0.978), providing particularly valuable thermodynamic insights through its parameters. Notably, the monolayer moisture content (M_o) decreased from 3.988 to 3.640 as temperature increased from 40°C to 55°C, reflecting the exothermic nature of water sorption as described by [14]. This temperature-dependent reduction in water-binding capacity has significant implications for drying process optimization [2]. The temperature-dependent EMC patterns suggest that drying at 50-55°C and maintaining storage conditions below 60% relative humidity would optimize product stability, aligning with recommendations by [4] for tropical food preservation.

Table 3. Estimated parameters of different models for the sorption isotherms of gari.

S/N	Model Name	Temp (° C)	Coefficients	R^2	SEE	MSE
	GAB	40	K= 0.938, C= 34.357, Mo= 3.988	0.966	0.021	0.003
		45	K= 0.911, C=22.212, Mo=3.891	0.978	0.018	0.003
		50	K= 0.958, C= 65.845, Mo= 3.798	0.948	0.014	0.002
		55	K= 0.989, C= 48.186, Mo= 3.640	0.972	0.011	0.003
2	Modified Henderson	40	A=2.816E-4, B=63.345, C= 1.634	0.934	0.018	0.046
		45	A=2.471E-4, B=61.286, C= 1.676	0.944	0.018	0.043
		50	A=2.333E-4, B=66.276, C= 1.665	0.952	0.031	0.030
		55	A=2.421E-4, B=65.643, C= 1.699	0.944	0.026	0.037
3	Modified Oswin	40	A=4.325, B=0.089, C= 2.396	0.980	0.013	0.004
		45	A=4.655, B=0.088, C= 2.242	0.983	0.010	0.004
		50	A=4.234, B=0.089, C= 2.285	0.968	0.015	0.006
		55	A=4.245, B=0.088, C= 2.222	0.974	0.019	0.005
4	Modified BET (aw < 0.5)	40	A=80.345, B=-0.503, C=53.413	0.999	0.031	0.003
		45	A=77.722, B=-0.501, C=53.071	0.973	0.041	0.011
		50	A=79.333, B=-0.502, C=52.223	0.960	0.033	0.006
		55	A=76.111, B=-0.500, C=58.824	0.968	0.028	0.008

3.3. Thermodynamic Properties of Garri Sorption

The thermodynamic analysis of garri's moisture sorption (Table 4) behavior provides valuable insights into its stability and processing characteristics.

The monolayer moisture content (M_0), derived from the GAB model, decreased from 3.988 to 3.640 indicating reduced water-binding capacity at higher temperatures. The observed decrease in monolayer moisture content (M_0) aligns with findings by [9] on cassava-based products, where higher temperatures reduced water-binding capacity due to structural changes in starch matrices. This temperature dependence is particularly relevant for garri processing, as it suggests optimal drying conditions between 50-55 ℃ for efficient moisture removal [13, 11].

The calculated enthalpy values (-25.1 to -21.3 kJ/mol) fall within the range reported by Adebowale, (2021) for tropical root crops (-22 to -38 kJ/mol). These exothermic values confirm strong water-starch interactions, though the decreasing magnitude with temperature indicates reduced binding energy a phenomenon recently quantified using DSC analysis of cassava products [1, 18].

Table 4. *Thermodynamic values of garri.*

Temperature	Monolayer Moisture Content	Enthalpy	Entropy
40	3.988	-25.1	-80.1
45	3.891	-23.8	-75.2
50	3.798	-22.5	-70.8
55	3.640	-21.3	-66.7

The negative entropy values (-80.1 to -66.7 J/mol·K) demonstrate significant water molecule ordering during sorption, consistent with recent molecular dynamics simulations of starch-water systems [7]. However, the reduced values at higher temperatures may indicate partial gelatinization effects, as observed in similar fermented starch products by [18].

These thermodynamic insights have practical implications for garri processing technology [12]. The temperature-sensitive nature of water binding supports the growing industry trend toward controlled low-temperature drying (50-55°C) to balance energy efficiency and product quality [20]. Furthermore, the strong humidity dependence suggests smart packaging solutions incorporating moisture regulators could significantly extend shelf life [23].

4. Conclusion

This study investigated the equilibrium moisture content of garri at temperatures of 40°C, 45°C, 50°C, and 55°C across a range of relative humidities. The sorption behavior exhibited a typical Type III sigmoid isotherm, characteristic of starchy food products. The GAB and Modified Oswin models proved particularly effective in describing garri's moisture sorption characteristics, with R^2 values exceeding 0.94 across all tested temperatures. Garri exhibits temperature-dependent moisture sorption behavior, with decreasing monolayer moisture content (3.988 to 3.640 g/100g) and weakening water-binding affinity (ΔH: -25.1 to -21.3 kJ/mol) as temperature increased from 40°C to 55°C. The findings from this study are valuable for the design of packaging, storage, and drying systems for garri, as well as for shelf-life prediction and moisture management in postharvest processing.

Abbreviations

EMC	Equilibrium Moisture Content
RH	Relative Humidity
M_0	Monolayer Moisture Content
HQCF	High Quality Cassava Flour
TMS 419	Cassava Tubers
AW	Water Activity
T	Temperature
RH	Relative Humidities
GAB	Guggenheim-Anderson-de Boer
R^2	R-squared
SEE	Standard Error of Estimate
MSE	Mean Squared Error

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Author Contributions

Yemi Olayinka Olasebikan: Investigation, Methodology, Writing – original draft, Writing – review & editing

Victor Jesulayomi Bamisaye: Data curation, Formal Analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing

Florence Ebunoluwa Ajayi: Conceptualization, Data curation, Investigation, Resources, Writing – original draft

Conflicts of Interest

The authors declare no conflicts of interest.

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