

Effects of drying techniques on the sorption properties of *TMS-30572* dried cassava chips

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Abstract: The distinguishing attributes of preserved a Nigerian variety cassava chips depend on their moisture content, the periodic passage of moisture, and interactions with moisture during storage. The water activity level, which corresponds to the equilibrium moisture content range, was determined by the use of moisture isotherms. The moisture sorption isotherms of the cassava chips were determined at 27°C in the room temperature and 10%-80% relative humidity range using the standard static gravimetric method, while the cassava chips were subjected to sorption and measured periodically between 10%-80% relative humidity until the equilibrium moisture content was reached. The modified Henderson sorption model was tested to fit the experimental data. A nonlinear regression analysis was used to evaluate the constants of the sorption GAB and MGAB models. The GAB and MGAB models were good fits for predicting the moisture sorption isotherms of sun-dried cassava chips, while the MGAB model was a good fit for predicting the moisture sorption isotherms of solar and cabinet-dried cassava chips. The GAB and MGAB models exhibited the best fit for predicting the moisture adsorption isotherms of sun-dried cassava chips at 27°C. Further studies should be conducted on the storage of the “TMS-30572” variety of cassava chips using appropriate packaging materials, and investigations of the isothermal attributes and other temperature characteristics of the cassava chip product should be performed because it aligns with several sustainable development goals (SDGs).

Keywords: Cassava chips, Equilibrium moisture content, Water activity, Sorption isotherms, Relative humidity

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1 Introduction

Cassava (*Manihot esculenta*) is a woody shrub that lasts long, usually up to 2 or 3 seasons; it usually has an edible root; and it typically thrives in tropical and subtropical regions globally, where crops such as maize, sorghum, and sweet potatoes cannot grow (Kando and Bitane, 2023). Cassava is an important food material in tropical Africa that contains nutrients such as carbohydrates, calcium, vitamins B and C, and essential minerals in ample proportions (Bayata, 2019).

The composition of nutrients, however, varies with the different forms, climate, environmental influences during cultivation, lifespan of the harvested crop, and state of the soil (Bayata, 2019).

Cassava is mainly a subsistence crop grown for food consumption. According to Cock and Connor (2021), cassava grows well in poor soils with limited labour requirements. It offers food security during conflicts since invaders are unable to destroy or exhume crops easily because it thrives underground (Cock and Connor, 2021). Cassava can be planted in the same space as vegetables, plantation crops such as coconut, oil palm, coffee, yam, sweet potato, groundnut, or other legumes (Cock and Connor, 2021). In addition to functioning as food, cassava plays a

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versatile role, and the products obtained from it have multiple applications in various food products, such as biodegradable products, confectionery, drugs, food, glues, monosodium glutamate, paper, plywood, sweeteners, and textiles (Cock and Connor, 2021). Chips and pellets from cassava also have applications in alcohol production and animal feed formulation (Thongmee, 2023).

Cassava can be processed into various forms, which include *garri*, *lafun*, and *fufu* (Fawole and Kolapo, 2022). Furthermore, cassava can be harnessed to generate derivatives of industrial market value comprising adhesives, chips, flour, pellets, and starch, which are raw materials in the livestock feed, alcohol/ethanol, textile, confectionery, wood, food, and soft drink industries (Fawole and Kolapo, 2022). Cassava chips are pieces of dry, irregular slices of cassava that vary in size but do not exceed 5 cm or 6 cm in length, as reported by Shimpy et al. (2023). A reduction in the size of cassava roots (chipping) shortens the drying time and ensures the efficient elimination of cyanide components present in fresh cassava roots (Nzuta et al., 2022). Cassava roots can be chipped manually, using a knife, or by machines, usually in the form of a rotating disc perforated with holes with a cutting edge or provided with interchangeable corrugated blades (Nzuta et al., 2022).

Water activity is a crucial tool for determining and managing the shelf life of food products (Labuza and Altunakar, 2020; Wang et al., 2024). The shelf life of a product is the amount of time it will continue to be safe, retain its intended sensory, chemical, physical, and microbiological qualities, and adhere to its nutritional labels (Lohita and Srijaya, 2024). Dry starch or many cereal-based products lose their sensory crispness with increasing water activity. The presence of numerous elements, including oxygen content, pH, preservatives usage, processing and storage conditions, redox potential and water activity, all affect shelf life (Olufayo and Ogunkunle, 1996; Hawa et al., 2020). By empirically measuring and managing the water activity of food, spoilage and

microbial infection can be predicted, chemical stability can be maintained, and nonenzymatic browning reactions and spontaneous autocatalytic lipid oxidation reactions can be minimized. Furthermore, enzyme activity can be regulated, nutrients and vitamins can be preserved in food, and physical properties of food can be optimized, as demonstrated by Olufayo and Ogunkunle (1996) and Hawa et al. (2020).

According to Ajala and Ngody (2020), cassava plants undergo postharvest physiological deterioration, a disadvantage of which is that moisture content reduction, size reduction, and drying of cassava chips can be minimized. According to the studies of Dos Santos Cotta et al. (2023); Fadeyibi and Alaba (2020), information from moisture sorption isotherms is critical for solving deterioration problems in Cassava and its byproducts. Determination of packaging requirements, maintenance of physical and microbiological stability, optimization of nutritional characteristics, and making cassava chips available for further processing, as reported by Ajala and Ngody (2020).

This study aimed to investigate the sorption characteristics of cassava chips using cabinet, solar and sun-drying techniques. The specific objectives of this study were to determine the moisture sorption isotherms of cassava chips dried by different methods, to relate the moisture sorption isotherms to the storability of the cassava chips, and to determine which sorption model best fits the drying methods used.

2 Materials and methods

2.1 Preparation of cassava chips

The Owodunni food processing laboratory at Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Oyo State, Nigeria, with Latitudes: 4°15' and 4°16', Longitudes: 8°9' and 8°10', provided basic, locally built cassava chipping machine used in the production process. The harvested roots of the "TMS-30572" variety were sifted for extraction, and unwanted components were removed. The roots

were weighed, and the backs were peeled with knives and then washed thoroughly in running water. The rinsed roots were chipped using a chipping machine that uniformly produced cassava chips measuring 4-5 cm in length and 1.5 cm in thickness. To lower the moisture level, the chips were collected in perforated sacks and compressed with a hydraulic press. Furthermore, the pressed cassava chips were subjected to cabinet drying, sun drying, and solar drying. Cooled dried chips were weighed, collected in high-density polyethylene bags, and stashed at room temperature (Figure 1). The initial moisture content was determined in triplicate by a moisture content analyser.

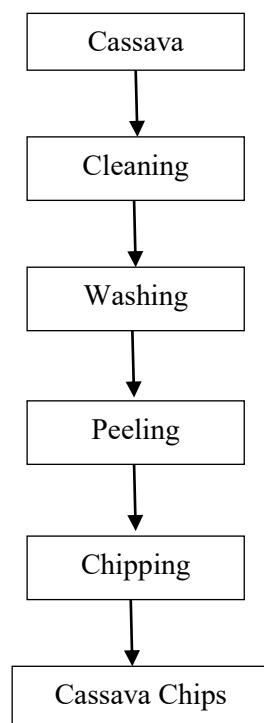


Figure 1 Flow chart for the production of cassava chips

2.2 Preparation of different relative humidity solutions from concentrated tetra oxo sulfate (VI) acid (H₂SO₄)

By definition, relative humidity (*RH*, %) is the ratio of the partial pressure of water on food in an atmosphere of pure water (*P*, bar) Mathematically (Equation 1) Where *P_i* is actual vapor pressure measured, and *P* is the saturation vapor pressure.

$$RH (\%) = \frac{P_i}{P} \times \frac{100}{1} \quad (1)$$

The method of Chen et al. (2023) was used to create a microclimate for the determination of adsorption and desorption of the cassava chip. The

total pressure of the water using the steam data (**Supplementary file III**) obtained via interpolation at 27°C is 0.03564. The water partial pressure (bar) over aqueous H₂SO₄ (sulfuric acid) solution was adapted from the data of Fuentes and Casas (2023), from which the equivalent *RH* corresponding to the percentage weight of H₂SO₄ at a temperature of 27°C was obtained (**Supplementary file II**). This solution was used to mix H₂SO₄ with distilled water for 10%, 20% and 30% *RH*s.

2.3 Adsorption isotherm determination

The static gravimetric technique was employed to calculate the adsorption isotherm. Three identical one-gram samples of cassava chips were weighed into moisture pans and kept at the proper temperature and water activity within desiccators. The samples were kept in desiccators at room temperature with varying relative humidity levels between 10% and 80% The samples were weighed on a regular basis until consistent weights were reached, which served as a means of monitoring their equilibration. According to Fuentes and Casas (2023), the moisture content was computed by taking into account both the starting moisture content and the amount of moisture obtained or lost until equilibration. To create the isotherm curve, the moisture content of the dry basis-equilibrated sample was plotted against the relative humidity.

2.4 Estimating the desorption isotherms

By moving the cassava chips in the range of 10, 20, 30, ... 80, the samples utilized in the adsorption experiment were used in the desorption procedure with relative humidity at the same temperature to the immediately lower relative humidity value. At room temperature, the desiccators were kept at humidity levels of 10%, 20%, 30%, and 70%. When the samples in the desiccators reached equilibrium moisture content, three consecutive readings of a consistent weight were obtained (Fuentes and Casas, 2023). The equilibrium moisture content was plotted against the relative humidity to obtain the isotherm curve. According to Luampon and Charmongkolpradit (2019), sigmoid sorption isotherms are those whose

curves are concave downwards, which accounts for the presence of multiple layers at a material's interior surface.

2.5 Determination of water activity) and equilibrium moisture content

Water activity (a_w) and the equilibrium moisture content (EMC) were determined by using Equations 2 and 3 according to studies of Zhang et al. (2017) and Atienza et al. (2024), where equilibrium relative humidity is ($ERH\%$).

$$a_w = \frac{ERH(\%)}{100} \quad (2)$$

$$EMC = \frac{\text{Average adsorbed moisture}}{\text{Total Moisture}} \times 100 \quad (3)$$

2.5 Local isotherm concept

The Henderson equation (Equations 4 and 5), according to the studies of Aviara (2020), and Atienza et al. (2024), describes the local isotherm as the range of water activity the food samples can undergo for further storage.

$$1 - a_w = e^{-kTM^n} \quad (4)$$

$$\log(-\ln(1 - a_w)) = \log kT + n \log M \quad (5)$$

where, a_w is the water activity (0-1), M is the moisture content (%), T is the absolute Temperature ($^{\circ}C$), N and k are constants.

$\log(-\ln(1 - a_w))$ was plotted against $\log M$ to

determine the moisture content and water activity at which an L_1 break occurred in the Henderson plot. L_1 break represents the monolayer moisture content of optimum chemical stability.

2.6 Isotherm equations and modelling

Table 1 displays the three highly recommended isotherm equations that were examined using the experimental data as $M = f(a_w, T)$. The experimental data were fitted using the SAS nonlinear regression approach to simulate the sorption isotherms. Three distinct metrics were utilized to assess the models' accuracy: mean bias error (MBE), chi-squared (χ^2) and coefficient of fit (R^2). These error equations are defined in Equations 6 to 8 according to the studies of Adomako et al. (2024), Zheng and Bentler (2024) and Majd et al. (2024).

$$MBE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{pred,i} - MR_{exp,i}) \right] \quad (6)$$

$$(\chi^2) = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pred,i})^2}{N - z} \quad (7)$$

$$R^2 = 1 - \frac{ESS}{TSS} \quad (8)$$

With TSS being the Total Sum of Squares and ESS as the Explained Sum of Squares

Table 1 Cassava chip sorption isotherm models

| Model | $M = f(a_w, T)$ |
|-------|---|
| GAB | $M = \frac{abca_w}{(1 - ca_w)(1 - ca_w + bca_w)}$ |
| MGAB | $M = \frac{a(c/T)ba_w}{(1 - ba_w)[(1 - ba_w + (c/T)ba_w)]}$ |
| MOE | $M = (a + bT) \left(\frac{a_w}{1 - a_w} \right)$ |

AB stands for Guggenheim, Anderson, and de Boer formula. MOE is the modified Oswin equation; MGAB stands for the modified Guggenheim, Anderson, and de Boer equation. M is the equilibrium moisture content. (% dry basis): a , b , c is constant model parameters, respectively; T is absolute temperature ($^{\circ}C$).

3 Results and discussion

3.1 Initial moisture contents of dried cassava chips

The initial moisture content (MC) was determined

by using a moisture analyser (MAC 50/NH) at a temperature of 120 C. The initial moisture contents of the sun-, solar-, and cabinet-dried cassava chips were 10.133%, 11.171%, and 11.408%, respectively (**Supplementary File I**). The sorption characteristics of cassava chips using cabinet, solar and sun-drying techniques were evaluated in this study. The initial moisture content of sun, solar, and cabinet-dried cassava chips can be attributed to the drying method, air circulation and weather conditions, sample size and drying duration, and drying surface.

These factors can influence the drying process efficiency and the final moisture content of the final product. The safe moisture content for dried cassava chips is between 12.6% and 14% (Ogunjimi and Ogunjimi, 2016). A more controlled environment is used during cabinet drying, which could result in a reduced moisture content. Regarding moisture content, the cassava mash was dried by both dryers from an initial moisture content of 49.74% w.b. to a safe moisture level (w.b.) of 10.45% (Alonge et al., 2007).

The ultimate moisture content can also be affected by the size of the cassava chips and the length of the

drying process. A higher moisture content could be the result of larger chips or longer drying durations. Freshly picked cassava roots can have moisture contents ranging from 62.5% to 75.4% on a wet basis (Silayo et al., 2013). The final moisture content and the effectiveness of the drying process can both be influenced by the drying surface. A sun-drying study of Cassava roots revealed that the wire mesh tray displayed the highest drying performance, followed by the woven mat surface. This can be explained by the fact that the wire mesh drying surface allows fast removal of moisture from the Cassava roots, as demonstrated by Simo-Tagne et al. (2021).

Table 2 Adsorption data for the dried cassava chips

| <i>RH</i> (%) | a_w | Weight sample (g) | Average adsorbed moisture(g) | Average dry matter (g) | Total moisture (g) | EMC %db |
|-----------------------------|-------|-------------------|------------------------------|------------------------|--------------------|---------|
| Sun dried cassava chips | | | | | | |
| 10 | 0.1 | 1 | -0.086 | 0.899 | 0.015 | 1.669 |
| 20 | 0.2 | 1 | -0.074 | 0.899 | 0.027 | 3.003 |
| 30 | 0.3 | 1 | -0.053 | 0.899 | 0.048 | 5.339 |
| 40 | 0.4 | 1 | -0.0484 | 0.899 | 0.0529 | 5.889 |
| 50 | 0.5 | 1 | -0.042 | 0.899 | 0.059 | 6.563 |
| 60 | 0.6 | 1 | -0.024 | 0.899 | 0.077 | 8.565 |
| 70 | 0.7 | 1 | -0.0123 | 0.899 | 0.0887 | 9.863 |
| 80 | 0.8 | 1 | -0.00433 | 0.899 | 0.105 | 11.717 |
| Solar dried cassava chips | | | | | | |
| 10 | 0.1 | 1 | -0.09 | 0.888 | 0.022 | 2.44 |
| 20 | 0.2 | 1 | -0.01 | 0.888 | 0.0313 | 3.524 |
| 30 | 0.3 | 1 | -0.075 | 0.888 | 0.037 | 4.167 |
| 40 | 0.4 | 1 | -0.063 | 0.888 | 0.049 | 5.518 |
| 50 | 0.5 | 1 | -0.048 | 0.888 | 0.064 | 7.205 |
| 60 | 0.6 | 1 | -0.032 | 0.888 | 0.08 | 8.972 |
| 70 | 0.7 | 1 | -0.002 | 0.888 | 0.109 | 12.28 |
| 80 | 0.8 | 1 | -0.017 | 0.888 | 0.11 | 12.39 |
| Cabinet dried cassava chips | | | | | | |
| 10 | 0.1 | 1 | -0.0833 | 0.886 | 0.0307 | 3.365 |
| 20 | 0.2 | 1 | -0.0593 | 0.886 | 0.0547 | 6.175 |
| 30 | 0.3 | 1 | -0.0527 | 0.886 | 0.0613 | 6.92 |
| 40 | 0.4 | 1 | -0.0473 | 0.886 | 0.0668 | 7.54 |
| 50 | 0.5 | 1 | -0.0457 | 0.886 | 0.0683 | 7.71 |
| 60 | 0.6 | 1 | -0.0303 | 0.886 | 0.0837 | 9.448 |
| 70 | 0.7 | 1 | -0.0177 | 0.886 | 0.0963 | 10.87 |
| 80 | 0.8 | 1 | -0.00333 | 0.886 | 0.111 | 12.53 |

3.2 Adsorption and desorption isotherms of cassava chips

The results of adsorption and desorption with their corresponding water activity and equilibrium moisture contents for sun-, solar-, and cabinet-dried cassava chips are shown in Tables 2 and 3, respectively. The isotherm curves for the adsorption and desorption of the three different drying methods are shown in Figures 2, 3, and 4. The typical shape of the isotherm pattern of the cassava chips reflects the

way in which water binds the system (Okakpu and Okakpu, 2020). The isotherm curve flow of the cassava chips appears to be sigmoid, similar to the type II classification of the Brunauer model (Mathlouthi and Rogé, 2003). The isotherm shows that the equilibrium moisture content (*EMC*) of the cassava chips increased as the water activity increased at constant temperature (Satimehin and Alakali, 2009). The E.M.C. for the adsorption and desorption processes did not have the same values, as

reported by Abiona et al. (2021); the difference is called the hysteresis effect. The results of adsorption and desorption with their corresponding water activity and equilibrium moisture contents for sun-, solar-, and cabinet-dried cassava chips are crucial for understanding the moisture sorption behavior of the

dried cassava chips. The isotherm curves for adsorption and desorption of the three different drying methods utilized on the cassava chips provide valuable information about the interaction between the cassava chips and water activity under different drying conditions.

Table 3 Desorption data for dried cassava chips

| RH (%) | a_w | Weight sample (g) | Average desorbed moisture(g) | Average dry matter (g) | Total moisture (g) | EMC %db |
|-----------------------------|-------|-------------------|------------------------------|------------------------|--------------------|---------|
| Sun dried cassava chips | | | | | | |
| 10 | 0.1 | 1 | -0.00667 | 0.899 | 0.0203 | 2.258 |
| 20 | 0.2 | 1 | -0.003 | 0.899 | 0.044 | 4.896 |
| 30 | 0.3 | 1 | -0.0033 | 0.899 | 0.05 | 5.567 |
| 40 | 0.4 | 1 | -0.00367 | 0.899 | 0.0556 | 6.194 |
| 50 | 0.5 | 1 | -0.01567 | 0.899 | 0.0613 | 6.825 |
| 60 | 0.6 | 1 | -0.007 | 0.899 | 0.0823 | 9.158 |
| 70 | 0.7 | 1 | -0.0207 | 0.899 | 0.0843 | 9.381 |
| 80 | 0.8 | 1 | -2.809 | 0.899 | -2.708 | 11.717 |
| Solar dried cassava chips | | | | | | |
| 10 | 0.1 | 1 | -0.0213 | 0.886 | 0.0328 | 3.703 |
| 20 | 0.2 | 1 | -0.00333 | 0.886 | 0.058 | 6.558 |
| 30 | 0.3 | 1 | -0.0136 | 0.886 | 0.0637 | 7.19 |
| 40 | 0.4 | 1 | 0.0327 | 0.886 | 0.067 | 7.6 |
| 50 | 0.5 | 1 | -0.0157 | 0.886 | 0.0681 | 7.69 |
| 60 | 0.6 | 1 | -0.0093 | 0.886 | 0.0868 | 9.8 |
| 70 | 0.7 | 1 | -0.0145 | 0.886 | 0.0966 | 10.9 |
| 80 | 0.8 | 1 | 0.00333 | 0.886 | 0.111 | 12.53 |
| Cabinet dried cassava chips | | | | | | |
| 10 | 0.1 | 1 | -0.089 | 0.888 | 0.023 | 2.59 |
| 20 | 0.2 | 1 | -0.078 | 0.888 | 0.0337 | 3.72 |
| 30 | 0.3 | 1 | -0.07 | 0.888 | 0.0417 | 4.69 |
| 40 | 0.4 | 1 | -0.06 | 0.888 | 0.0517 | 5.82 |
| 50 | 0.5 | 1 | -0.045 | 0.888 | 0.0667 | 7.51 |
| 60 | 0.6 | 1 | -0.032 | 0.888 | 0.0797 | 8.97 |
| 70 | 0.7 | 1 | -0.027 | 0.888 | 0.109 | 12.3 |
| 80 | 0.8 | 1 | -0.0017 | 0.888 | 0.11 | 12.39 |

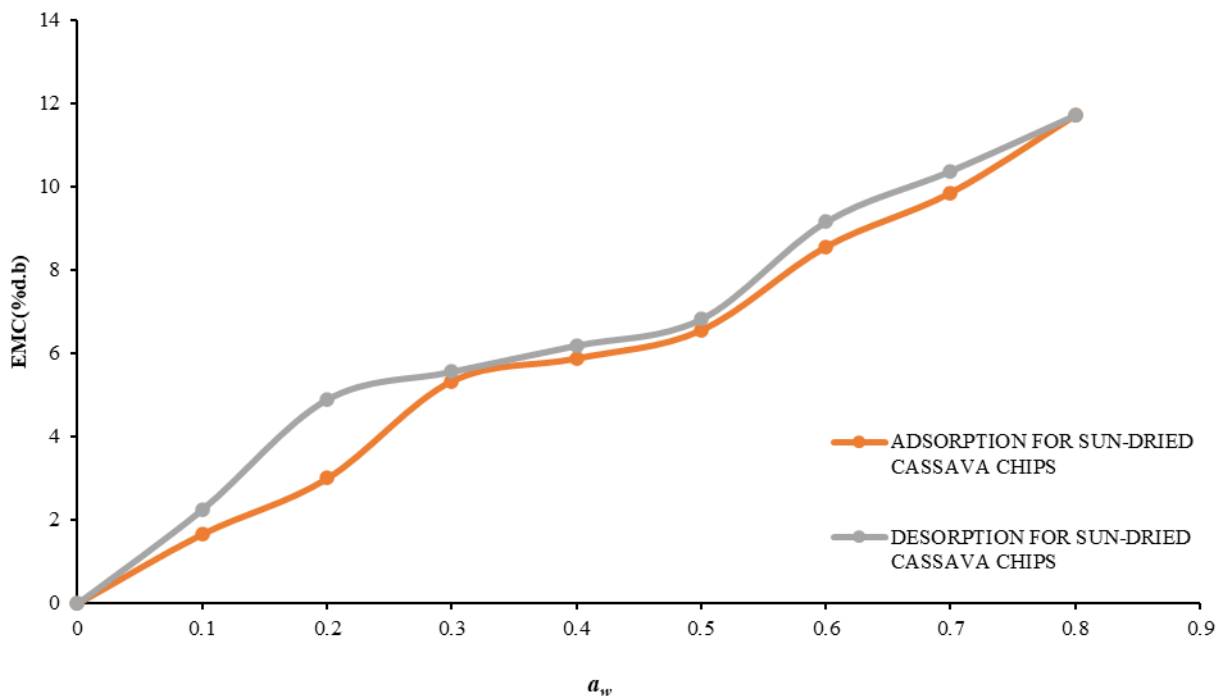


Figure 2 Isotherm curves for sun dried cassava chips

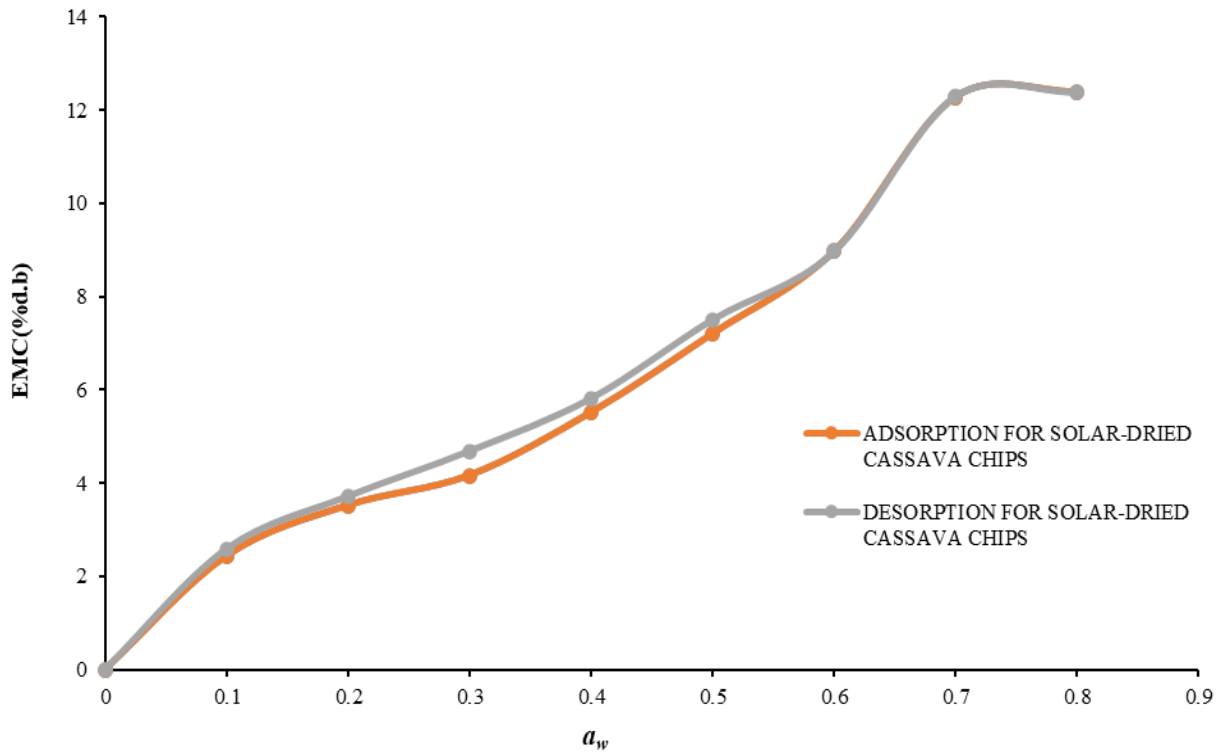


Figure 3 Isotherm curves for solar dried cassava chips

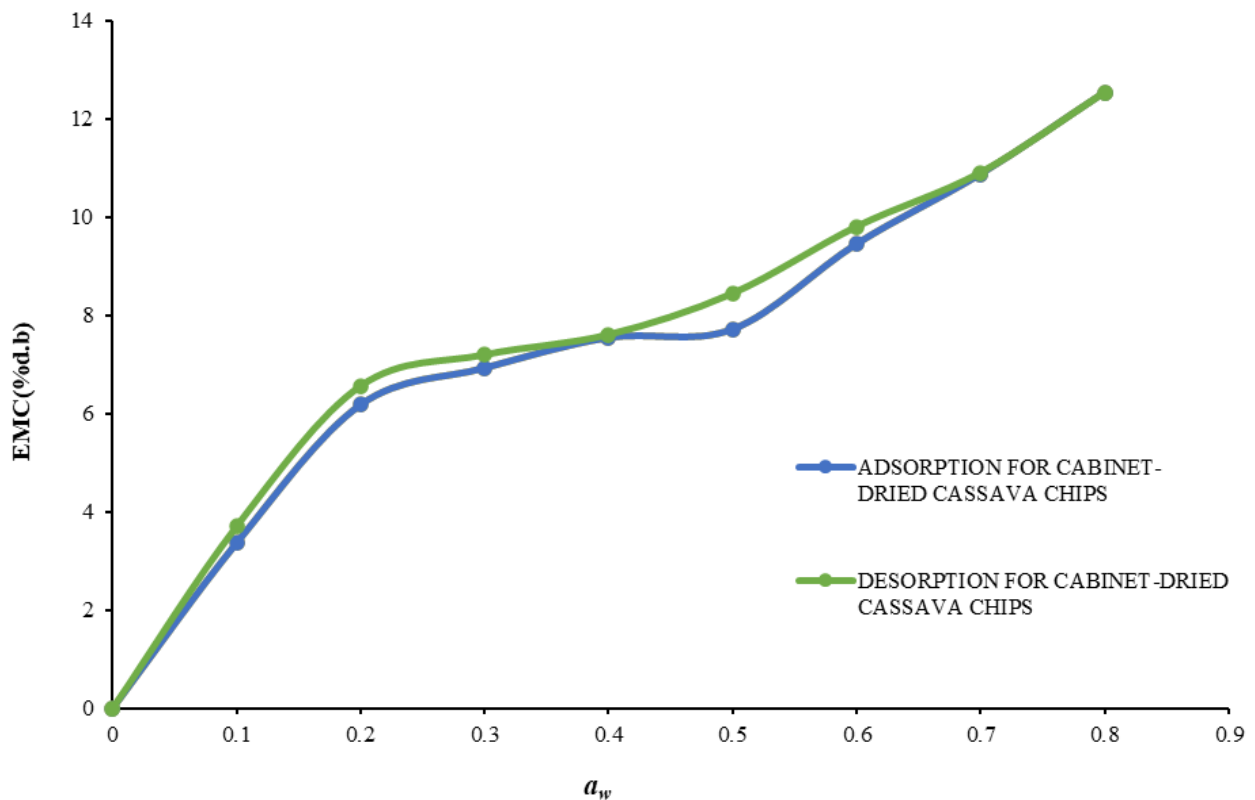


Figure 4 Isotherm curves for cabinet-dried cassava chips

3.3 Local isotherm concepts

The local isotherm data are shown in **Table 4**. The Henderson plot for sun-dried, solar-dried and cabinet-dried cassava chips was generated by plotting

$\log(-\ln(1-a_w))$ against $\log(M)$, as illustrated in **Figure 5**. The boundaries of LI, LI-LII and LII-LIII were determined for sun-, solar- and cabinet-dried cassava chips, as shown in Table 4, by finding the

antilogarithmic value of the intersection of the two breaking points on the horizontal axis. The results were subsequently used to determine the optimum water activity range on the isotherm curve, as shown in Figures 6, 7 and 8. The determination of the quality and safety of the dried Cassava products observed in this study corroborated the findings of Abass et al. (2019), who evaluated the chemical and trace metal composition of already processed Cassava chips. The different forms of curve behavior identified in the isotherm dynamics of the Cassava chips are

temperature dependent, which elicits moisture sorption hysteresis owing to the difference in the desorption isotherm path compared to the adsorption isotherm path (Van Der Werf et al., 2022). The difference in sorption behavior can be attributed to the drying method used for the dried cassava chips. The adsorption capacity was found to be greater for products obtained by certain drying methods, such as spray drying, than for others, leading to differences in the isotherm behaviour, as reported by Van Der Werf et al. (2022).

Table 4 Local isotherm data for dried cassava chips

| a_w | $1-a_w$ | $-\ln(1-a_w)$ | $\text{Log}(-\ln(1-a_w))$ | EMC at 27°C (M) | $\text{Log}(M)$ |
|---------------------|---------|---------------|---------------------------|-----------------|-----------------|
| Sun dried chips | | | | | |
| 0.1 | 0.9 | 0.10536052 | -0.9773221 | 1.669 | 0.22245634 |
| 0.2 | 0.8 | 0.22314355 | -0.6514157 | 3.003 | 0.47755533 |
| 0.3 | 0.7 | 0.35667494 | -0.4477274 | 5.339 | 0.72745992 |
| 0.4 | 0.6 | 0.51082562 | -0.2917273 | 5.889 | 0.77004155 |
| 0.5 | 0.5 | 0.69314718 | -0.1591745 | 6.563 | 0.8171024 |
| 0.6 | 0.4 | 0.91629073 | -0.0379667 | 8.565 | 0.93272737 |
| 0.7 | 0.3 | 1.2039728 | 0.08061668 | 9.863 | 0.99400903 |
| 0.8 | 0.2 | 1.60943791 | 0.20667423 | 11.717 | 1.06881643 |
| Solar dried chips | | | | | |
| 0.1 | 0.9 | 0.10536052 | -0.9773221 | 2.44 | 0.38738983 |
| 0.2 | 0.8 | 0.22314355 | -0.6514157 | 3.524 | 0.5470359 |
| 0.3 | 0.7 | 0.35667494 | -0.4477274 | 4.167 | 0.6198235 |
| 0.4 | 0.6 | 0.51082562 | -0.2917273 | 5.518 | 0.7417817 |
| 0.5 | 0.5 | 0.69314718 | -0.1591745 | 7.205 | 0.85763399 |
| 0.6 | 0.4 | 0.91629073 | -0.0379667 | 8.972 | 0.95288926 |
| 0.7 | 0.3 | 1.2039728 | 0.08061668 | 12.28 | 1.08919837 |
| 0.8 | 0.2 | 1.60943791 | 0.20667423 | 12.39 | 1.09307131 |
| Cabinet dried chips | | | | | |
| 0.1 | 0.9 | 0.10536052 | -0.9773221 | 3.365 | 0.52698507 |
| 0.2 | 0.8 | 0.22314355 | -0.6514157 | 6.175 | 0.79063696 |
| 0.3 | 0.7 | 0.35667494 | -0.4477274 | 6.92 | 0.84010609 |
| 0.4 | 0.6 | 0.51082562 | -0.2917273 | 7.54 | 0.87737135 |
| 0.5 | 0.5 | 0.69314718 | -0.1591745 | 7.71 | 0.88705438 |
| 0.6 | 0.4 | 0.91629073 | -0.0379667 | 9.448 | 0.97533988 |
| 0.7 | 0.3 | 1.2039728 | 0.08061668 | 10.87 | 1.03622954 |
| 0.8 | 0.2 | 1.60943791 | 0.20667423 | 12.53 | 1.09795107 |

Note: where M is the moisture content, a_w is the water activity and EMC is the equilibrium moisture content.

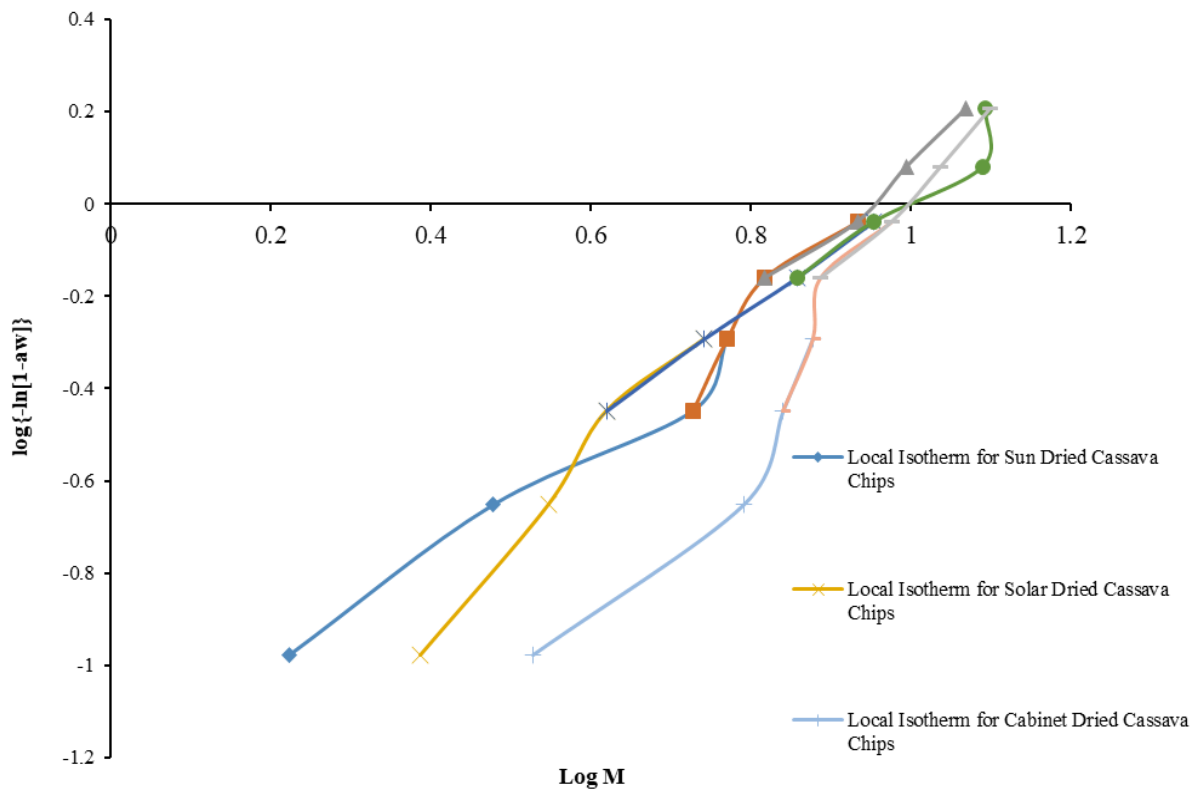


Figure 5 Henderson plot for the dried cassava chips

Table 5 Moisture content (%D. B) and a_w which L1 break occurs in the Henderson plot

| Sample | 1st Break | a_w | 2nd Break | a_w | LI-LIII Boundary |
|--------|-----------|-------|-----------|-------|------------------|
| A | 5.34 | 0.3 | 8.57 | 0.6 | 60 |
| B | 4.17 | 0.3 | 4.17 | 0.7 | 70 |
| C | 6.92 | 0.3 | 9.45 | 0.6 | 60 |

Note: where A= sun dried cassava chips, B= solar-dried cassava chips, C= cabinet-dried cassava chips

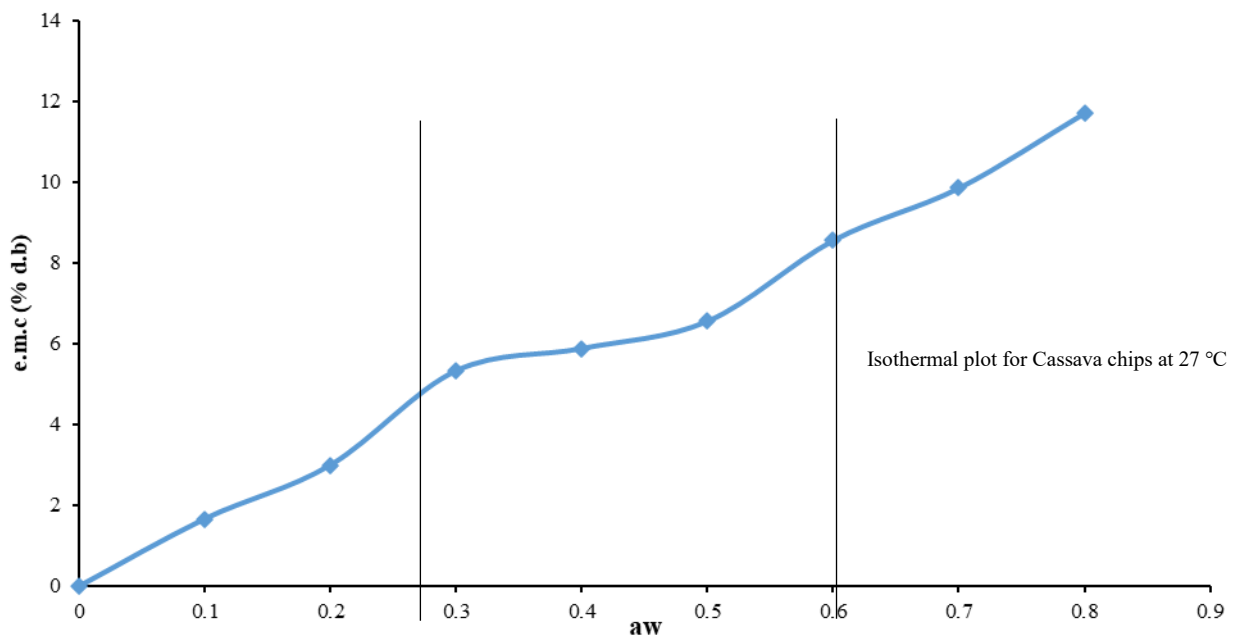


Figure 6 Isothermal plot for sun-dried cassava chips

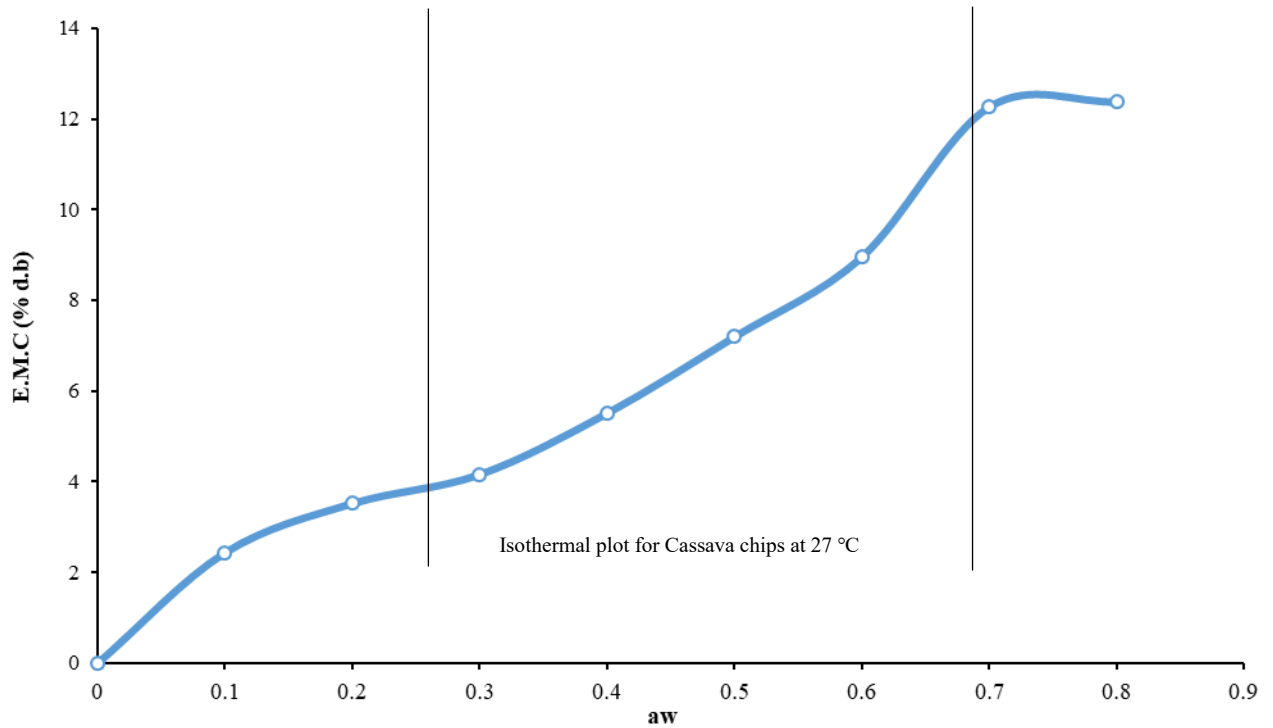


Figure 7 Isothermal plot for solar-dried cassava chips

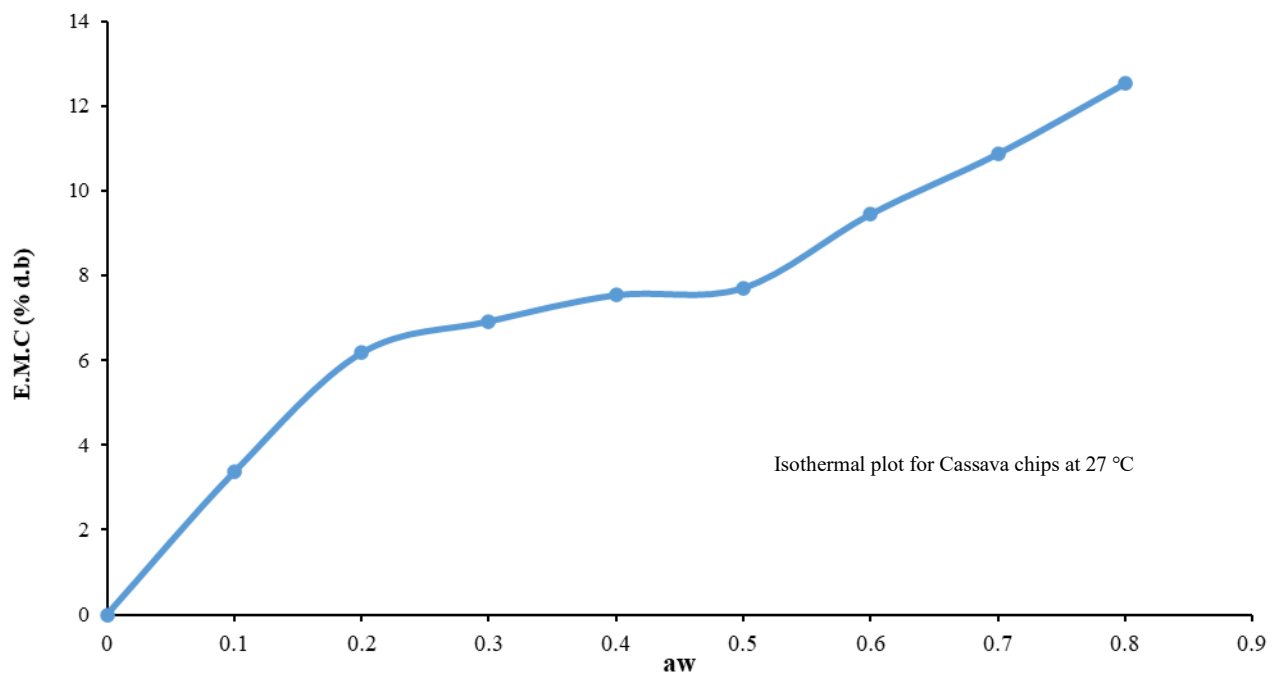


Figure 8 Isothermal plot for cabinet-dried cassava chips

The GAB and MGAB models were generally suitable for predicting the adsorption isotherms of sun-dried cassava chips. The analysis indicated that the projected validity of the GAB and MGAB models was identical, with the following equations in terms of the coefficient of fit: GAB, $R^2=0.988$; GAB, $\chi^2 = 0.137634$; GAB, $MBE = 0.011181$; MGAB,

$R^2=0.988$; GAB, $\chi^2 = 0.137634$; and MGAB, $MBE = 0.011181$. Closely following this in validity for R^2 values is the MOE model with ($R^2 = 0.969$), ($\chi^2 = 0.355338$) and $MBE = 0.046302$, which gave the least level of dependability in this context. Hence, for the sun-dried samples, the GAB and MGAB

models both fit best because they both had the highest values ($R^2=0.988$) and lowest values ($\chi^2 = 0.137634$) and $MBE = 0.011181$, which are identical.

The MGAB model was generally suitable for predicting the adsorption isotherms of solar-dried cassava chips. The analysis indicated that the R^2 values of the GAB and MGAB models were highly similar to those of the MGAB model in terms of the coefficient of fit ($R^2=0.966$, $\chi^2 = 0.504977$, and $(MBE = -0.41927)$). Similarly, the R^2 values of the GAB ($R^2=0.966$), ($\chi^2 = 0.504977$), and $(MBE = -0.41914)$ models were similar, while the lowest R^2 values were obtained for the MGAB model ($R^2 = 0.965$), ($\chi^2 = 0.285814$) and $(MBE = 0.009554)$), which had the lowest level of validity in this context. Hence, for the solar-dried sample, the GAB model fit best because it has the highest value ($R^2=0.988$) and lowest value ($\chi^2 = 0.137634$), which are the same as those in Table 6.

The MGAB model was suitable for predicting the adsorption isotherms of cabinet-dried cassava chips, and the analysis indicated that GAB and MGAB had very similar degrees of validity with respect to the equations in terms of the coefficient of fit, MGAB ($R^2=0.972$), ($\chi^2 = 0.228991$) and $MBE = 0.002611$. Similarly, the reliability of the R^2 values of the GAB ($R^2=0.972$), ($\chi^2 = 0.228991$) and $MBE = 0.002612$ models are similar, and the least fitting model is the MOE model, with $R^2 = 0.965$, ($\chi^2 = 0.285814$) and $(MBE = 0.009554)$ which gave the lowest level of validity in this context. Hence, for the cabinet sample, the MGAB models fit best because they have the highest value ($R^2=0.972$) and lowest values ($\chi^2 = 0.228991$) and

$MBE = 0.002611$.

This study investigated the suitability of different models for predicting the adsorption isotherms of sun-, solar-, and cabinet-dried cassava chips. The GAB and MGAB models were found to be generally suitable for predicting the adsorption isotherms of sun-dried Cassava chips, with both models exhibiting a high degree of reliability in terms of the coefficient of fit. The analysis indicated that both models have the same degree of very high reliability of prediction, with GAB and MGAB having identical values for R^2 , χ^2 , and MBE. The MOE model was found to have the least degree of reliability in this context (Ajala and Ngody, 2020).

For solar-dried Cassava chips, the MGAB model was found to be generally suitable for predicting the adsorption isotherm. Both the GAB and MGAB models exhibited a very close degree of very high reliability of prediction, with the MGAB model having slightly higher R^2 , χ^2 , and MBE values than the GAB model. The MOE model again exhibited the least degree of reliability in this context (Ajala and Ngody, 2020).

For cabinet-dried Cassava chips, the MGAB model was found to be suitable for predicting the adsorption isotherm. Similar to the other drying methods, both the GAB and MGAB models exhibited a very close degree of high prediction reliability, with the MGAB model again having slightly higher R^2 , χ^2 , and MBE values than the GAB model. The MOE model exhibited the least degree of reliability in this context (Ajala and Ngody, 2020). The absorption modelling prediction findings suggest that the GAB and MGAB models are generally suitable for predicting the adsorption isotherms of dried Cassava chips, with the MGAB model showing slightly greater reliability than the GAB model in some cases. The MOE model consistently exhibited the least degree of reliability across all drying methods.

Table 6 Estimated values for fitting models with their evaluation indicators

| Equation | Equation Constant | | | MBE | χ^2 | R^2 |
|-----------------------------|-------------------|----------|---------|----------|----------|-------|
| | a | b | c | | | |
| Sun Dried Cassava Chips | | | | | | |
| GAB | 7.035 | 4.958 | 0.624 | 0.011181 | 0.137634 | 0.988 |
| MGAB | 7.035 | 0.624 | 133.855 | 0.011181 | 0.137634 | 0.988 |
| MOE | 3.951E4 | -1.463E3 | 0.435 | 0.046302 | 0.355338 | 0.969 |
| Solar-Dried Cassava Chips | | | | | | |
| GAB | 8.789 | 3.354 | 0.609 | -0.41914 | 0.504977 | 0.966 |
| MGAB | 8.789 | 0.609 | 90.544 | -0.41927 | 0.504977 | 0.966 |
| MOE | 2.072E4 | -767.055 | 0.465 | 0.299483 | 0.728613 | 0.951 |
| Cabinet-Dried Cassava Chips | | | | | | |
| GAB | 6.352 | 20.454 | 0.638 | 0.002612 | 0.228991 | 0.972 |
| MGAB | 6.352 | 0.638 | 552.252 | 0.002611 | 0.228991 | 0.972 |
| MOE | 1.228E5 | -4.549E3 | 0.301 | 0.009554 | 0.285814 | 0.965 |

Note: where a, b, and c are model constants, mean bias error (MBE), chi-squared (χ^2) and the coefficient of fit (R^2), respectively.

4 Conclusion

Adsorption and desorption isotherms for cassava chips dried by three different methods; sun, cabinet and solar drying, are all sigmoidal in shape. The humidity region of 30 and 60 at 27°C, with a corresponding moisture content ranging from 5.34% d.b. to 8.57% d.b., is expected to provide a better storage medium for sun-dried products. The humidity region of 30 and 70 at 27°C, with a corresponding moisture content ranging from 4.17% d.b. to 12.3% d.b. is expected to provide a better storage medium for the solar-dried product. The humidity region of 30 and 60 at 27°C, with a corresponding moisture content ranging from 6.92% d.b. to 9.45% d.b., is expected to provide a better storage medium for the cabinet-dried product. The Guggenheim-Anderson-de Boer (GAB), MGAB and MOE models are acceptable for describing the adsorption and desorption isotherms of sun-dried cassava chips at 27°C. The GAB and MGAB models were the best fit for predicting the moisture adsorption isotherms of sun-dried cassava chips at room temperature, with $R^2=0.988$, $\chi^2 = 0.137634$ and $MBE = 0.01$. The MGAB model proved the best fit for predicting the adsorption moisture isotherm for cabinet-dried cassava chips at room temperature ($R^2=0.972$), ($\chi^2 = 0.228991$) and $MBE = 0.002611$. The MGAB model proved the best fit for predicting the adsorption

moisture isotherm for solar-dried cassava chips at room temperature ($R^2=0.966$, $\chi^2 = 0.504977$ and ($MBE = -0.41927$)). Adsorption and desorption isotherms showed the occurrence and moisture sorption hysteresis in cassava chips at room temperature. Further studies should explore the storage of “TMS-30572” variety of cassava chips with appropriate packaging materials, and investigations of the isothermal attributes and other temperature characteristics of cassava chips end products should be performed to align with sustainable development goals (SDGs); zero hunger (SDG 2) is achievable by improving the storage of cassava chips and reducing food losses, responsible consumption and production practices (SDG 12) is achievable by the use of appropriate packaging materials and the optimization of storage conditions for cassava chips, efficient storage and reduced food losses can contribute to lower greenhouse gas emissions (SDG 13) associated with cassava chip production, and collaboration between researchers, industry, and government agencies will be essential to achieving the recommended study on the storage of cassava chips (SDG 17). These recommendations aligns with multiple SDGs, impressing the importance of sustainable cassava chips production and good consumption practices.

Authors' contributions

PIO and GOO conceptualized and investigated the manuscript, and **PIO** wrote the original draft. **PIO** collated and analysed the study results. **GOO** provided administrative support and supervised the study. Both authors read and approved the final draft of the manuscript.

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Competing Interests

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