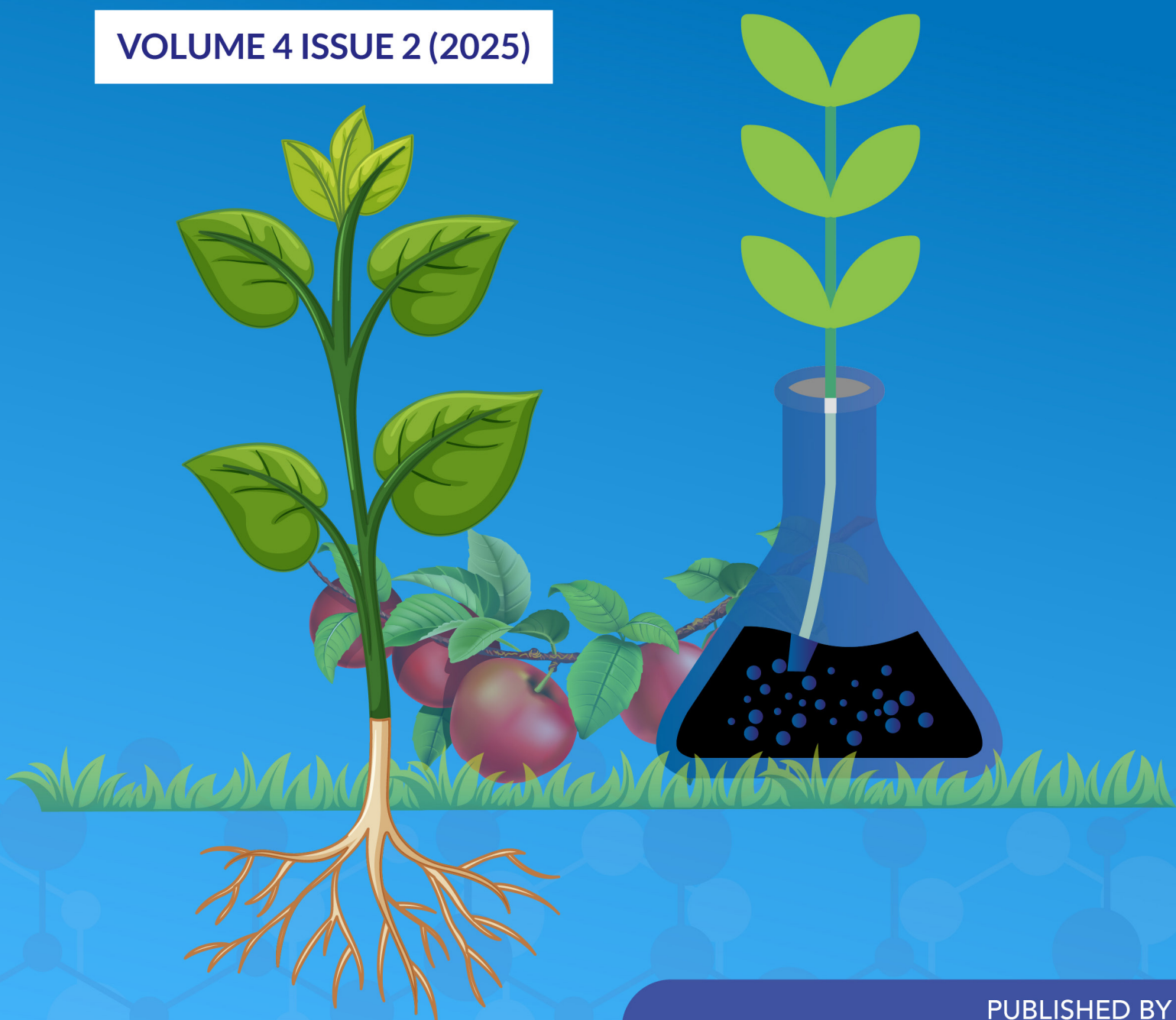




American Journal of Food Science and Technology (AJFST)

ISSN: 2834-0086 (ONLINE)

VOLUME 4 ISSUE 2 (2025)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Moisture Adsorption Characteristics of Spray-Dried Composite Tropical Fruit Purees and Application to Shelf Life Prediction in Flexible Packages

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Article Information

Received: December 01, 2024

Accepted: January 08, 2025

Published: July 03, 2025

Keywords

Flexible Packages, Moisture Sorption Isotherms, Monolayer Moisture Content, Optimal Storage, Spray-Drying, Tropical Fruit Purees, Water Activity

ABSTRACT

The moisture adsorption behavior of spray-dried watermelon, orange, and mango composite puree was examined at temperatures of 20°C, 25°C, 30°C, 40°C, and 50°C across a water activity range of 0.11–0.95 by gravimetric static method and data obtained analyzed using the BET, GAB, and Oswin models. The sorption data and water vapor permeability of commercial aluminum pouches, low density polyethylene (LDPE), Melinex 813, and Propafilm C were utilized to predict product shelf lives under ambient storage conditions. The experimental data exhibited the type III isotherms, characteristic of foods rich in soluble components. The GAB model provided the best fit to the adsorption data. BET monolayer moisture contents decreased with increasing temperature, suggesting fewer available water-binding sites at higher temperatures. Aluminum pouches demonstrated superior moisture protection compared to the other packaging options. This study offers valuable insights for optimizing storage strategies and selecting packaging materials for spray-dried composite fruit products with practical applications in the food industry.

INTRODUCTION

The preservation and storage stability of fruit products remain critical challenges in the food industry, particularly for tropical fruits which are often characterized by high moisture content and seasonal availability. Tropical fruits such as watermelon (*Citrullus lanatus*), orange (*Citrus sinensis*), and mango (*Mangifera indica*) are highly valued for their unique flavors, nutritional properties, and bioactive compounds. Watermelon, with its high water content (>90%) and rich lycopene composition, provides antioxidant properties and potential health benefits. Oranges are renowned for their high vitamin C content, flavonoids, and essential minerals, while mangoes are excellent sources of provitamin A carotenoids, vitamin C, and polyphenols (Vicente *et al.*, 2022). However, these fruits' high moisture content (80-92%), coupled with their rich nutrient profile that supports microbial growth and seasonal nature, necessitate effective preservation methods to ensure year-round availability and reduced post-harvest losses.

Spray drying has emerged as an effective method for extending the shelf life of fruit products while maintaining their nutritional and sensory qualities (Shishir & Chen, 2017). This technology involves the transformation of liquid feed into dried particles through rapid atomization in a hot drying medium, typically air (Seth *et al.*, 2018). The process offers several advantages including operational flexibility, rapid drying rates, and the production of free-flowing powders with controlled particle size. For tropical fruit purees, spray drying provides an efficient means

of moisture removal while preserving heat-sensitive components and minimizing thermal degradation of bioactive compounds (Santos *et al.*, 2018).

Understanding moisture sorption characteristics is fundamental to predicting and controlling product stability during storage, especially when considering the hygroscopic nature of fruit powders (Barbosa-Cánovas *et al.*, 2020). These characteristics, typically represented through moisture sorption isotherms, provide essential information about water-solid interactions and help determine optimal storage conditions. Moreover, thermodynamic parameters derived from moisture sorption data offer valuable insights into the molecular mechanisms governing moisture binding and product stability.

Flexible packaging materials, varying in their moisture and oxygen barrier properties, can significantly influence product stability. The interaction between product moisture sorption characteristics and packaging material properties determines the moisture transfer rates and ultimately affects the product's shelf life. Understanding these relationships is essential for selecting packaging materials that can effectively protect spray-dried products from environmental factors while maintaining their quality attributes (Lechevalier, 2016; Wu *et al.*, 2021).

While extensive research exists on individual fruit powders, there is limited comprehensive data on the moisture sorption behavior of composite tropical fruit purees in their spray-dried form. Additionally, the practical application of such data in predicting shelf life stability

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across different packaging materials remains relatively unexplored. This gap is particularly significant given the growing market demand for tropical fruit products and the need for efficient preservation methods.

This study investigated the moisture sorption characteristics of spray-dried composite tropical fruit purees (watermelon, orange, and mango) and examined their implications for shelf life prediction in various flexible packaging materials. Through the analysis of sorption isotherms, modelling of sorption behavior, and evaluation of thermodynamic properties, this research aimed to provide crucial insights for optimizing storage conditions and packaging selection in the food industry.

MATERIALS AND METHODS

Sources of Raw Materials and Preliminary Handling

Watermelon, oranges, and mangoes were obtained from the “Railway market” in Makurdi, Benue State, Nigeria. They were thoroughly washed, cleaned and kept in the refrigerator for 12 hours prior to product development.

Fruit Purees Production

Watermelon Fruit Puree Production

After washing and sorting, the fruits were peeled manually using stainless steel knives, followed by slicing, removal of the seeds, and blending of pulps in a household electric blender (Kenwood Electricals, UK) at speed number 3 for 15 s into smooth pastes, which were pasteurised at 70 oC for 15s in 250 ml glass beakers with aluminum foil coverings. After cooling, the watermelon purees were kept in a refrigerator before use for composite puree formulation (Maurice, 2018).

Production of Orange Fruits Puree

Orange fruit puree was produced with slight modifications as described by Obasi *et al.* (2017). Essentially, the fruits were sorted, washed, peeled and sliced using stainless steel knives. After the removal of the seeds, the slices were blended into a smooth paste using the house hold electric blender. The orange puree was then pasteurized at 70 oC for 15s in 250 mL glass beakers with aluminium foil covers. The pasteurized orange puree was rapidly cooled in an ice bath and promptly stored in a refrigerator prior to use for mixed puree formulation.

Production of Mango Fruits Puree

This was done by the method of Labaky *et al.* (2020).

The mango fruits were sorted, washed and blanched by immersion in a boiling hot water bath maintained at 98 oC for 5 min. The blanched mango fruits were then cooled in running tap water, peeled using stainless steel knives and the fleshy mesocarp sliced to obtain pieces which were blended in the Kenwood mixer in the presence of 0.2 M citric acid buffer (pH 5.2) into a smooth slurry. The slurry was then stored in the freezer compartment of a household refrigerator prior to use for composite puree formulation.

Composite Fruit Purees Formulation

The composite fruit puree compositions are shown in Table 1 Each puree type was treated with commercial maltodextrin as a carrier agent respectively to obtain a dextrose equivalent (DE) of 30 for each group. The composite purees together with the malodextrins were each blended into smoothies and subjected to preliminary sensory evaluation which indicated that the composite puree sample comprising 50% watermelon, 30% orange and 20% mango composite puree (code: 618) was the most acceptable smoothie and hence was used for the spray drying experiment.

Spray Drying Operations

Spray drying of the composite fruits puree containing 50 % watermelon, 30 % orange and 20 % mango was as described by Sabhadinde (2014) using a pilot plant spray-dryer (Simon Dryers Ltd, Cheshire, England.) with a co-current airflow. The speed of the blower was set at 2400 rpm for all the drying. Distilled water was pumped into the dryer at a set flow rate at 10 rpm (10 rpm ~ 30 mL/min) to achieve inlet and outlet temperatures of 200 °C and 120 °C, respectively. The dryer was run at this condition for about 10 min prior to the introduction of the feed. The feed puree was passed through the spray-dryer chamber (500 mm x 21 mm) with the aid of a centrifugal pump. The speed of rotation of the pump controls the feed flow rate, which passes from the atomizer nozzle with an inner diameter of 0.5 mm. The inner temperature and feed rate were maintained at 160°C and 400 ml/h respectively. After the spray-drying operation, the powder obtained was collected in a pre-weighed, insulated glass bottle connected at the end of cyclone collector and packed in aluminium pouches which were stored at 25°C in a desiccator containing activated silica gel prior to prompt use for analyses.

Table 1: Composite purees formulation

Sample Code	Puree composition (%)		
	Watermelon	Orange	Mango
573	30	50	20
618	50	30	20*
335	20	50	30
804	50	20	30
732	20	30	50
408	30	20	50

*Most acceptable sample upon which quality analyses was carried out

Measurement of Equilibrium Moisture Content and Water Activity

Equilibrium moisture content was determined gravimetrically by exposing the samples to atmospheres of known relative humidities following the method described by (Ariahu *et al.*, 2005). Sulphuric acid (H₂SO₄) solutions of 10, 20, 30, 40, 50 and 60 % were used to provide water activities ranging from 0.15 to 0.96. A thermostatically controlled biochemistry incubator (Model: SPX-80-II, Searchtech Instruments) and 500 mL plastic containers were used for temperature and humidity controls respectively. The solutions made from the acid (200mL each) were carefully introduced into the plastic containers. A screen made of wire gauze was arranged in the plastic containers above the acid solutions to provide a platform for the samples to rest. The experiment was carried out at four temperatures (20, 25, 30, 40 and 50 °C). The equivalent moisture contents were determined by material balance from the initial moisture contents 1.

$$EMC: MW_1 + 100(W_3 - W_2) / (W_1 + (W_3 - W_2)) \quad (1)$$

where; *M*=initial moisture content of the sample, *W*₁=weight of sample during sorption, *W*₂=initial weight of the sample and crown cork, *W*₃=final weight of the sample and crown cork at equilibrium, EMC= Equilibrium Moisture Content

Moisture Sorption Models

The equilibrium moisture data was fitted using the Brunauer–Emmett–Teller (BET), GAB and Oswin models. These models were chosen for their reported fit for starchy foods. They are the most widely used model that gives a good fit to data for a variety of foods over the *a_w* region of 0.05 to 0.45 (Chirife & Iglesias, 1978; Rizvi, 1995) in (Ocheme *et al.*, 2013). The models are;

$$BET \text{ Model: } a_w / (1 - a_w) M = 1 / (M_0 C) + ((C - 1) a_w) / (M_0 C) \quad (2)$$

$$GAB \text{ Model: } M = (M_0 G k a_w) / ((1 - k a_w)(1 - k a_w + G k a_w)) \quad (3)$$

$$Oswin \text{ Model: } M = A [a_w / (1 - a_w)]^B \quad (4)$$

where; *M*= equilibrium moisture content, *M*₀ = monolayer moisture content and *A*, *B*, *G*, *K* and *C* are constants related to heat of sorption, *a_w* = water activity The isotherm model parameters were obtained using OriginLab 2024 through linear and polynomial regression methods as the case may be. The goodness of fit of different models used was evaluated using correlation coefficient (*r*²)

The net isosteric heat of sorption was calculated by applying Clausius-Clapeyron equation to the isosteres obtained at constant moisture content following the procedure reported by Ariahu *et al.* (2005). By plotting ln (*a_w*) versus 1/*T* for a specific moisture content, Δ*H_{st}* was evaluated from the slope (-Δ*H_{st}*/*R*). The differential entropy of sorption (Δ*S_o*) was also obtained from the intercept, *C*, coefficient (Δ*S_o*/*R*) of the same plot. Applying this at different moisture contents allowed the dependence of Δ*H_{st}* and Δ*S_o* with moisture to be determined as follows:

$$\ln a_w = C_{st} - \Delta H_{st} / R \quad 1/T \quad (5)$$

Application of Moisture Sorption to Shelf Life Prediction

The relationship between effective diffusivity and

storage temperature at 85 % RH was evaluated. From the parameters obtained from the packaging films (Aluminum Pouch, LDPE, Melinex 813 and Propafilm C) and sorption data, the shelf life of the instant fufu flour samples can be predicted following the expression for shelf life predictions by Karel (1975) as cited in Offiah *et al.*, (2016)

$$\ln (M_e - M_i) / (M_e - M_c) = (B/x)(A/W_s)(P_0/b)t_s \quad (6)$$

where; *M_e*=equilibrium moisture content at outside relative humidity (obtained from sorption isotherm), *M_i*=Initial moisture content of packaged food, *M_c*=Critical moisture content of packaged food (from sorption isotherm), *B*=moisture permeability of packaging materials, *b*=slope of sorption isotherm, *W_s*=weight of solid food, *A*=package surface area, *x*=thickness of the packaging material, *P₀*=vapor pressure of pure water at ambient temperature, *t_s*=shelf life.

A working isotherm straight line equation derived from a given sorption isotherm is given as;

$$M = Y + b a_w \quad (7)$$

where *b*=slope, *Y*=intercept at *a_w*=0 (representing initial moisture content, *M_i*), *M*=moisture content (gH₂O/100 g solids) at given *a_w*. The water vapour permeability of the different packaging films at 85 % RH are given as follows; Aluminum pouch (0.098 gH₂O/m².day.mmHg), Low-density polyethylene (0.8169 gH₂O/m².day.mmHg), Melinex 813 (0.88 gH₂O/m².day.mmHg), Propafilm C (0.122 gH₂O/m².day.mmHg). The surface area of the packaging material was taken as 0.25 m² with the weight of the sample to be packaged being 500 g.

RESULTS AND DISCUSSION

Effect of Temperature and Water Activity on Moisture Sorption Isotherms

As presented in Figure 1, the equilibrium moisture content was observed to be increasing as the water activity increased; but decreased with an increase in temperature. Also known as the Flory-Huggins Isotherms, the isotherms observed in this study were of J-shaped (Type III). This type of isotherm is common in foods with soluble components like sugars. Authors have reported similar types of isotherm types in literature (Domínguez-Chávez *et al.*, 2023). This shape implies that with the presence of the sugars, the food material sorbs small amounts of water at low water activity and large amounts of water at high relative humidity. Pedro *et al.* (2010) observed similar results for spray-dried passion fruit. The observed differences in moisture sorption capacity can be explained by the differences in bulk porosity and the pore size of the dried materials. Such drying techniques such as Freeze-drying and spray drying, resulted in a highly porous product with small pores, which sorbed more water (Tsami *et al.*, 1998). The behavior of the isotherms can be attributed to physical sorption occurring on highly active sites at low water activities, as water molecules primarily interact with surface hydroxyl groups of crystalline sugar. The observed decrease in equilibrium moisture content with rising temperature aligns with findings from other researchers (Ocheme *et*

al., 2013; Pedro *et al.*, 2010; Senge *et al.*, 2016). This trend may result from the reduced affinity of water molecules for the product at higher temperatures. This trend is related to the excitation state of molecules reported by Diosady *et al.* in (Ariahu *et al.*, 2005). The attractive forces between molecules are lower at high temperatures due to an increase in the kinetic energy of water molecules, allowing the connection between moisture and sorption sites to be broken, which reduces the moisture content of the product (Yadav & Mishra, 2023). Dalgıç *et al.* (2012) have also reported similar results for freeze-dried mint leaves. The effect of spray drying on the moisture sorption isotherm of coffee extract has also been studied and it aligns with the results in this study (Villegas-Santiago *et al.*, 2020). Similar results were also observed for spray-dried sweetened yoghurt powder (Seth *et al.*, 2018). An increase in moisture content with rising water activity was observed, with a more pronounced increase occurring in the water activity range of 0.5 to 1.0. This suggests that at water activity levels above 0.5, microbial growth, enzymatic reactions, and lipid oxidation are likely to accelerate, leading to faster spoilage of the spray-dried fruit puree composites.

Model Regression Parameters and Derivative

The regression parameters for the GAB, BET, and Oswin models are presented in Tables 2, 3, and 4, respectively. It was observed that the monolayer moisture content (Mo) decreased with increasing temperature. The Mo values are critical for identifying storage and preservation conditions, as exceeding these values could lead to deteriorative changes. It represents the minimum amount of water bound to active sites to give a monolayer coverage and maximum stability of storage foods (Yang *et al.*, 2016). The monolayer moisture contents determined using the BET and GAB models were found to range from 6.60 to 15.50 g H₂O/100 g solids and 9.98 to 30.87 g H₂O/100 g solids, respectively. Notably, the BET monolayer values were significantly lower than those obtained from the GAB model. Authors reported lower BET and GAB monolayer moisture contents ranging from 1.18-6.89 g H₂O/100 g solids and 4.52-6.59 g H₂O/100 g solids respectively; for spray-dried coffee extract (Villegas-Santiago *et al.*, 2020). This reduction in monolayer values could be explained by the reduction in the total number of active sites for water binding as a result of physical and/or chemical changes in

the product induced by temperature during the freezing process. Several researchers have observed similar scenarios (Domínguez-Chávez *et al.*, 2023). Though there was a general reduction in the monolayer moisture content, the decreasing trend was not clear as there was an initial decrease in Mo and then a subtle increase. This could be due to several factors which affect sorption in foods which can be complex (Harini, 2023).

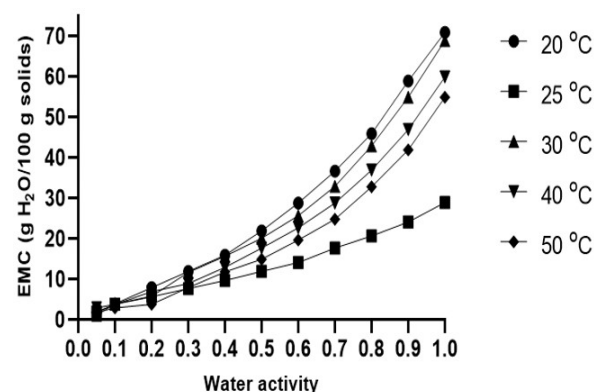


Figure 1: Moisture sorption isotherms of spray-dried tropical fruit composite purees

Fitting of Sorption Models

Sorption experimental data for five temperatures (20 °C, 25 °C, 30 °C, 40 °C, and 50 °C) were fitted to three models: BET, GAB, and Oswin, within their theoretically appropriate ranges. The quality of the fit for each model was assessed using the correlation coefficient (r^2), with the values presented in Tables 2, 3, and 4 for the BET, GAB, and Oswin models, respectively. The r^2 value, which indicates how well a model explains the variability of the predicted values, suggests that models with r^2 values closer to 1 are more suitable (Gichau *et al.*, 2020). The r^2 values ranged as follows: GAB (0.81–0.96), BET (0.50–0.87), and Oswin (0.49–0.62). Among the models, the GAB model had the lowest %RMS (5.8 – 7.6) and hence provided the best fit, as evidenced by its r^2 values being closer to 1 compared to the Oswin and BET models. This finding agrees with results reported by Pedro *et al.* (2010), who studied the sorption isotherms of passion fruit pulp and Villegas-Santiago *et al.* (2020), who analyzed the drying process of coffee extract.

Table 2: GAB Adsorption Regression Parameters for spray-dried composite tropical fruit puree

Sample	Temperature	K	C	Mo	r^2
	20	0.67	1.84	30.87	0.96
	25	0.70	6.13	9.98	0.88
	30	0.87	8.75	11.89	0.80
	40	0.82	4.11	13.40	0.84
	50	0.80	2.35	13.97	0.81

r^2 =correlation coefficient, Mo=monolayer moisture content, G and K are GAB constants

Table 3: BET Adsorption Regression Parameters for spray-dried composite tropical fruit purees

Sample	Temperature	C	Mo	So	r ²
	20	2.64	15.50	544.65	0.74
	25	7.86	6.60	232.65	0.72
	30	10.19	9.91	348.17	0.87
	40	4.77	10.12	355.57	0.73
	50	2.59	10.14	356.29	0.50

r²=correlation coefficient, Mo=monolayer moisture content (g H₂O/100g solids), So=surface area of sorption (m²/100g solids), C=BET constant

Table 4: Oswin Adsorption Regression Parameters for spray-dried composite tropical fruit purees

Sample	Temperature	n	C	r ²
	20	0.28	8.96	0.49
	25	0.21	6.11	0.50
	30	0.23	11.12	0.62
	40	0.26	7.88	0.56
	50	0.29	5.92	0.52

A and B are Oswin constant, r²=correlation coefficient

Thermodynamic Properties of Spray-Dried Composite Tropical Fruit Purees

Net Isosteric Heat Of Sorption

The net isosteric heat of sorption exhibited strong dependency on EMC of spray-dried composite tropical fruit purees (Figure 2). The net isosteric heat was maximum (3.3×10^{-4} kJ/mol) at the lowest EMC (2 % db) which decreased with the increase in EMC. This finding is also corroborated by several workers (Edrisi Sormoli & Langrish, 2015; Yogendrarajah *et al.*, 2015). This could be attributed to the availability of highly active polar sites that initially require greater interaction energy. Once the available polar sites become less, binding energy also diminishes (Seth *et al.*, 2018). The isosteric heat of sorption decreased swiftly up to 6 % moisture content (db) followed by a gradual decrease with increasing moisture content. This implied that the water bound in the 'monolayer region' is difficult to remove compared to the 'condensed water region' of isotherm (Seth *et al.*, 2018). The high correlation coefficients ($r^2 \geq 0.869$) confirm the validity and effectiveness of the Clausius-Clapeyron equation in describing the sorption energetics of the spray-dried tropical fruit puree composites, as shown in

Table 5. As the moisture content increases, the heat of sorption approaches that of pure water, indicating that the moisture exists predominantly in a free form. This underscores the strong dependence of isosteric heat on moisture content, with the energy required for sorption (beyond the latent heat) being significantly higher at low moisture content (Yazdani *et al.*, 2006). Additionally, this suggests that the heat of adsorption for the initial layers of water molecules exceeds the heat of condensation of pure water. The heat of sorption values at specific moisture contents offer valuable insights into the state of the sorbed water, serving as an indicator of the physical, chemical, and microbiological stability of food materials under specific storage conditions. The variation in sorption heat with moisture content is particularly useful for calculating energy consumption and designing efficient drying equipment. Additionally, it aids in understanding the balance between water-water and water-solid interactions. Water sorption in foods is inherently complex, as the main water-sorbing constituents—such as proteins, starch, cellulose, and sugars—each contain distinct polar groups that create energetically preferential sites for water binding (Labuza & Altunakar, 2020).

Table 5: Regression parameters for Clausius–Clapeyron equation relationship between lnaw and 1/T for adsorption isotherms

Regression parameter	Moisture content (gH ₂ O/100 g solids)							
	2	3	4	5	6	8	10	12
N	5	5	5	5	5	5	5	5
A	-0.039	-0.049	-0.028	-0.027	-0.026	-0.023	-0.021	-0.019
B	8.96	12.32	6.43	6.29	6.13	5.64	5.23	4.76
r ²	0.933	0.985	0.896	0.920	0.944	0.948	0.940	0.869
ΔH _{st}	0.00033	0.00041	0.00024	0.00023	0.00022	0.00019	0.00017	0.00016
ΔS _o	-0.0745	-0.1024	-0.0535	-0.0523	-0.0510	-0.0469	-0.0435	-0.0395

n = no. of entries; r²=correlation coefficient; b= intercept coefficient; a= slope; ΔH_{st}=net isosteric heat (kJ/mol); ΔS_o=net entropy of sorption (kJ/mol.°C).

Entropy of Sorption

Like isosteric heat of sorption, sorption entropy exhibited strong dependency on EMC (Figure 2). The sorption entropy gives the status of the available sorption sites for water binding on the surface (Yogendrarajah *et al.*, 2015). The entropy of sorption (ΔS°) values were determined from the intercept coefficients obtained through least-square linear regression of the relationship between $\ln a_w$ and $1/T$ at constant moisture contents. Using the Clausius-Clapeyron equation, ΔS° was calculated as $C_{st} = \Delta S^\circ / R$. Negative ΔS° values were observed, increasing as moisture content increased. This reflects the thermodynamic compensation between the heat and entropy of moisture sorption. At lower moisture contents, water molecules are tightly bound to the sorbent surfaces, exhibiting a low degree of freedom and low entropy of sorption. In contrast, at higher moisture contents, water molecules form multilayers over the tightly bound first layer, possessing greater degrees of freedom and, consequently, higher entropy of sorption (Li *et al.*, 2011; Yang *et al.*, 2016). For the spray-dried tropical fruit purees, the entropy of sorption increased up to approximately 6 % moisture content and then became asymptotic with further increases in moisture content. This behavior may be attributed to a balance between the increasing moisture content and the availability of hydrophilic sites, which prevents significant fluctuations in entropy. Similar asymptotic tendencies in various products have been reported in the literature (Ariahu *et al.*, 2005; Li *et al.*, 2011; Sengeev *et al.*, 2018).

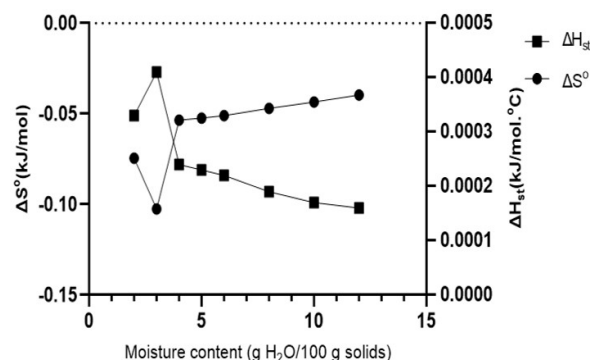


Figure 2: Net isosteric heat and net entropy of sorption of spray-dried composite tropical fruit purees

Shelf life Prediction of Spray-Dried Composite Tropical Fruit Purees

As anticipated, the shelf life of the product decreased with increasing initial storage moisture content and storage temperature across all packaging types. Storage conditions, particularly high ambient temperature and relative humidity, pose significant challenges for the stability of dried products (Anandito *et al.*, 2017). Higher storage temperatures are predicted to shorten shelf life due to the increased transmission rate of water vapor (Gichau *et al.*, 2020). Regardless of temperature, aluminum pouches were predicted to offer the longest shelf life due to their low water vapor transmission rate

(0.122 g H₂O/m².day.mmHg). For instance, at 20 °C, aluminum pouches were estimated to achieve a shelf life of 73.08 months, the longest among the tested packaging materials. In contrast, the shelf life for the same packaging decreased significantly to 9.31 months at 50 °C, highlighting the influence of temperature on product stability (Figure 3). These shelf-life estimations focused on the water vapor permeability of the packaging materials. However, further investigations are necessary to understand the impact of gas permeability, particularly to oxygen and carbon dioxide, which could contribute to lipid oxidation and affect product quality (Gichau *et al.*, 2020; Seth *et al.*, 2018).

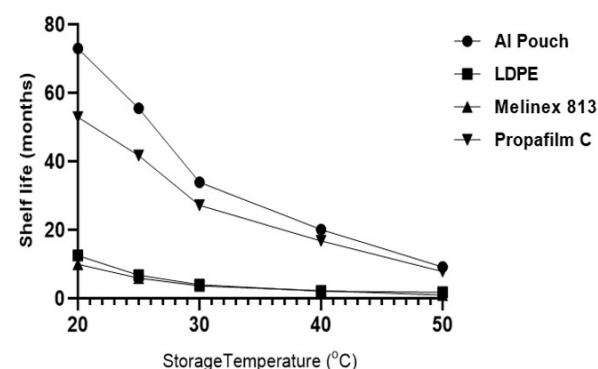


Figure 3: Shelf life Prediction of Spray-dried composite tropical fruit purees

CONCLUSION

This study provides comprehensive insights into the moisture sorption behavior and storage stability of spray-dried composite tropical fruit purees. The investigation revealed that the spray-dried products exhibited Type III isotherms, characteristic of high-sugar materials, with the BET model providing the best fit for the experimental moisture sorption data. This finding is particularly significant for predicting moisture content under various storage conditions. The thermodynamic analysis revealed important relationships between moisture content and binding energy, as demonstrated by the increase in net isosteric heat of sorption with increasing moisture content, indicating the presence of thermodynamic compensation. The negative values of net entropy of sorption, which approached zero with increasing moisture content, suggest reduced molecular mobility and increased order in the system at lower moisture content. These thermodynamic parameters provide valuable insights into the water-solid interactions that govern product stability. The comparative analysis of different flexible packaging materials demonstrated that aluminum pouches offered superior protection and predicted longer shelf life (73.08 months at 20 °C) compared to other packaging options. This finding has significant practical implications for the food industry, particularly in the selection of appropriate packaging materials for spray-dried fruit products. These results contribute to the fundamental understanding of moisture sorption phenomena in composite fruit

systems and provide practical guidelines for the storage and packaging of spray-dried tropical fruit products. The findings can be applied to optimize storage conditions and packaging selections, ultimately leading to improved product stability and extended shelf life.

REFERENCES

- Anandito, R. B. K., Siswanti, Purnamayati, L., & Sodik, H. (2017). Shelf-life determination of fish Koya using critical moisture content approach. *Proceedings of the Pakistan Academy of Sciences: Part B*, 54(3), 201–206.
- Ariahu, C. C., Kaze, S. A., & Achem, C. D. (2005). Moisture sorption characteristics of tropical fresh water crayfish (*Procambarus clarkii*). *Journal of Food Engineering*, 75(2006), 355–363. <https://doi.org/10.1016/j.jfoodeng.2005.03.062>
- Barbosa-Cánovas, G. V., Fontana, A. J., Schmidt, S. J., & Labuza, T. P. (2020). *Water activity in foods: Fundamentals and applications*. <https://doi.org/10.1002/9781118765982>
- Dalgıç, A. C., Pekmez, H., & Belibağlı, K. B. (2012). Effect of drying methods on the moisture sorption isotherms and thermodynamic properties of mint leaves. *Journal of Food Science and Technology*, 49(4), 439–449. <https://doi.org/10.1007/s13197-011-0302-7>
- Domínguez-Chávez, A. N., García-Amezquita, L. E., Pérez-Carrillo, E., Serna-Saldívar, S. R. O., & Welti-Chanes, J. (2023). Water adsorption isotherms and phase transitions of spray-dried chickpea beverage. *LWT*, 187, 115323. <https://doi.org/10.1016/j.lwt.2023.115323>
- Edrisi Sormoli, M., & Langrish, T. A. G. (2015). Moisture sorption isotherms and net isosteric heat of sorption for spray-dried pure orange juice powder. *LWT-Food Science and Technology*, 62(1), 875–882. <https://doi.org/10.1016/j.lwt.2014.09.064>
- Gichau, A. W., Okoth, J. K., & Makokha, A. (2020). Moisture sorption isotherm and shelf life prediction of complementary food based on amaranth–sorghum grains. *Journal of Food Science and Technology*, 57(3), 962–970. <https://doi.org/10.1007/s13197-019-04129-2>
- Harini, A. S. (2023). Water Activity Prediction and Moisture Absorption Isotherms in Plant Food Preservation. *Agricultural, Biologicals and Food Science*, 2(1), 23–31. <https://doi.org/10.46632/abfs/2/1/4>
- Labuza, T. P., & Altunakar, B. (2020). Water activity prediction and moisture sorption isotherms. In *Water activity in foods: Fundamentals and applications* (pp. 161–205). <https://doi.org/10.1002/9781118765982.ch7>
- Lechevalier, V. (2016). Packaging: Principles and technology. In *Handbook of food science and technology 2: Food process engineering and packaging* (pp. 269–315).
- Li, X., Cao, Z., Wei, Z., Feng, Q., & Wang, J. (2011). Equilibrium moisture content and sorption isosteric heats of five wheat varieties in China. *Journal of Stored Products Research*, 47(1), 39–47. <https://doi.org/10.1016/j.jspr.2010.10.001>
- Ocheme, O. B., Ariahu, C. C., & Ingbian, E. K. (2013). Moisture Sorption Characteristics of Dakuwa (Nigerian Cereal / Groundnut Snack). *International Journal of Food Engineering*, 9(4), 499–504. <https://doi.org/10.1515/ijfe-2012-0242>
- Offiah, L. O., Ariahu, C. C., & Igyor, M. A. (2016). Effect of malting and fermentation on the proximate composition and sensory properties of maize (*Zea mays*) and African yam bean (*Sphenostylis stenocarpa*) based Tortilla. *The International Journal of Engineering And Science*, 5(8), 1–6.
- Pedro, M. A. M., Telis-Romero, J., & Telis, V. R. N. (2010). Effect of drying method on the adsorption isotherms and isosteric heat of passion fruit pulp powder. *Ciência e Tecnologia de Alimentos*, 30(4), 993–1000. <https://doi.org/10.1002/pd.1970140602>
- Santos, D., Maurício, A. C., Sencadas, V., Santos, J. D., Fernandes, M. H., & Gomes, P. S. (2018). Spray drying: An overview. *Biomaterials-Physics and Chemistry-New Edition*, 9–35.
- Sengev, I. A., Ariahu, C. C., Abu, J. O., & Gernah, D. I. (2016). Moisture adsorption and thermodynamic properties of sorghum-based complementary foods. *International Journal of Food Engineering and Technology*, 2(1), 26–33. <https://doi.org/10.11648/j.ijfet.20170101.11>
- Sengev, I. A., Ariahu, C. C., Abu, J. O., & Gernah, D. I. (2018). Moisture Desorption Isotherms and Thermodynamic Properties of Sorghum-Based Complementary Foods. *European Journal of Biophysics*, 6(2), 23–31. <https://doi.org/10.11648/j.ejb.20180602.11>
- Seth, D., Dash, K. K., Mishra, H. N., & Deka, S. C. (2018). Thermodynamics of sorption isotherms and storage stability of spray dried sweetened yoghurt powder. *Journal of Food Science and Technology*, 55(10), 4139–4147. <https://doi.org/10.1007/s13197-018-3340-6>
- Shishir, M. R. I., & Chen, W. (2017). Trends of spray drying: A critical review on drying of fruit and vegetable juices. *Trends in Food Science and Technology*, 65, 49–67.
- Tsami, E., Krokida, M. K., & Drouzas, A. E. (1998). Effect of drying method on the sorption characteristics of model fruit powders. *Journal of Food Engineering*, 38(4), 381–392. [https://doi.org/10.1016/S0260-8774\(98\)00130-7](https://doi.org/10.1016/S0260-8774(98)00130-7)
- Vicente, A. R., Manganaris, G. A., Darre, M., Ortiz, C. M., Sozzi, G. O., & Crisosto, C. H. (2022). Compositional determinants of fruit and vegetable quality and nutritional value. In *Postharvest handling* (pp. 565–619). Academic Press.
- Villegas-Santiago, J., Gómez-Navarro, F., Domínguez-Niño, A., García-Alvarado, M. A., Salgado-Cervantes, M. A., & Luna-Solano, G. (2020). Effect of spray-drying conditions on moisture content and particle size of coffee extract in a prototype dryer. *Revista Mexicana de Ingeniería Química*, 19(2), 767–781. <https://doi.org/10.24275/rmiq/Proc767>
- Wu, F., Misra, M., & Mohanty, A. K. (2021). Challenges

- and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. *Progress in Polymer Science*, 117, 101395.
- Yadav, S., & Mishra, S. (2023). Moisture sorption isotherms and storage study of spray-dried probiotic finger millet milk powder. *Journal of Stored Products Research*, 102(November 2022), 102128. <https://doi.org/10.1016/j.jspr.2023.102128>
- Yang, L., Xin, W., Ping, J., & Xing-jun, L. (2016). Sorption equilibrium moisture and isosteric heat of adsorption of Chinese dried wheat noodles. *Journal of Stored Products Research*, 67, 19–27. <https://doi.org/10.1016/j.jspr.2016.01.007>
- Yazdani, M., Sazandehchi, P., Azizi, M., & Ghobadi, P. (2006). Moisture sorption isotherms and isosteric heat for pistachio. *European Food Research and Technology*, 223(5), 577–584. <https://doi.org/10.1007/s00217-006-0256-6>
- Yogendrarajah, P., Samapundo, S., Devlieghere, F., De Saeger, S., & De Meulenaer, B. (2015). Moisture sorption isotherms and thermodynamic properties of whole black peppercorns (*Piper nigrum* L.). *LWT-Food Science and Technology*, 64(1), 177–188. <https://doi.org/10.1016/j.lwt.2015.05.045>