IRA-International Journal of Applied Sciences
ISSN 2455-4499; Vol.21, Issue 02 (Q2. 2026)
Pg. no. 55-70.
IRA Academico Research

Influences of Intermittent Drying on Local Fruits: The Case of Mangoes, Bananas, Potatoes, and Sweet Potatoes

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Type of Work: Peer Reviewed.
DOI: https://dx.doi.org/10.21013/jas.v21.n2.p2

Review history: Submitted: February 26, 2026; Revised: March 18, 2026; Accepted: May 13, 2026.

How to cite this paper:
Sidwaya, S. E., Tiendrebeogo, S. E., Tubreoumya, G. C., Windnigda, Z., Batiana, A. L., & Zerbo, D. (2026). Influences of Intermittent Drying on Local Fruits: The Case of Mangoes, Bananas, Potatoes, and Sweet Potatoes. *IRA-International Journal of Applied Sciences* (ISSN 2455-4499), 21(2), 55-70. https://dx.doi.org/10.21013/jas.v21.n2.p2

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This paper is peer-reviewed under IRA Academico Research's Peer Review Program.

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ABSTRACT

In the context of promoting local agricultural products in the face of significant post-harvest losses in West Africa, optimizing drying methods is a key challenge. This research explores the impact of various intermittent drying regimes applied to four fresh products, namely mangoes (Mangifera indica), bananas (Musa sapientum), potatoes (Solanum tuberosum), and sweet potatoes (Ipomoea batatas) from the market in Ouagadougou (Burkina Faso). The objective is to evaluate the influence of intermittent drying kinetics on product quality. The samples, with an average unit mass between 150 and 350 g, were dried in an oven at 50°C, according to intermittent regimes varying from $\alpha = 1/2, 1/3, 1/4, 2/3$, and $3/4$ (drying time/rest time ratio). The reduced moisture content curves were obtained and the drying rate calculated. The drying time was shortened by 50%. The results indicate that for intermittent treatment, $\alpha = 1/2$ for bananas, sweet potatoes, and potatoes, and $\alpha = 3/4$ for mangoes, allows hygroscopic equilibrium to be achieved. The Langmuir and Peleg models were used to analyze the desorption isotherms. Peleg showed the best fit for bananas ($R^2 = 0.98394$; RMSE = 0.00272), while Langmuir proved more effective in describing mangoes ($R^2 = 0.99708$; RMSE = 0.00557), sweet potatoes ($R^2 = 0.99825$; RMSE = 0.00078), and potatoes ($R^2 = 0.9989$; RMSE = 0.00303) in a range of water activity from 20 to 88%. These results indicate that intermittent drying accelerates the drying of fruits and tubers while preserving their physical, structural, and nutritional qualities.

Keywords: Intermittent drying, product quality, desorption isotherms, moisture content, drying kinetics.

1. Introduction

The drying of food products is an essential method for developing countries that depend mainly on agriculture for their food self-sufficiency. It is defined as the removal of moisture from a material or substance following a decrease in water activity. This can delay the rate of degradation and prolong the preservation of a quality product [1]. Food processes use significant amounts of labor, machinery, and energy to convert edible raw materials into higher-value food products. Due to rising energy prices and efforts to reduce greenhouse gas emissions, it has become important to improve energy efficiency, replace energy-intensive operations with new ones, and increase the use of renewable energy in the food industry [2]. Many researchers have studied drying techniques with the aim of preserving food products:

Mohammad Kamruzzaman and al. [3] proposed a thorough review of intermittent food drying that highlights the nutritional and quality benefits compared to continuous drying. However, only drying phenomena and hygroscopic properties are addressed.

Mongui [4] assessed the thermal performance of solar drying systems for mango, banana, and tomato by examining the drying chemistry and the biochemical quality of the dried products. However, this study focuses on continuous regime operation. The intermittent drying behavior and the desorption isotherm characteristics were not addressed.

Antonio Calín-Sánchez and al. [5] compared various traditional and innovative methods of fruit and vegetable drying, including solar drying, without including intermittent drying or desorption modeling for the study of hydrological stability.

Baltacioglu and al. [6] examined the sorption and hydrostatic phenomena during the continuous solar drying of menthe leaves without addressing the case of intermittent regimes.

Intermittent drying has been considered one of the most energy-efficient drying processes [3,7,8] even improving the quality of dried products [9].This approach is based on alternating active drying periods with rest periods, allowing moisture to be redistributed within the products [10].

The analysis of the previous studies reveals that the impact of the intermittent regime on the drying kinetic of tropical products is still largely underexplored. This study was conducted within this framework, with the overall goal of analyzing the impact of the intermittent drying regime on the drying kinetic and desorption isotherms of four tropical products: mangoes (Mangifera indica), bananas (Musa sapientum), potatoes (Solanum tuberosum), and sweet potatoes (Ipomoea batatas). This study approach, which combines the use of different intermittent regimes, and type of products (fruits and tubers) provides a better understanding of the influence of the intermittent drying on the drying kinetic and the desorption isotherms of these tropical products.

2. Materials and Methods

2.1. Experimental Materials

This study used a variety of local mangoes, bananas, sweet potatoes, and potatoes as plant material sourced from market gardens in various regions of BURKINA FASO. The products used were sourced from the fruit market in Ouagadougou, the capital of Burkina Faso. The average unit weight of the different products is around 300 g, 350 g, 250 g, and 150 g for mangoes, bananas, sweet potatoes, and potatoes, respectively, with an average water content of 86%, 70%, 68%, and 80%, respectively.

The experimental apparatus comprises a MEMMERT UFP 600 oven (**Figure 1.a**) with forced convection containing four racks on which the products to be dried are placed at a temperature of 50°C.

Weighings are performed every half hour using a precision electronic scale accurate to 0.01 g (**Figure 1.b**), until the mass between three consecutive weighings is almost constant.

To facilitate the aeration of the products during the resting phase, a ventilation system equipped with four SYNON fans (**Figure 1.c**), arranged in series and operating at constant speed, was installed.

An X-SENSE smart thermohygrometer, type STH51, SBS50 (**Figure 1.d**), is used at various locations (oven air outlet, oven air inlet, and room ambient conditions) to measure the relative humidity of the air.

a. *Oven MEMMERT UFP 600 type STH51, SBS50*

b. *Precise electronic scale at 0,01 g*

c. *Ventilation system ; SYNON*

d. *X-SENSE smart*

Figure 1 : Experimental equipment

2.2. Experimental method

2.2.1. Sample preparation

The products are washed with water before being peeled and cut to the desired size and shape, then weight to obtain their initial mass. The bananas were sliced into thin rounds approximately 0.3 to 0.5 cm thick (**Figure 2.a**). The potatoes are thoroughly washed to remove all traces of soil or plant residue, then peeled and cut into thin slices with an average thickness of between 2 and 3 mm (**Figure 2.b**). In the case of sweet potatoes**,** the first phase of the process involves selecting white sweet potatoes in good condition. The tubers are thoroughly rinsed with water to remove soil, residue, and unwanted substances. They are sliced into thin rounds between 0.1 and 0.12 inches thick (**Figure 2.c**). The mangoes are first washed, then rinsed under running water to remove any impurities that may be on their surface. They are peeled, pitted, and cut into medium slices approximately 3 to 4 mm thick (**Figure 2.d**).

The mesured sample of each product was then placed on the drying rack, without overlapping to ensure adequate air circulation around each piece**.** During the experiment, the environmental conditions in the room where the dryer is located are: an average temperature of 33°C and an average relative humidity of 48 to 50%. The oven is therefore set to a constant temperature of 50°C for all four products.

a. *Bananas (Musa sapientum)*

b. *Potatoes (Solanum tuberosum)*

c. *Sweet potatoes (Ipomoea batatas*

d. *Mangoes (Mangifera indica)*

Figure 2 : The experimental samples

2.2.2. Test conditions

The experimental device is started up by activating the heating system until a set temperature of 50°C is reached. The products to be dried are then placed on a sliding support grid designed to allow air to circulate both above and below the samples. The products are spread out in a thin layer and oriented parallel to the direction of the hot air flow to ensure uniform drying. The drying is carried out intermittently by controlling the supply of thermal energy. This intermittency is achieved by modulating the operating conditions of the oven, in particular the temperature of the drying air and the periods of hot air supply. The drying cycle consists of a heating phase, during which the products are exposed to hot air, followed by a pause phase during which the products are removed from the oven and exposed to ambient conditions. During the experiment, the mass of the samples is measured at regular intervals in order to monitor the evolution of the drying kinetics, both during the heating phases and during the pause phases. These measurements make it possible to analyze the influence of the intermittent regime on the mass loss and drying behavior of the products. Weighing is performed every 60 minutes. The different intermittent drying regimes of the four products are recorded in **Table 1**.

Table 1: different values of α for experimenting with intermittent drying of mango, banana, potato, and sweet potato at 50°C

Intermittence α	**Drying period τ_{on} (minutes)**	**Off period τ_{off} (minutes)**	**Cycle duration (minutes)**
1/2	60	60	120
1/3	60	120	180
1/4	60	180	240
2/3	120	60	180
3/4	180	60	240

Where α is defined as the ratio between the duration of hot air supply during a cycle and the total duration of the drying cycle as expressed in **Equation(1)** [11,12].

$$\alpha = \frac{\tau_{on}}{\tau} = \frac{\tau_{on}}{\tau_{on} + \tau_{off}} \tag{1}$$

2.3. Determination of drying kinetics in intermittent mode

Once the drying equilibrium has been reached, the samples are then placed in an oven at 105°C for 24 hours to determine their dry masses m_s. The equilibrium moisture content of the sample products is determined by:

$$X_{eq} = \frac{m_{eq} - m_s}{m_s} \tag{2}$$

Where $\boldsymbol{m_{eq}}$, $\boldsymbol{m_s}$ represent the equivalent mass of the product and the dry mass of the product, respectively. The reduced moisture content, a dimensionless quantity, is obtained using the equation below:

$$Xr = \frac{m(t)}{m_i} \tag{3}$$

or $\boldsymbol{m_i}$, $\boldsymbol{m(t)}$ is the mass of the product at the initial time and at time t, respectively (in g). The drying rate is calculated using the equation below :

$$\frac{dX}{dt} = \frac{X_t - X_{t+dt}}{\Delta t} \tag{4}$$

Where **t** = drying time(min) ; $\mathbf{X_t}$ = reduced moisture content at time *t* and $\mathbf{X_{t+dt}}$ = reduced moisture content at *t+dt*

2.4. Desorption isotherms of products under intermittent conditions

Sorption isotherms illustrate the relationship between the water content of a product and water activity at a specific temperature. Numerous studies have documented the determination of desorption isotherms for agri-food products. However, research on the determination of desorption isotherms in intermittent conditions for bananas, mangoes, sweet potatoes, and potatoes remains very limited.

2.4.1. Experimental method for desorption isotherms

To experimentally establish the desorption isotherms of these products under intermittent conditions, we use the static gravimetric technique at a constant temperature of 50°C. This technique guarantees uniform relative humidity in the product environment at a specific temperature. In order to obtain the desorption isotherm points, the samples are weighed in advance before being placed in the oven. The different products are displayed as shown in **Figure 3**.

a. Potatoes *b. Bananas*

c. mangoes d. *sweet potatoes*

Figure 3 : The arrangement of the products on the drying racks

At regular intervals, weighings are carried out every hour using an electronic scale accurate to 0.01 g, until the difference in weight between three consecutive measurements is virtually imperceptible. Once equilibrium is reached, the samples are placed consecutively in an oven at 105°C for 24 hours to establish their dry mass. The moisture content of a moist product located in an atmospheric environment with stable relative humidity tends toward hygroscopic equilibrium. Hygroscopic equilibrium is considered to be achieved when the product no longer undergoes any change in mass, which means that the water activity of the product corresponds to the relative humidity of the air. [13].

2.4.2. Theoretical framework for desorption isotherms

For the study of intermittent desorption isotherms of the products, eight theoretical models from the literature were used to interpret the sorption curves obtained [14]. These models are presented in **Table 2**.

Table 2 : Theoretical models of water content as a function of water activity

Models	*Equations*	*Models Parameters*	*References*
HENDERSON	$X_{eq} = \left(\frac{-\ln(1-A_W)}{A} \right)^{\frac{1}{B}}$	*A, B*	[15]
GAB	$X_{eq} = \frac{X_m CKA_w}{(1-KA_w)(1-KA_w+CKA_w)}$	X_m, *C et K*	[16]
OSWIN	$X_{eq} = A\left(\frac{A_w}{1-A_w} \right)^B$	*A, B*	[17]
BET	$X_{eq} = \frac{X_m CA_w}{(1-A_w)(1-A_w+CA_w)}$	X_m *et C*	[18]

PELEG	$X_{eq} = K_1 A_w^{n1} + K_2 A_w^{n2}$	K_1, K_2, n_1, *et* n_1	[19]
HASLEY	$X_{eq} = \left(\frac{A}{\ln\left(\frac{1}{A_w}\right)} \right)^{\frac{1}{B}}$	*A, B*	[20]
LANGMIR	$X_{eq} = \frac{1}{A + BA_w^{\frac{1}{C}}}$	*A, B et C*	[21]
IGLESIAS	$X_{eq} = A + B\left(\frac{A_w}{1 - A_w} \right)$	*A, B*	[22]

The theoretical analysis of desorption isotherms requires the use of statistical techniques such as regression and correlation. To choose the best equation that takes into account variations in the drying curves of the samples, we used the correlation coefficient R^2 and the root mean square error (RMSE) as the main criteria. [23]. The values calculated for the models were used to determine the quality of the fit.

- For the correlation coefficient R:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (X_{i,\exp} - X_{i,pre})^2}{\sum_{i=1}^{n} (\overline{X_{pre}} - X_{i,pre})^2} \qquad (5)$$

- Root mean square error RMSE:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_{i,pre} - X_{i,\exp})^2} \qquad (6)$$

Or $X_{i,exp}$; $X_{i,pre}$ represents the ratio between the experimental and predicted moisture content values, and n is the number of observations [23].

3. Results and Discussion

3.1. Change in reduced moisture content of the products under continuous and intermittent conditions at 50°C

Error! Reference source not found. show the evolution of reduced moisture content (Xr) of mangoes, bananas,potatoes, and sweet potatoes over time under continuous and the five intermittency regimes : α = 1/2, 1/3, 1/4, 2/3 and 3/4 with relative humidity between 60 and 78%.Tests conducted at a temperature of 50°C reveal different kinetic behaviors depending on the intermittent rate used.

Overall, in terms of drying kinetics, continuous drying appears to be more effective for tubers (sweet potatoes and potatoes) and fruits (bananas and mangoes). Optimized intermittent drying (1/2 for tubers and bananas, 3/4 for mangoes) prolongs total drying by stimulating moisture redistribution through internal diffusion (Fick's law) and capillary forces during the stop phases, counteracting diffusive blockage and the crusting phenomenon observed in continuous drying after hygroscopic equilibrium, thus avoiding cracks and excessive shrinkage, particularly for mangoes with low porosity. This strategy improves the final quality of the products. In terms of energy efficiency, it reduces consumption by 30-50% and shortens the overall time. In the case of mangoes, they have high but irregular porosity during drying, which makes diffusion more complex. Studies have shown that the high sugar concentration in the fruit complicates moisture removal and slows down the process of achieving the desired final moisture content [24]. To overcome this resistance, mangoes are subjected to more continuous drying, which gives them sustained energy to compensate for the effect of sugars. The same phenomena were observed in the study conducted by FOKONE and al. [25] on the "Amélie" mango, which has an optimal reduced water content for $\alpha=3/4$. For bananas, it have a softened cell structure and undergo a significant transformation of starch into soluble sugars, which causes tissue softening and promotes the diffusion of internal water to the outside [27].

Unlike fruit, which has a high internal resistance to diffusion due to the presence of sugar, tubers have a low resistance to water vapor diffusion due to their starch content [30-31]. As a result, when heated continuously, these types of products are susceptible to surface crusting, which blocks water vapor diffusion inside the product. Intermittent operation helps prevent this phenomenon by supporting uniform water vapor distribution from very humid areas to less humid areas, promoting efficient drying. The results that identify $\alpha = 1/2$ as the ideal intermittence ratio for peeling pears are consistent with those obtained by Polat et al. [27], who demonstrated that with a PR = 2 ($\alpha = 1/2$), a satisfactory balance between energy efficiency, color preservation, and internal structure is reached, with less microstructural degradation compared to $\alpha = 1/3$ or $\alpha = 1/4$. Furthermore, Kumar et al. [3] have shown that the intermittence rate $\alpha = 1/2$ is the effective rate that has been suggested by several authors in the context of intermittent scheduling.

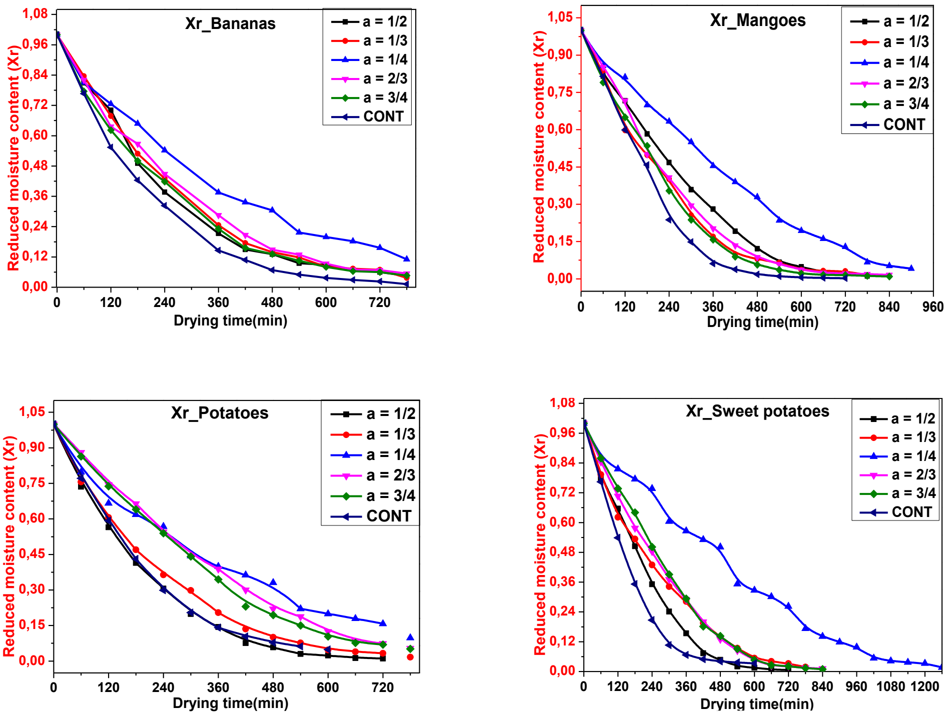


Figure 4 : The evolution of the reduced moisture content under continuous and intermittent regime

3.2. Evolution of drying rate for the continuous and the optimal intermittent regime at 50°C

Figure 5 illustrates the progression of the drying rate for both continuous and intermittent drying processes, as well as for a range of elementary cycles and drying air temperatures. Generally speaking, when the drying air temperature rises throughout each phase, the drying rate increases as well, indicating the intensification of heat and mass transfer.

Surface moisture is rapidly removed as soon as drying resumes following each intermittent drying-specific rest interval. As a result, the drying rate increases noticeably just after each rest period (**Figure 5**). This tendency is attributable to the transfer of moisture from the core of the material to the surface during the rest periods, a phenomenon usually referred to as the quenching effect. During the active phases, this redistribution encourages more effective evaporation and lessens internal water content gradients.

Furthermore, the ability to better control the items' surface time, six complete cycles for bananas and tubers, and four cycles for mangoes. This research implies that intermittent drying leads in a lower ultimate water content than continuous drying. For tubers (α = 1/2), slow diffusion is associated with high density and low porosity [28]. Bananas (α = 1/2) have a low sugar content, which maintains optimized drying similar to tubers. For mangoes, α = 3/4, their high sugar content causes vitrification, requiring prolonged cycles [24]. As a result, intermittent drying works better in terms of drying kinetics and the quality of the finished product. These results are consistent with observations conducted by Váquiro and al. [31], Fokone and al.[26].

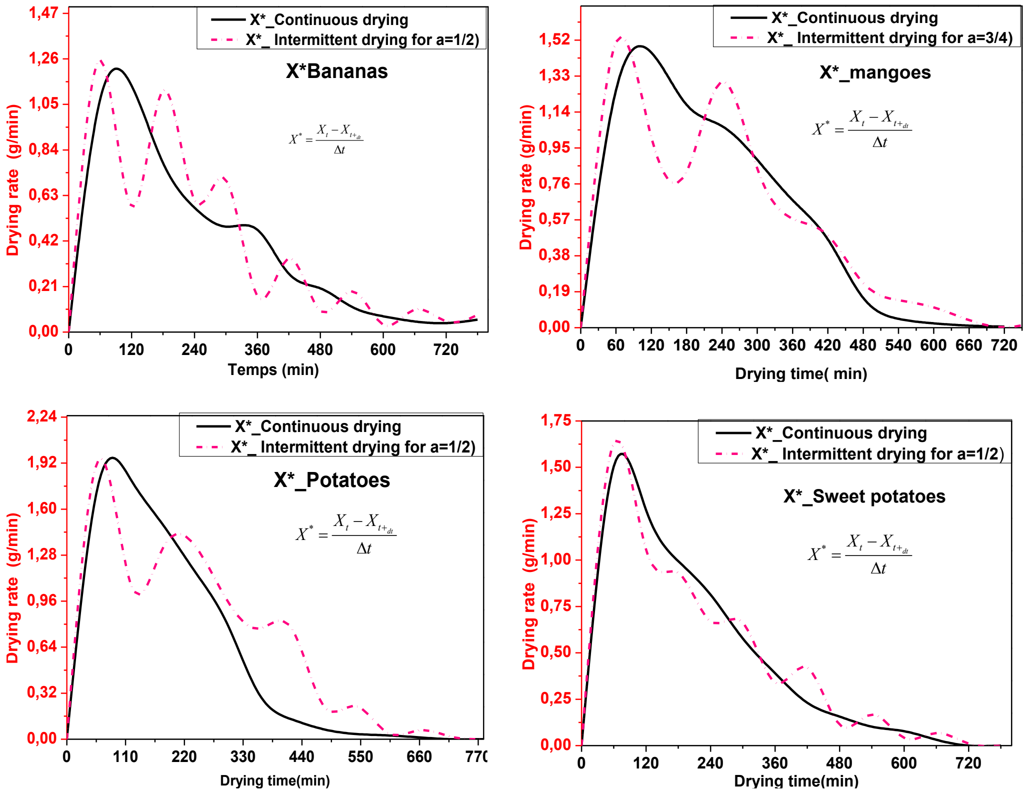
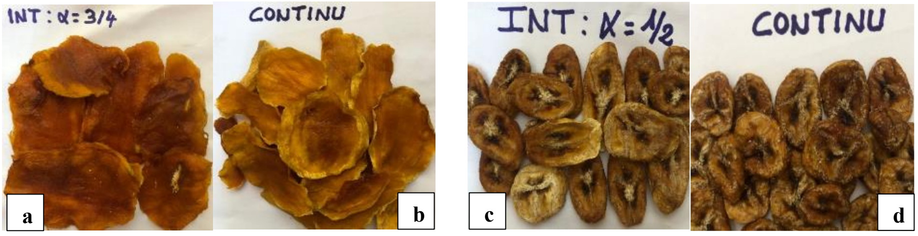


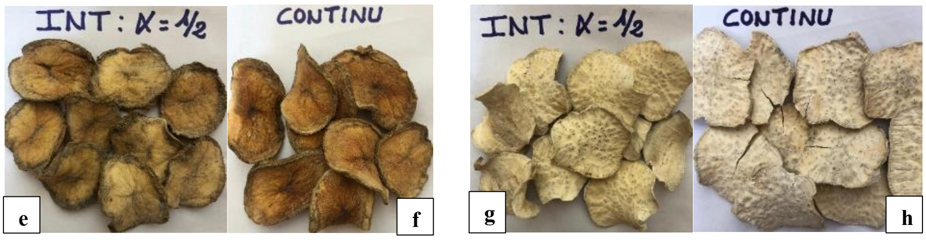
Figure 5 : Drying rate for the optimal intermittent and continuous drying

3.3. Analysis of the texture of dried products

To understand the impact of the drying method (intermittent or continuous) on product quality, it is necessary to perform a textural analysis of the dried samples. As shown in **Figure 6**, intermittently dried products have a superior texture and visual qualities compared to those dried continuously. This is because intermittent drying preserves the cellular structure and porosity of the products. As a result, they are less rigid, more flexible, fairly brittle, and easier to chew, with a soft and elastic texture. In contrast, continuous drying causes considerable shrinkage, densification of the material, and hardening of the surface, making the products more rigid, brittle, or overly crispy, and less appetizing to eat. Furthermore, although continuous drying accentuates the appearance of dark colors, often associated with organoleptic degradation and an impression of lower quality, intermittent drying preserves a color closer to that of the fresh product by reducing browning. Intermittent drying preserves a color closer to that of the fresh product by reducing browning.



Texture of dried mangoes *Texture of dried bananas*



Texture of dried potatoes *Texture of dried sweet potatoes*

Figure 6 : Texture of different products under continuous and intermittent regimes

3.4. Evolution of the desorption isotherm of the studied products

The relevance of the Peleg and Langmuir models for representing product desorption isotherms was assessed by comparing performance indicators, including the coefficient of determination R^2 and the root mean square error (RMSE). As indicated in **Table 3**, Peleg model proved to be the best for smoothing bananas isotherms ($R^2 = 0.98394$ and RMSE = 0.00272) for relative humidities ranging from 20 to 86%, while Langmuir model performed better for mangoes, sweet potatoes, and potatoes ($R^2 = 0.99708$ and RMSE = 0.00557 for mango, $R^2 = 0.99825$ and RMSE = 0.00078 for potatoes, and finally $R^2 = 0.9989$ and RMSE = 0.00303 for potatoes) with relative humidities ranging from 20 to 88%.

These results are based on the ability of Peleg model to illustrate sorption processes within complex biological matrices [30], whereas Langmuir's model, originally designed for homogeneous adsorbates, appears more appropriate for systems exhibiting monolayer saturation [31]. These results are consistent with various authors in the scientific literature using sorption models depending on the type of product [13,14,32]. Subsequently, Jin Park and al. [33] showed that Peleg model provided a better fit for the desorption of mint leaves from gardens at temperatures of 40 and 50°C. Lankouande [14] confirms good smoothing of the tomato desorption curves using Peleg's model at different temperatures (25, 40, and 50°C). In summary, examination of the desorption isotherms demonstrated that the Peleg and Langmuir models are ideally suited to the data obtained from the experiments. Several researchers have proven the effectiveness of Peleg's model, which can be adapted to various aquatic activities, in representing the hygroscopic behavior of the products studied. These results corroborate the suitability of these models for accurately modeling the desorption process in food materials.

Table 3 : Estimated parameter values for various models

Products	**Bananas**			**Mangoes**			**Swett potatoes**			**Potatoes**		
Models	R^2	RMSE	Parameter	R^2	RMSE	Parameter	R^2	RMSE	Parameter	R^2	RMSE	Parameter
HENDERSON	0.9747	0.00428	A= 1.63447 B= 0.58401	0.95254	0.09053	A= 0.9331 B= 0.5085	0.977	0.01039	A= 1.3557 B= 0.4842	0.9583	0.11877	A= 0.80558 B= 0.53525
GAB	0.97342	0.0045	Xm=18.008 C= 0.01262 K= 0.77932	0.93859	0.11714	Xm=127.9 C=0.0040 K=0.8241	0.96571	0.01549	Xm=-13.928 C=-0.01589 K=0.83847	0.9454	0.15527	Xm=131.949 C=0.00549 K=0.80476
OSWIN	0.95394	0.00779	A=0.25146 B=0.94445	0.91808	0.15626	A=0.62844 B=1.06902	0.95122	0.02204	A=0.28699 B=1.11717	0.9228	0.21986	A=0.8329 B=1.02651
BET	0.95194	0.00813	Xm=0.2259 C=1.15898	0.92153	0.14969	Xm=0.7740 C=0.63776	0.95465	0.02048	Xm=0.39927 C=0.53454	0.9248	0.2142	Xm=0.92026 C=0.76354
PELEG	0.98394	0.00272	K1=0.0186K2=2.4068 n1=-1.1200 n2=3.958	0.9802	0.03777	K1=3.9882K2=3.9882n1=4.21379 n2=4.21681	0.99495	0.00228	K1=2.06172 K2=2.06172 n1=4.47674 n2=4.47653	0.9866	0.03794	K1=4.62433 K2=4.62433 n1=3.90707 n2=3.90707
LANGMIR	0.98003	0.00338	A=-0.2326 B=0.6177 C=3.05671	0.99708	0.00557	A=0.16866 B=0.02638 C=7.2857	0.99825	0.00078	A=0.18287 B=0.12758 C=5.71813	0.9989	0.00303	A=0.12306 B=0.03247 C=6.05032

4. Conclusion

In summary, the results show that the intermittent drying process is crucial for regulating the rate of dehydration, the inter-nal distribution of moisture, and the final quality of the product. The drying behavior consistently showed two distinct phases: first, rapid removal of free water, followed by a phase regulated by diffusion. Furthermore, the ideal intermittent ratio was linked to the structure of the product. For bananas, sweet potatoes, and potatoes, a regime of $\alpha = 1/2$ at 50°C proved to be the most effective. In contrast, mangoes require a higher ratio of $\alpha = 3/4$ to ensure better internal moisture regulation given their fibrous structure. The significant correspondence between experimental data and sorption modeling also reveals that intermit-tent drying has a significant impact on desorption isotherm curves. The Peleg model accurately illustrates the behavior of bananas, while the Langmuir model is more suitable for describing the reactions of mangoes, sweet potatoes, and potatoes over a wide range of water activity (20 to 88%). In addition to moisture removal, the process significantly improves textural properties such as hardness, brittleness, and chewiness, highlighting the structural influence of drying irregularity. Overall, this research establishes a clear connection between drying dynamics, sorption patterns, and textural changes in intermittent con-texts. It provides a robust scientific foundation for refining drying methods that increase efficiency while maintaining the structural and physicochemical quality of tropical food products in industrial and domestic settings.

Conflict of interest

No conflict of interest to disclose.

Acknowledgments

The authors express their gratitude to all the staff of the Laboratory of Environmental Physics and Chemistry at Joseph KI-ZERBO University, as well as to Mr. Tiendrebéogo S. Eloi of the Physics departement, High school of Education (Burkina Faso). They also thank the entire team for their decisive contribution to the success of this study.

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