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Numerical and experimental study of the intermittent drying method applied to green banana slices dehydration

Abstract*– Drying is a traditional and widely used method for extending the shelf life of perishable fruits by reducing moisture content to levels that inhibit microbial growth and biochemical deterioration. Conventional continuous drying methods, while effective, often involve prolonged exposure to high temperatures, leading to high energy consumption and potential quality loss due to surface burning or carbonization. Intermittent drying, which alternates heating and resting phases, has emerged as a promising alternative that enhances energy efficiency and preserves product quality by allowing moisture to redistribute within the fruit during off periods. This technique is particularly suitable for fruits like bananas, which have high initial moisture content and are sensitive to heat-induced degradation. In this study, intermittent drying of bananas was conducted using a tray dryer under controlled conditions. Key parameters such as inlet and outlet air psychrometric properties, drying time, and energy consumption were measured. Drying kinetics were modeled using Fick's diffusion law to describe moisture transfer during the process. The results demonstrated that intermittent drying reduces overall energy consumption and mitigates the risk of surface overheating compared to continuous drying. Additionally, this method helps maintain important nutritional components, such as carotene, by minimizing thermal damage. The findings contribute valuable insights into optimizing drying processes for bananas, a fruit with significant global consumption and post-harvest losses. By improving energy efficiency and product quality, intermittent drying supports sustainable food preservation practices and aligns with efforts to reduce energy use and enhance food security worldwide.

Keywords-- Intermittent Drying, Continuous Drying, Energy Efficiency, Fick's Law, Heat Transfer

I. INTRODUCTION

Drying is a fundamental process in food preservation that involves the partial removal of moisture from foodstuffs, while dehydration refers to achieving a completely dry state. This physical process plays a crucial role in stabilizing fruits, effectively preventing deterioration caused by biological changes such as enzymatic activity and microbial growth. The primary objectives of drying are to extend the storage life of products, reduce their weight and volume, and ultimately lower transportation costs while improving handling efficiency.

Moisture within fruits is primarily eliminated through two mechanisms: capillary action and diffusion. Capillary action facilitates the movement of water through the cell cavities, allowing moisture to flow toward the surface. Concurrently, diffusion enables moisture to migrate from areas of higher concentration within the fruit to areas of lower concentration at the surface. This dual mechanism is essential for effective drying, as it ensures that moisture is removed efficiently from the interior of the fruit [1].

Fruits are susceptible to decay due to various biochemical reactions, enzymatic processes, and microbial growth, all of which are significantly influenced by water content. The presence of moisture not only supports microbial proliferation but also contributes to chemical spoilage through non-enzymatic browning reactions [2]. Consequently, drying industrial edible products is critical in food processing; however, a substantial proportion of annual agricultural production is lost due to inadequate processing methods. In developing countries, losses can reach as high as one-third of total production, highlighting the need for improved drying techniques.

The drying process is inherently energy-intensive, prompting researchers and practitioners to develop methods aimed at reducing energy consumption while addressing concerns related to global warming. One promising approach that has emerged in recent years is intermittent drying. This method is particularly advantageous for materials experiencing a decreasing falling rate period during drying. Intermittent drying has been shown to enhance carotene content in dried fruits, thereby improving their nutritional quality.

Intermittent drying involves varying drying conditions over time, including humidity, air temperature, and pressure, which can be achieved by controlling the supply of thermal energy. The primary goal of this technique is to facilitate moisture transfer from the center of the fruit to its surface while minimizing damage to the sample. A common implementation of this method is the ON/OFF type of intermittency, which introduces tempering periods that help equalize internal moisture content and temperature throughout the material [3].

Air temperature plays a significant role in determining product quality during the drying process. Higher temperatures can reduce drying time but may also cause surface damage and increase energy consumption. Conversely, lower temperatures may enhance product quality but result in prolonged drying times. Therefore, optimizing temperature settings is crucial for achieving an ideal balance between efficiency and product integrity.

In summary, understanding the principles and mechanisms underlying the drying process is essential for improving food preservation techniques. As this study investigates intermittent drying methods for bananas using tray dryers under current operational conditions, it aims to contribute valuable insights into optimizing energy efficiency while maintaining product quality in food processing applications.

II. MATERIALS AND METHODS

Next, we will detail the various activities conducted during the experimental phase of this research focused on the banana drying process. The study utilized green silk bananas, which were sliced into discs approximately 5 cm in diameter and 0.3 cm thick. This specific slicing dimension was chosen to ensure uniform drying and facilitate effective moisture removal during the drying process. After slicing, the banana samples were placed in Petri dishes to maintain their integrity before being transferred to a desiccator for initial moisture assessment.

A random selection of these samples was then taken to a moisture balance, which allowed for precise determination of the initial moisture content present in the fruit. This measurement is critical as it establishes a baseline for evaluating the effectiveness of the drying process. The remaining samples were subsequently placed in the dryer, strategically positioned at three distinct levels: high, middle, and low zones within the drying chamber. This arrangement was designed to assess the impact of varying airflow and temperature distribution on the drying efficiency across different sample locations.

Prior to introducing the banana slices into the dryer, it was essential to ensure that the equipment had reached a stable operating condition with the desired temperature settings for each test. The dryer was preheated and maintained at a constant temperature, controlled through a PID (Proportional-Integral-Derivative) controller, which ensures precise regulation of temperature and humidity levels throughout the drying process.

In addition to calibrating the Arduino sensors for accurate temperature and humidity measurements, experimental tests were conducted for both continuous and intermittent drying methods at temperatures of 50 °C and 60 °C. The continuous drying process at 50 °C resulted in complete drying within approximately 10 hours, while at 60 °C, this was achieved in about 8 hours. In this continuous mode, the dryer remained operational throughout the entire duration of the process to facilitate consistent moisture removal.

Conversely, intermittent drying at 50 °C achieved moisture removal in roughly 9 hours, while at 60 °C, it took about 7 hours. This method involved a cycle where the dryer operated for two hours followed by an hour of inactivity until the desired dryness was attained. The ON/OFF cycling is particularly advantageous as it allows for periods of moisture redistribution within the product, potentially enhancing overall quality.

Figure 1 illustrates the experimental setup utilized in this investigation. The equipment comprises an air conditioning system designed to regulate ambient conditions within the dryer, a temperature probe for monitoring internal temperatures accurately, and an electrical panel that oversees overall system performance. Additionally, a PID controller is integrated into the system to manage temperature fluctuations effectively and maintain optimal drying conditions throughout each trial.

The methodologies employed in this research not only aim to optimize drying efficiency but also focus on preserving product quality by minimizing thermal damage during processing. By systematically investigating these parameters, this study seeks to contribute valuable insights into effective banana drying techniques that can be applied in both industrial and small-scale settings.

Fig. 1. Tray dryer.

The Solidworks Flow Simulation add-on is used to observe the air path through the drying chamber when the stainless steel plates are installed, which can be seen in Fig. 2.

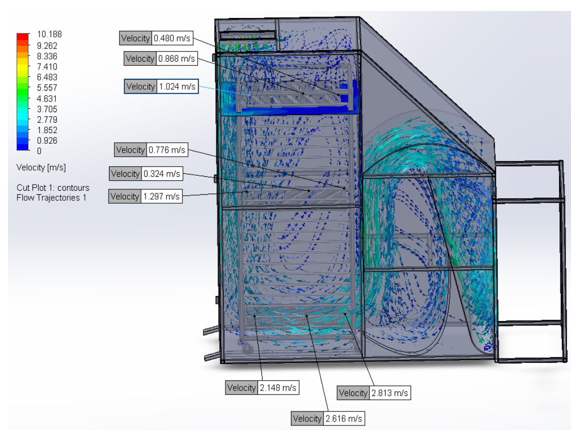


Fig. 2. Simulation of air in the dryer with steel plates in Solidworks Flow Simulation.

The weight data obtained experimentally is expressed as the moisture on a dry basis as stated in Eq. (1).

$$MR = \frac{X_t - X^*}{X_0 - X^*} \quad (1)$$

After converting and plotting the data in a moisture ratio (RM) versus time diagram, a regression analysis is conducted to model the drying kinetics using empirical expressions based on Fick's law. As indicated in [4], the optimal fitting models for banana drying are presented in Table 1.

TABLE 1
MATHEMATICAL MODELS UTILIZED FOR THE KINETICS OF BANANA DRYING

N°	Model name	Model
1	*Newton*	$MR = e^{-kt}$
2	*Two terms*	$MR = ae^{-k_0 t} + be^{-k_1 t}$
3	*Simplified Fick Diffusion*	$MR = ae^{\left[-c\left(\frac{t}{L^2}\right)\right]}$
4	*Henderson & Pabis*	$MR = ae^{-kt}$
5	*Page Modified II*	$MR = e^{\left[e^{-c\left(\frac{t}{L^2}\right)}n\right]}$
6	*Page*	$MR = e^{[-kt^n]}$
7	*Page Modified I*	$MR = e^{(-(kt)^n)}$
8	*Page Modified III*	$MR = ae^{[-kt^n]}$
9	*Wang & Singh*	$MR = 1 + at + bt^2$
10	*Peleg*	$MR = 1 - \frac{t}{a + bt}$
11	*Silva et al.*	$MR = ae^{[-at-b\sqrt{t}]}$
12	*Midillini et al.*	$MR = ae^{[-kt^n]} + bt$
13	*Logarithmic*	$MR = ae^{[-kt]} + c$
14	*Fick Diffusion Approximation*	$MR = ae^{-kt} + (1-a)e^{-kt}$

Another critical parameter in the analysis of drying kinetics is the determination of effective diffusivity (Deff). This is achieved through the application of Fick's second law, which is articulated in the following equation (Eq. (2)).

$$\frac{\partial X}{\partial t} = D_{eff} \frac{\partial^2 X}{\partial x^2} \quad (2)$$

The solution to the aforementioned equation is derived using Crank's method, which assumes a thin film model characterized by an initially uniform moisture distribution, constant diffusivity, and negligible shrinkage. This is represented by Equation (3).

$$MR = \frac{8}{\pi^2} \sum_n^{\infty} \frac{1}{(2n1)^2} * \exp\left[\frac{-(2n1)^2 \pi^2 D_{eff} t}{4H^2}\right] \quad (3)$$

Assuming that the time is very long, the first term of the summation can be considered, leaving us with the following expression of Eq. (4).

$$MR = \frac{8}{\pi^2} \exp\left[\frac{-(2n1)^2 \pi^2 D_{eff} t}{4H^2}\right] \quad (4)$$

From this, using the Arrhenius Eq. (5), the activation energy, which expresses the dependence of the effective diffusivity of moisture on temperature, can be calculated.

$$D_{eff} = D_0 e^{\left(\frac{-Ea}{R(T+273.15)}\right)} \quad (5)$$

The coefficient of determination (R2) serves as the primary criterion for selecting the mathematical model that best describes the experimental data obtained during the drying process of banana slices. This metric reflects the proportion of variance in the dependent variable that can be explained by the independent variable. A value of R2 closer to 1 indicates a superior fit of the model to the response variable.

$$R^2 = \frac{\left[\sum_1^n MR_{exp} * MR_{calc}\right]^2}{\sum_1^n MR_{exp}{}^2 * MR_{calc}{}^2} \quad (6)$$

III. Analysis and Results

Tests for moisture determination were carried out with the Ohaus model MB200 moisture balance. A portion of the samples of the material to be dried in the tray dryer was selected at random and then taken to the moisture balance. This procedure allows us to state with greater certainty that the remaining samples, subjected to drying in the dryer, will present a similar moisture content to the samples evaluated on the moisture balance. [1] recommends a constant and controlled heating temperature of 105–110 °C, where the change in weight of the sample will be continuously recorded throughout the process until a constant weight is reached. Taking the average of all the tests, an initial moisture content of 72±0.84% was obtained. Table 3 below shows the average for each of the 50 °C and 60 °C tests.

These results agree with [5], who state that bananas contain approximately 74% moisture on a wet basis. Other authors [6], using the AOAC 925.45 method, obtained that the Luvhele variety banana has an initial moisture content on a wet basis of 78.73%. On the other hand, authors such as [7] present an initial moisture content of 57.23% moisture on a wet basis and [8], for the Simmonds variety, found that the moisture content of plantain on a wet basis was 66.2%. This is because different varieties of plantain present their own moisture content and even this can vary within the same variety due to changes of the environment and environmental conditions to which it is subjected during its growth and/or storage.

TABLE 2A
INITIAL MOISTURE ON WET BASIS IN BANANA SLICES (CONTINUOUS).

N° Test	50 °C Continuous	60 °C Continuous
1	71.8%	71.3%
2	72.5%	70.8%
3	71.7%	72.6%
Mean	72%	71.567%
Standard deviation	0.436	0.929

TABLE 2B
INITIAL MOISTURE ON WET BASIS IN BANANA SLICES (INTERMITTENT).

N° Test	50 °C Intermittent	60 °C Intermittent
1	71.6%	73.6%
2	71.2%	72.2%
3	71.5%	73.2%
Mean	71.43%	73%
Standard deviation	0.208167	0.721

These findings align with, which reports that bananas contain approximately 74% moisture on a wet basis. Other studies, such as, utilizing the AOAC 925.45 method, found that the Luvhele variety banana has an initial moisture content of 78.73% on a wet basis.

Conversely, reported an initial moisture content of 57.23% for another variety, while indicated that the Simmonds variety plantain has a moisture content of 66.2% on a wet basis. Variability in moisture content among different banana varieties can be attributed to environmental factors and conditions experienced during growth and storage, leading to differences even within the same variety.

To find the final moisture content, the same procedure was used as for the initial moisture content. Once constant weights were obtained in the dryer, they were taken to the moisture balance to determine the final moisture content that the dryer was able to achieve according to the conditions determined in each test.

The average of all the tests resulted in a final moisture content of 1.733±0.1923%.

TABLE 3A
INITIAL MOISTURE ON WET BASIS IN BANANA SLICES (CONTINUOUS).

N° Test	50 °C Continuous	60 °C Continuous
1	2.1%	1.5%
2	1.9%	1.6%
3	1.8%	1.8%
Mean	1.93%	1.63%
Standard deviation	0.1528	0.1528

TABLE 3B
INITIAL MOISTURE ON WET BASIS IN BANANA SLICES (INTERMITTENT).

N° Test	50 °C Intermittent	60 °C Intermittent
1	1.9%	1.8%
2	1.6%	1.4%
3	1.7%	1.5%
Mean	1.73%	1.56%
Standard deviation	0.1528	0.2082

The primary criterion for selecting the most appropriate equation to describe the drying curve is the coefficient of determination, denoted as R2. Tables 4, 5, 6, and 7 present the R2 values obtained for each experimental setting. The results indicate that the models with the highest R2 values are the Two-Terms, Page, and Midilli et al. models, which consistently yield superior results across all continuous and intermittent tests. Conversely, the model exhibiting the poorest fit is the Wang and Singh model, with R2 values ranging from 0.90506 to 0.98538.

At 50 °C under continuous drying, the Midilli et al. model achieved R2 values of 0.99768, 0.99771, and 0.99808 for tests 1, 2, and 3, respectively. At 60 °C continuous, the model obtained R2 values of 0.99993, 0.99909, and 0.99942 for the same tests.

For intermittent drying at 50 °C, the Midilli et al. model yielded R2 values of 0.99501, 0.99501, and 0.99142 for tests 1, 2, and 3, respectively. At 60 °C intermittent, the model achieved R2 values of 0.99743, 0.99779, and 0.99948 for the corresponding tests.

Overall, the Midilli et al. model demonstrated the best fit across all conditions, closely followed by the Page model. As a modification of the Page equation, the Midilli et al. model incorporates coefficients a and b that remain near 1 and 0, respectively, resulting in fits comparable to those of Page's equation (parameters k and n).

In a related study by, drying kinetics of plantain (Musa acuminata, Cavendish subgroup) were analyzed at temperatures of 40 °C, 50 °C, 60 °C, and 70 °C using six mathematical models (excluding Midilli et al.). The authors concluded that the Page and Silva et al. models best described plantain drying kinetics. While these models primarily correlate moisture loss with time, they provide accurate predictions of drying times despite not accounting for variables such as temperature, pressure, geometry, or porosity. Thin-film models remain effective due to their simplicity and minimal data requirements.

Figures 3–6 illustrate how well the Midilli et al. model aligns with experimental data across all tests under both continuous and intermittent drying conditions.

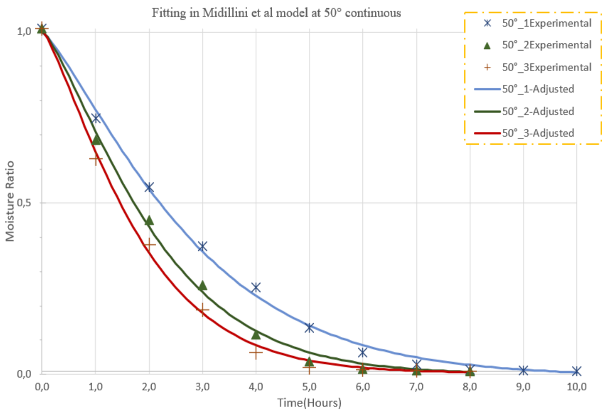


Fig. 3. Fitting of the Midillini et al. model for experimental data at 50 °C continuous

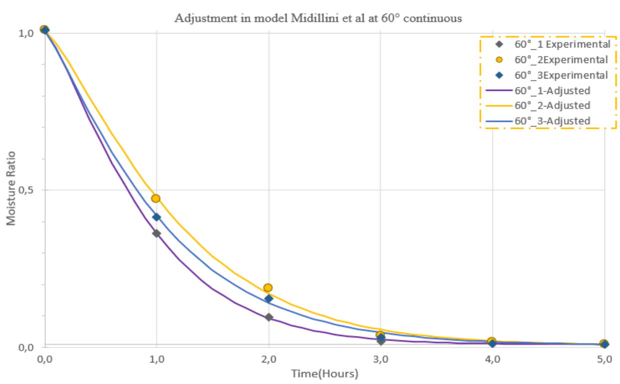


Fig. 4. Fitting of the Midillini et al. model for experimental data at 50 °C intermittent.

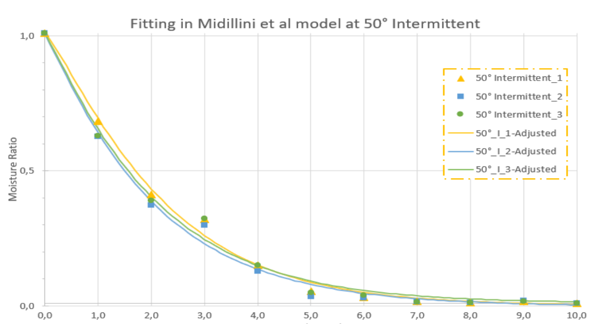


Fig. 5. Fitting of the Midillini et al. model for experimental data at 60 °C continuous.

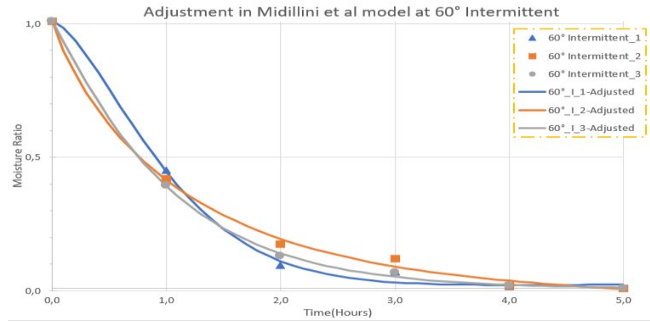


Fig. 6. Fitting of the Midillini et al. model for experimental data at 60 °C intermittent.

Tables 4 and 5, shows a sensory evaluation which is limited to a visual analysis of color and texture for intermittent drying and continuous drying, this is because coloration and texture are the main aspects that are considered when a product is to be marketed.

TABLE 4
COMPARISON OF COLOR AND TEXTURE OF INTERMITTENT AND CONTINUOUS DRYING AT 50 °C

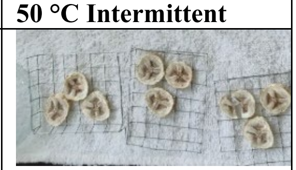
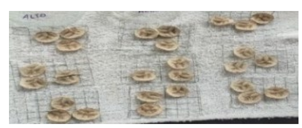
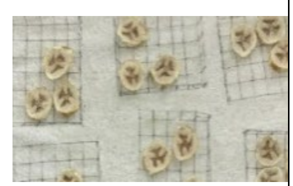
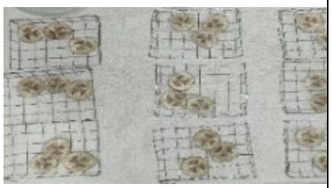
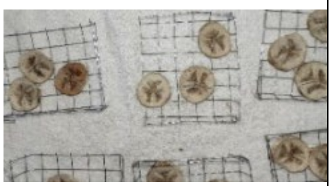
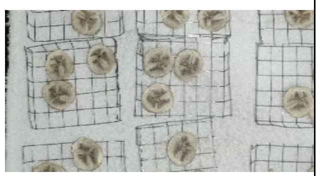
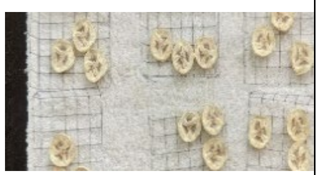
	50 °C Continuous	50 °C Intermittent
1		
2		
3		
	Marked cracks are observed in the tests, especially in test 3, where they are quite large. Cracks are also noticeable in most of the banana slices in test 1, more than in test 2, and have a dark coloration.	It can be seen at first glance that the coloration has improved a lot, no cracks are observed except in 4 or 5 banana slices, the rest of the cracks are not so visible unless they are carefully and carefully observed.

TABLE 5
COMPARISON OF COLOR AND TEXTURE OF INTERMITTENT AND CONTINUOUS DRYING AT 60 °C

	60 °C Continuous	**60 °C Intermittent**
1		
2		
3		
	An even darker and more marked coloration than the test at 50 °C is observed, and the presence of cracks is still observed.	A light color and few presences of cracks in the slices are observed.

IV. CONCLUSIONS

All continuous and intermittent drying processes resulted in an average final moisture content on a wet basis ranging from 1.567% to 1.933%. These low moisture levels create an environment that is hostile to mold and yeast proliferation, facilitating long-term storage and preservation of the product.

The drying process applied to green silk banana slices demonstrated a temperature dependence; increasing the temperature generally reduced drying time, except for the 60 °C setting. Mathematical models fitted to the drying curve of green silk bananas identified the Midilli et al. model as the best fit for both continuous and intermittent drying at 50 °C and 60 °C.

Average effective diffusivity values were found to be 9.83207×10^{-11} m/s^2 and 2.121333×10^{-10} m/s^2 for continuous drying at 50 °C and 60 °C, respectively. For intermittent drying at these temperatures, the effective diffusivity values were 1.017497×10^{-10} m/s^2 and 2.01×10^{-10} m/s^2, indicating an increase in effective diffusivity with higher temperatures.

The addition of steel plates in the dryer enhanced air velocity in the drying bed from 0.62188 m/s to 1.258 m/s, resulting in reduced drying time and energy consumption. Intermittent drying proved to be more energy-efficient than continuous drying. Notably, drying banana slices at 60 °C with intermittent periods optimized both electricity consumption (12.753 kWh) and drying time (5 hours).

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