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Sustainable superheated steam drying of unripe banana (*Musa acuminata* cv. Hom Thong): Effects on mathematical modeling

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Abstract Results indicated that the moisture ratio was significantly influenced by both drying temperature and slice thickness. Higher drying temperatures and thinner slices facilitated greater moisture migration during the drying process. Statistical analysis revealed that the modified Page model provided the best fit for estimating the moisture ratio of unripe banana slices with a 1 mm thickness (R^2 = 0.9963, RMSE = 0.0115, and χ^2 = 0.0001). For 2-mm and 3-mm thickness samples, the Page model performed better in describing the drying behavior. Both models were found to be effective in predicting the drying kinetics, demonstrating their potential for optimizing the SSD process in UBF production.

Keywords: Mathematical modeling, Superheated steam drying, Sustainability, Thin-layer drying, Unripe banana

Introduction

Bananas are a staple fruit grown in tropical and subtropical regions, valued for their high content of carbohydrates, proteins, vitamins, minerals, polyphenols, and other essential nutrients (Shi *et al.*, 2020). Bananas are extensively consumed worldwide and hold significant economic importance, especially in developing countries, where they serve as both a primary source of income and a vital food resource in banana cultivating areas (Yang *et al.*, 2022). According to the Food and Agriculture Organization (FAO), global banana production reached 139 million t in 2023 (FAO, 2023).

The primary component of unripe bananas is starch, which typically constitutes 70-80% of their composition. However, this starch content diminishes considerably as the bananas ripen (Leonel *et al.*, 2020). Unripe bananas are rich in resistant starch (RS), a type of starch that resists digestion, in the small intestine and can be fermented by probiotics in the colon to support their growth (Khoozani *et al.*, 2020). As a prebiotic, RS undergoes fermentation in the human large intestine by colonic microflora, producing short-chain fatty acids that have beneficial effects, such as glycemic

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modulation, plasma lipid regulation, and reductions in diabetes, and cholesterol-levels (Nwakego *et al.*, 2022; Sardá *et al.*, 2016a). Thus, RS is regarded as a crucial functional food ingredient for human nutrition and enhances the functional characteristics of gluten-free products as a beneficial substitute for wheat flour (Cheng *et al.*, 2024; Sardá *et al.*, 2016b).

Due to these functional benefits, unripe banana flour (UBF) has been developed and is used as a food ingredient in various applications, including bread (Guadalupe-Moyano *et al.*, 2022; Khoozani *et al.*, 2020), biscuits (Mabogo *et al.*, 2021), pasta (Zheng *et al.*, 2016), and noodles (Liu *et al.*, 2020).

The production of UBF requires the development of a rapid dehydration method that preserves its nutritional value. Hot-air drying (HAD) is the traditional method used for UBF production, as it is cost-effective (Khoozani *et al.*, 2019). However, HAD is highly time- and energy-intensive (Menon *et al.*, 2020; Sobulska *et al.*, 2022). Various drying techniques for UBF production have been explored, including spouted bed drying (Bezerra *et al.*, 2013), sun drying (Falade and Oyeyinka, 2015), pulsed-fluidized bed agglomeration (Rayo *et al.*, 2015), pulsed-vacuum air drying (La Fuente *et al.*, 2017), spray drying (Rayo *et al.*, 2015), microwave oven drying (Alam *et al.*, 2023), and freeze-drying, which is a non-thermal method (Ahmed *et al.*, 2020; Khoozani *et al.*, 2019).

Superheated steam drying (SSD) has emerged as an effective technique for drying various food products (Bennamoun and Ndukwu, 2023). SSD is non-polluting, offers high production rates, consumes less energy compared to traditional drying methods operating at similar temperature and flow rate conditions (Menon *et al.*, 2020; Sobulska *et al.*, 2022).

Recently, there has been growing interest in studying the drying behavior of food products using mathematical models. These models are critical for simulating drying processes, optimizing parameters, scaling up technology from laboratory to commercial production, and improving overall efficiency (Sehrawat *et al.*, 2016).

A recent study has shown that substituting HAD with SSD reduced drying time by 75%. Additionally, the produced UBF exhibits a notable increase in resistant starch (RS) content, as well as enhanced hydration properties (Phothisoot *et al.*, 2023). However, recent studies have not utilized a mathematical approach to estimate the decrease in moisture over time. Whenever transitioning from the pilot scale to the industrial scale, it is important to have a comprehensive understanding of the drying characteristics and the ability to predict the outcomes of the drying process accurately. Therefore, given the health benefits of UBF and advancements in its production using SSD, this study aimed to investigate the drying kinetics of unripe banana slice. Specifically, the research focused on the mathematical modeling of drying behavior at varying temperatures and slice thicknesses.

Materials and methods

Sample preparation

Bananas (*Musa acuminata* cv. Hom Thong, AAA group, Gros Michel subgroup) were harvested at 110 days after anthesis from a farm in Nakhon Pathom province, Thailand. The bananas were collected in the fully-green stage without any chemical treatment to accelerate ripening and were used at the first maturity stage, characterized by fully-green peels. After harvesting, the bananas were peeled, sorted for uniform size and color, and inspected to ensure the absence of physical defects. The fruits were then sliced into thicknesses of 1, 2, or 3 mm, using a slicing machine (Rubina 350; SIRMAN; Italy), with slices sorted to a diameter of 30–35 mm. The initial moisture content of the peeled bananas was determined using the AOAC method (AOAC, 1990), and the recorded value was 72±1% (wet basis).

Superheated steam drying

The schematic diagram of the superheated steam dryer used in this study is shown in Figure 1. The dryer was designed and developed at the Department of Food Engineering, Kasetsart University, Kamphaeng Saen Campus, Thailand. This technique employed superheated steam as the drying medium instead of dry air recycling the water removed from the product back into the drying process. In contrast to conventional air-drying methods, which require the replacement of wet air with heated air, SSD offers several advantages, including a higher convective heat transfer coefficient, improved drying efficiency, faster production rates, and reduced energy consumption (Menon *et al.*, 2020).

Experimental design

The experimental design of the study is illustrated in Figure 2. SSD was conducted on unripe banana slices with thicknesses (1, 2, or 3 mm) at drying temperatures of 75, 85, 95, or 105 °C. Moisture content was determined during the drying process using the AOAC method (AOAC, 1990) and expressed on a dry basis (%db), calculated using Eq. (1) (Shi *et al.*, 2020). Briefly, 1 g of banana slices was ground using a pestle and mortar, and the sample mass was measured using an analytical balance (BSA3202S-CW, Sartorius, Germany). The sample was dried at 105 °C in a hot-air oven (redLINE RF 115, BINDER GmbH, Germany) for 12 h to achieve a constant weight, recorded as the mass of dry matter.

$$M = \frac{W - W_d}{W_d} \text{ x } 100 \quad (1)$$

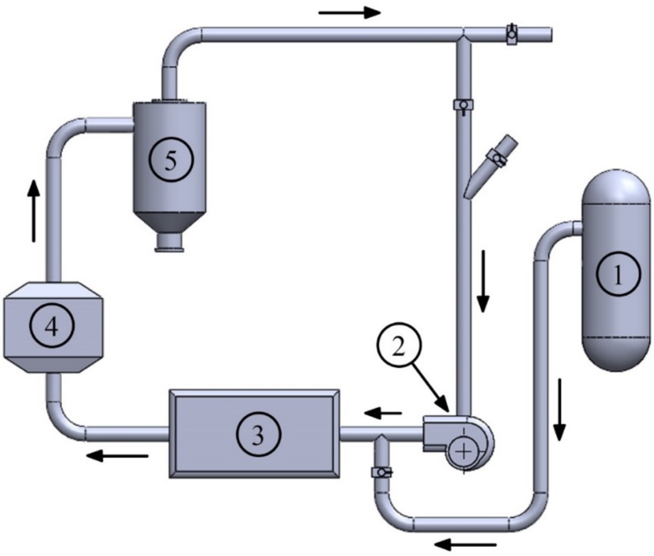

Figure 1. Schematic diagram of superheated steam dryer: 1) Boiler, 2) Blower, 3) Heater, 4) Drying chamber, and 5) Cyclone (modified from Phothisoot *et al.*, 2023)

The moisture content of the banana slices was monitored at 5-min intervals during the initial stages of drying, up to approximately 1 hour toward the end of the process. Drying was continued until the samples reached equilibrium moisture content.

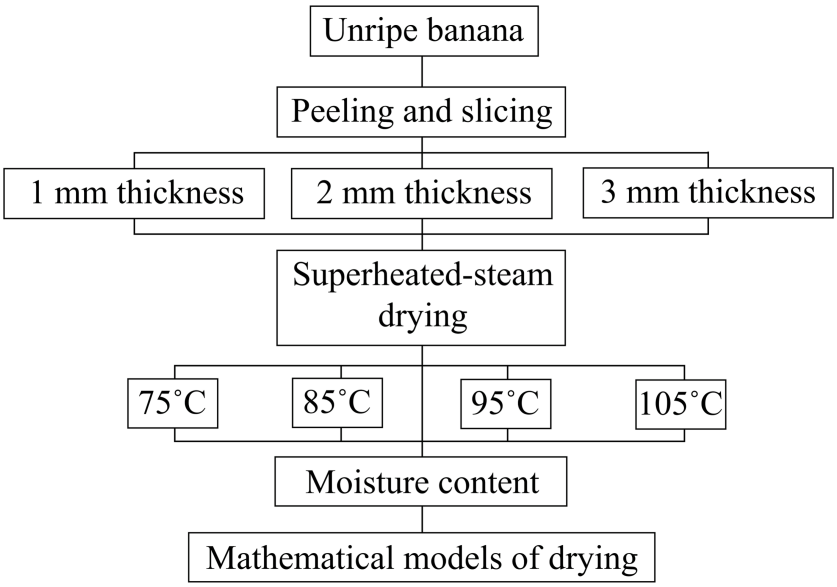

Figure 2. Schematic diagram of the experimental design

Mathematical models

Moisture content was expressed as a dimensionless moisture ratio (MR), calculated using Eq. (2) based on weight loss and solid content (Zhou *et al.*, 2022).

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (2)$$

where, M_t = moisture content at time t (%db)
M_i = initial moisture content (%db)
M_e = equilibrium moisture content (%db)

Several mathematical models were tested to describe the drying behavior of unripe banana slices (Table 1).

Table 1. Mathematical models tested for thin-layer drying of unripe banana

Model name	Model equation	References
1. Lewis	$MR = e^{(-kt)}$	Nasri, 2020
2. Henderson& Pabis	$MR = Ae^{(-kt)}$	Nasri, 2020
3. Page	$MR = e^{(-kt^n)}$	Pinheiro *et al.*, 2022
4. Modified Page	$MR = e^{-(kt)^n}$	Razola- Díaz *et al.*, 2023

Where, t = drying time (min)
k = drying constant obtained from experimental data (min^{-1})
A = empirical model constant (dimensionless)
n = empirical model constant (dimensionless)

Statistical parameters

The experimental data were analyzed using Microsoft Excel (version 16). To evaluate the fit of the tested models to the experimental data, the correlation coefficient (R^2), root mean square error (RMSE), and chi-square (χ^2) were calculated. The following equations were used for these statistical parameters (Gasa *et al.*, 2022; Zarein *et al.*, 2015):

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2} \quad (3)$$

$$RMSE = \left(\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N}\right)^{\frac{1}{2}} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N - z} \quad (5)$$

where, MR_{pre} = predicted result of moisture ratio
MR_{exp} = experimental result of moisture ratio
N = number of data points
z = number of parameters in the model

Results

Moisture ratio of unripe banana slices

The effect of drying temperature and slice thickness on the moisture ratio (MR) of unripe banana slices during the drying process is illustrated in Figure 3.

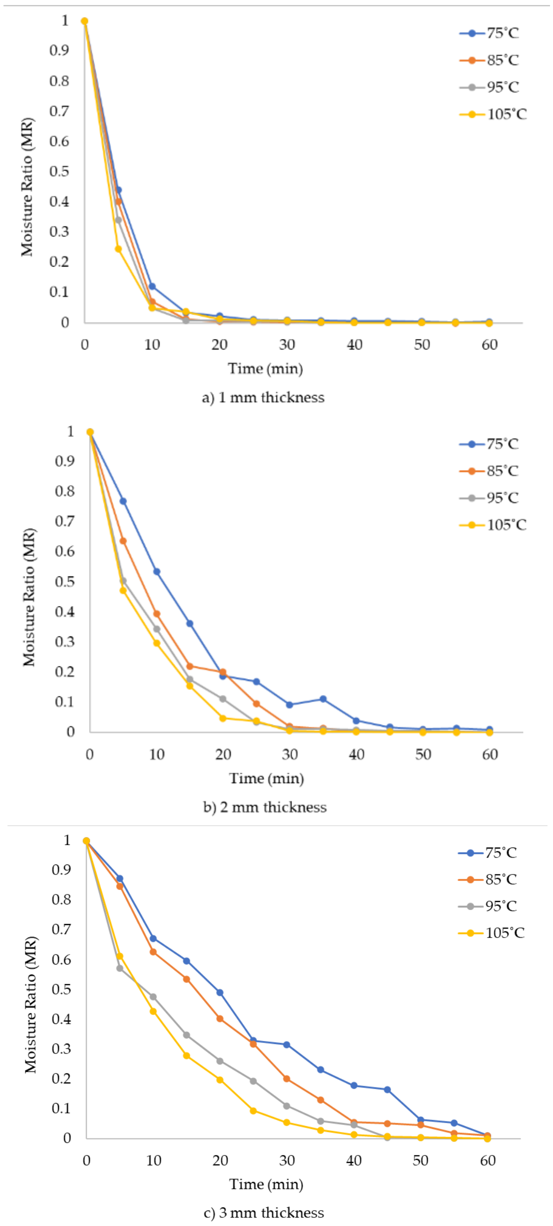

Figure 3. Changes in the moisture ratio (MR) of unripe banana slices under varying

Mathematical modeling of the drying process

The experimental moisture content data for SSD-dried unripe banana slices were converted into MR values and fitted to the four mathematical models presented in Table 1. The drying parameters for each model are summarized in Table 2. The parameters were used to predict MR values, which were then compared to experimental data. The conformity of each model was evaluated based on the coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2) values (Table 3).

Almost all of the models under various drying conditions had acceptable results, as evidenced by a high R^2 value greater than 0.9. The maximum R^2 value, 0.9957, was achieved by the Lewis model. The minimum RMSE value of 0.0115 was obtained by the modified Page model, while the lowest χ^2 of 3.9E-06 was observed for the Henderson model. The best statistical parameter results were not associated with the same model, making it difficult to draw a definitive conclusion about the best model. Thus, the relationship between MR_{exp} and MR_{pre} for the drying models across three thicknesses of unripe banana slices is shown in Table 4. A trendline for each model was generated to measure the slope, with a value close to 1 indicating higher precision. The modified Page model was found to be the most suitable for drying unripe banana slices with a thickness of 1 mm using SSD, showing R^2, RMSE, and χ^2 values in the range of 0.8843-0.9900, 0.0115-0.0264, and 0.0001-0.0008 respectively. The Page model was more suitable for describing the 2-mm and 3-mm thicknesses. The 2-mm samples exhibited R^2 values ranging from 0.9627 to 0.9842, RMSE values from 0.0174 to 0.0236, and χ^2 values from 0.0003 to 0.0006. The 3-mm samples showed R^2 values between 0.9019 and 0.9963, RMSE values from 0.0264 to 0.0402, and χ^2 values from 0.0005 to 0.0018.

Table 2. Parameters of mathematical drying models of unripe banana at various drying conditions

Model	Para-meters	Drying temperature (˚C)											
		1 mm thickness				2 mm thickness				3 mm thickness			
		75	85	95	105	75	85	95	105	75	85	95	105
Lewis	k	0.1193	0.1825	0.1657	0.1706	0.0795	0.1145	0.1143	0.1431	0.0526	0.0658	0.0831	0.1054
Henderson	k	0.0763	0.1745	0.1427	0.1381	0.0830	0.1189	0.1084	0.1430	0.0618	0.0750	0.1295	0.1127
and Pabis	A	6.0080	2.1253	2.0336	3.8679	1.1544	1.1985	1.2789	1.0055	1.4698	1.4643	2.3674	1.3550
Page	k	0.3849	0.3199	0.4881	0.4594	0.0425	0.0689	0.1380	0.1363	0.0170	0.0194	0.0862	0.0714
	n	0.7030	0.8619	0.7146	0.7465	1.1670	1.1333	0.9534	1.0134	1.2785	1.3139	0.9771	1.0955
Modified	k	0.2571	0.2665	0.3665	0.3528	0.0668	0.0944	0.1253	0.1399	0.0414	0.0498	0.0814	0.0899
Page	n	0.7030	0.8619	0.7146	0.7465	1.1670	1.1333	0.9534	1.0134	1.2776	1.3139	0.9771	1.0955

Table 3 Statistical results of mathematical drying models of unripe banana at various drying conditions

Model		Drying temperature (˚C)											
		1 mm thickness				2 mm thickness				3 mm thickness			
		75	85	95	105	75	85	95	105	75	85	95	105
Lewis	R^2	0.9473	0.9839	0.9878	0.9716	0.9902	0.9915	0.991	0.995	0.9417	0.9806	0.9947	0.9957
	RSME	0.04478	0.02935	0.06736	0.04829	0.04493	0.04349	0.02044	0.02034	0.08636	0.08551	0.03605	0.03823
	χ^2	0.00217	0.00093	0.00492	0.00253	0.00202	0.00205	0.00045	0.00045	0.00746	0.00792	0.00141	0.00158
Henderson & Pabis	R^2	0.8258	0.9526	0.9772	0.9236	0.9708	0.974	0.9916	0.9822	0.8859	0.06542	0.9943	0.9922
	RSME	1.50593	0.17102	0.25979	0.5561	0.02258	0.0309	0.07949	0.02092	0.08231	0.9673	0.20353	0.04934
	χ^2	24.7731	0.12098	0.12948	1.41254	0.09091	0.00359	0.00738	3.9E-06	0.02025	0.01967	0.188	0.01151
Page	R^2	0.8843	0.9672	0.99	0.9439	0.9627	0.9648	0.9641	0.9842	0.9019	0.9839	0.9835	0.9963
	RSME	0.04072	0.03727	0.01267	0.03709	0.0221	0.02361	0.02036	0.01739	0.03288	0.02637	0.04023	0.02189
	χ^2	0.00196	0.00152	0.00018	0.0015	0.00053	0.00061	0.00045	0.00033	0.00118	0.00076	0.00177	0.00052
Modified Page	R^2	0.8843	0.9672	0.99	0.9439	0.9627	0.9648	0.9641	0.9842	0.9120	0.9839	0.9835	0.9963
	RSME	0.01811	0.02643	0.01154	0.02212	0.04178	0.03411	0.02034	0.01744	0.08769	0.08757	0.04046	0.02774
	χ^2	0.00039	0.00076	0.00015	0.00053	0.0019	0.00127	0.00045	0.00033	0.00839	0.00837	0.00179	0.00084

Table 4. The relationship between MR_{exp} and MR_{pre} of drying models of various unripe banana thicknesses

Model	Trendline equation		
	1 mm thickness	2 mm thickness	3 mm thickness
Lewis	y = 0.9462x	y = 1.0318x	y = 1.0894x
Henderson & Pabis	y = 0.2007x	y = 0.8845x	y = 0.6637x
Page	y = 1.0216x	y = 1.0005x	y = 1.0006x
Modified Page	y = 1.0085x	y = 1.0280x	y = 1.0770x

Discussion

SSD has attracted growing interest in the food processing sector due to its potential to reduce drying time by up to 75% compared to HAD, while also enhancing the RS content and hydration properties of UBF (Phothisoot *et al.*, 2023). Given the complexity of the SSD process, accurate mathematical modeling is essential for understanding drying behavior and optimizing it, which is crucial for advancing future technological applications.

The MR of each sample decreased continuously over time, and the drying process could be divided into three distinct phases. Initially, there was a rapid decrease in MR, followed by a decelerated decline during the intermediate stage, and finally, a gradual reduction as the drying process reached completion. The model with the highest R^2, lowest RMSE, and χ^2 was considered most appropriate for characterizing the drying process (Gasa *et al.*, 2022).

These results indicate that various drying conditions cannot be described by a single mathematical model. Precise modeling of drying kinetics is essential for understanding the drying behavior and optimizing drying processes. Over recent years, significant attention has been paid to the development of mathematical models for studying the drying characteristics of various fruits and vegetables. For instance, drying avocado peel with HAD showed that the Page model provided the best fit across most tested temperatures (40, 60, and 80 °C) and airflow conditions (0, 0.8, and 1.6 m/s), though the Lewis model performed better at 80 °C (Razola- Díaz *et al.*, 2023). Similarly, the Henderson and Pabis model was reported to describe solar drying profiles of plantain, banana, and cassava effectively (Djebli *et al.*, 2020). Studies on banana slices dried using a heat pump system found that the Lewis, Henderson and Pabis, and Page models were well-suited to describe their drying behavior (Tunckal and Doymaz, 2020).

Additionally, HAD and SSD have shown similar modeling structures, further validating the use of these mathematical models in SSD applications (Le *et al.*, 2020). These findings reinforce the utility of mathematical modeling in predicting the drying kinetics of unripe banana slices and highlight the relevance of mathematical modeling in improving drying technology.

In conclusion, this study evaluated several thin-layer drying models to describe the drying behavior of unripe banana slices subjected to SSD. The primary objective was to identify the most suitable models for accurately representing the drying data and estimating the moisture ratio. The results demonstrated that the mathematical models effectively captured the key drying trends observed during the SSD process. Experimental data collected at drying temperatures of 75, 85, 95, and 105 °C, with slice thicknesses of 1, 2, and 3 mm, highlighted the influence of both drying temperature and slice thickness on the drying time. Among the tested models, the modified Page model was determined to be the most appropriate for estimating the MR of unripe banana slices with 1 mm thickness during SSD. However, for the 2-mm and 3-mm thickness samples, the Page model better described the drying behavior, based on its superior statistical performance. Both models reliably predicted the drying kinetics, providing a robust tool for understanding and optimizing the SSD process for unripe banana slices. Future research could explore alternative models or additional parameters that may further enhance efficiency and quality in SSD applications.

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Conflicts of interest

The authors declare no conflict of interest.

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