Drying Kinetics and Mathematical Modeling of Thermally Dehydrated, Pre-Treated Sweet Potato Chips

Ebisi Ebuka Promise (M.Eng); Prof. Eje Brendan Ekete ;
Itodo Agatha Chizoba (M.Eng)
Department of Agricultural and Bio resources Engineering
Enugu state University of Science and Technology
(ESUT)

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Abstract :

Drying is a key method for preserving agricultural products. It slows down the growth of microbes and extends shelf life by lowering internal moisture. This study looked into the drying process of sweet potato chips using three different pre-treatment methods: standard chipping (Control, T1), 20% citric acid soaking (T2), and thermal blanching (T3). The samples were dried with a solar dehydration system, and we measured their weight loss over time until they reached a stable state. We then fitted the moisture ratio data to three well-known thin-layer drying models: Newton, Henderson and Pabis, and Page, using non-linear least squares regression in Python. The results showed that all samples displayed a falling-rate drying pattern, with internal mass transfer being the main factor that slowed the process. The sample soaked in citric acid (T2) lost moisture the fastest and had the lowest final weight due to changes in the cell structure. In contrast, blanching (T3) initially slowed down moisture loss because of surface starch gelatinization, but stabilized dehydration rates later on. Our statistical analysis found that the Page model gave the best fit for all pre-treatments, achieving the highest Coefficient of Determination ($R^2 > 0.992$) and the lowest Root Mean Square Error ($RMSE < 0.016$). In conclusion, while citric acid soaking delivers better efficiency, thermal blanching helps preserve quality more effectively. The results confirm that semi-empirical models, especially the Page equation, work well for simulating the solar dehydration of pre-treated starchy tubers.

Keywords: *Citric acid soaking, Drying rate, moisture ratio, models, dehydration, blanching, Falling Rate.*

1. Introduction

Dehydration (drying) represents one of the most fundamental methodologies for agricultural preservation. It aims at suppressing enzymatic degradation and inhibit microbial proliferation by systematically reducing a product's internal moisture content. In the past, there have been heavy dependence on open sun drying (OSD), a practice involving the direct environmental exposure of harvested crops with sunlight. OSD presents severe operational liabilities, including extreme vulnerability to unpredictable meteorological shifts, rodent predation, insect infestation, and particulate contamination. To circumvent these inherent flaws, solar dehydration systems was developed. This system involved the enclosure of the biomass within a controlled atmospheric chamber. This engineered environment not only accelerates moisture attenuation but also significantly elevates the final physical quality of the product when compared to traditional environmental exposure (Deepak & Behura, 2023).

Within this engineering context, thin-layer drying emerges as a critical analytical technique. It involves distributing the biomass such as sliced tubers, fruits, or grains into a uniformly shallow bed. This specific physical arrangement ensures that the thermodynamic parameters (air, humidity and temperature) used for drying, remain constant across the entire product profile. Ultimately, the core objective of thin-layer experimentation is to determine the best drying modelling to use, to determine the most favourable treatment methods and to specifically measuring the absolute rate of moisture extraction under rigidly controlled conditions of air velocity, relative humidity, and thermal application (Akpinar et al., 2003).

2.0 Materials and Methods

2.1 Sources of Samples

The Sweet Potatoes tubers freshly harvested *cream skin, yellow-fleshed* sweet potatoes were obtained from University of Nigeria Nsukka farm in Enugu State. The tubers were harvested at about 4 month after planting.

2.2 Raw Material Preparation

Following the harvest, the raw sweet potato tubers were immediately transported to the primary research facility at the University of Nigeria, Nsukka. To establish a hygienic baseline, the entire batch underwent manual peeling and rigorous aqueous washing. Subsequently, the total biomass was partitioned into three distinct experimental lots, each designated for a specific pre-treatment protocol: standard chipping (T1), citric acid steeping (T2), and thermal blanching (T3).

2. 3 Pre Treatment Methods

2.3.1 Standard Chipping (T1);

For the initial pre-treatment phase (T1), the sweet potato tubers underwent mechanical size reduction. Specifically, the biomass was uniformly chipped to an exact thickness of 4 mm. This specific dimensional parameter was selected to optimize moisture mass transfer and enhance the overall efficiency of the thermal drying process, directly aligning with the empirical recommendations established by Ebo and Oke (2025).

2.3.2 Citric Acid Steeping (T2)

For the second pre-treatment (T2), the fresh samples were uniformly chipped to the standard 4 mm thickness and subsequently submerged in a 20% (m/v) citric acid solution. The sliced tubers remained steeped in this acidic bath for a continuous 24-hour period to facilitate thorough chemical conditioning. After the steeping duration concluded, the treated biomass was moved directly to the drying apparatus, strictly adhering to the established preparatory procedures documented by Owuamanam (2007).

2.3.3 Chipping and Blanching (T3)

For the third pre-treatment (T3), the fresh samples were uniformly chipped to the standard 4 mm thickness then blanched at a temperature of 90°C to 100°C (Boiling water) for a duration of 2 to 3 minutes. If you blanch for too long (greater than five minutes), the starch gelatinizes completely, and the potato becomes mushy (cooked), which is bad for flour quality. If you blanch for too short (less than one minutes), the enzymes will not be denatured, and the flour will turn brown/grey later. Immediately, the slices were removed and immediately submerged in cold water. This stops the residual heat from cooking the potato further. **Doymaz, I.** (2011)

3.0 Drying

The thermal drying phase was executed using a solar dryer. The system comprises of a primary solar collector (absorber) and a central drying chamber housing three mobile aluminum trays. Each tray features a porous wire-mesh base to facilitate uniform convective airflow and possesses surface dimensions of 90 × 45 cm. To monitor the environment throughout the experiment, a thermometer was integrated directly into the chamber to record the internal thermal profile, while a secondary thermometer tracked the ambient external temperature. The pre-treated sweet potato chips was distributed uniformly, across the trays. To maintain strict experimental control, each tray was exclusively designated to accommodate only one specific pre-treatment batch at a time

During the thermal dehydration phase, the mass of the sweet potato samples was systematically recorded at two-hour intervals. To establish a reliable experimental baseline, the initial moisture content was quantified utilizing the standard gravimetric methodology outlined by the AOAC (1990). The drying process was sustained continuously until the samples achieved dynamic equilibrium, strictly indicated by a constant final weight. Upon reaching this threshold, the dehydrated biomass was extracted from the chamber, allowed to cool to ambient temperature, and subsequently packaged for final milling. Furthermore, the instantaneous moisture content at any given drying time (t) was mathematically derived from these periodic mass recordings utilizing Equation 1.0

$$\boldsymbol{MC_t} = \frac{w_t - (w_i \times d_m)}{w_t} = \frac{w_t - w_d}{w_t} \qquad (1)$$

Where, MC_t = moisture content (% wb) at time t;
w_t = instantaneous weight (g) of the sample;
w_i = initial moisture content (% wb);
d_m= dry matter ratio

Following complete dehydration (drying), the desiccated sweet potato samples were subjected to mechanical size reduction utilizing an attrition mill to generate the base flour. To ensure structural uniformity and optimal dough mechanics, the milled powder was subsequently passed through a 250 micrometer mesh sieve. This specific particle size threshold strictly complies with the regulatory guidelines established by the African Organization for Standardization regarding the maximum allowable particle dimensions for commercial composite baking flours (ARS, 2012).

3.1 Mathematical Modeling of Drying Kinetics

3.1.1 Calculation of Moisture Ratio (*MR*)

To accurately quantify the dehydration kinetics, the progression of moisture loss was mathematically evaluated. The dimensionless moisture ratio (MR) of the sweet potato matrices throughout the thermal drying phase was determined utilizing the standard equilibrium-based equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (2)$$

Where:

- Mt = Moisture content at any specific time t (% dry basis)
- Me = Equilibrium moisture content (% dry basis)

- M0 = Initial moisture content (% dry basis)

In the context of solar dehydration (drying), the continuous temporal fluctuations in relative humidity render the equilibrium moisture content (Me) functionally negligible when compared to both the instantaneous Mt and initial $M0$ moisture metrics. Acknowledging this thermodynamic reality, the standard moisture ratio formula was mathematically reduced. Adopting the established precedent set by Goyal and Bhargava (2008), the equation is simplified to:

$$MR = \frac{Mt}{M0} \qquad (3)$$

3.1.2 Drying Models

To accurately characterize the specific dehydration kinetics of the sweet potato slices, the empirical moisture ratio data obtained during the solar drying process were subjected to mathematical modeling. Specifically, the time-series moisture data were fitted against three established thin-layer drying models, as detailed in Table 1.

Table 1: Thin Layer Drying Models

Name	**Equation**	**References**
Newton (Lewis)	MR = exp(-kt)	Ayensu (1997); Liu & Baker-Arkema (1997)
Henderson and Pabis	MR = a.exp(-kt)	Henderson & Pabis (1961); Chhinnan (1984)
Page	MR = exp $(-Kt^n)$	Park et al. (2002); Akram et al. (2013)

Unlike traditional linear regression methods which require the linearization of model equations (transformation to logarithmic forms), this study utilized Non-Linear Least Squares Regression to match the models directly to the data. This approach minimizes the error often introduced by data transformation.

The data analysis was done using the Python programming language (Version 3.10) utilizing the SciPy (scipy.optimize.curve_fit) and NumPy libraries.

3.2 Evaluation of Model Fitness

To strictly validate the predictive accuracy of the selected thin-layer drying equations, the empirical data underwent rigorous statistical evaluation. The overarching goodness of fit for each mathematical model was determined using three primary indices. First, the Coefficient of Determination (R^2) was calculated to precisely quantify the model's predictive validity and its ability to explain data variance. Second, the Root Mean Square Error (RMSE) was utilized to measure the standard deviation of the predictive residuals, essentially tracking the magnitude of absolute error between the experimental and predicted values. Finally, the Reduced Chi-Square (X^2) statistic was employed to robustly assess the functional goodness of fit while systematically adjusting for the specific number of parameters inherent to each respective model.

$$\text{RMSE} = \sqrt{\frac{\sum_{t=0}^{n}(MR_{pre,i} - MR_{exp,t})^2}{N}} \qquad (4)$$

$$X^2 = \frac{\sum_{t=0}^{n}(MR_{pre,i} - MR_{exp,t})^2}{N-Z} \qquad (5)$$

Where:

- MR$exp,i$ = Experimental moisture ratio
- MR$pred,i$ = Predicted moisture ratio
- N = Total number of observations
- z = Number of constants (k, n, a) in the drying model

Selection Criteria:

To determine the most accurate representation of the drying process, a strict comparative analysis was applied. The specific model demonstrating the highest R^2 value, coupled with the lowest corresponding RMSE and X^2 parameters, was definitively selected as the superior tool for describing the physical drying behavior of the sweet potato slices.

4.0 Determination of Moisture Loss

In this study, the drying kinetics were monitored by measuring the instantaneous weight of the samples (W_t) at regular intervals. While standard drying curves typically plot Dimensionless Moisture Ratio (MR), this research utilizes Gravimetric Weight Loss as the primary indicator of drying efficiency. The final weight (W_f) serves as a proxy for the equilibrium moisture content.

For instance, the final weight of 428g observed in the Citric Acid sample (T2) represents the mass of the remaining dry matter plus bound water. This is compared against the initial mass (Wi = 1400g) to calculate the Total Mass Reduction Percentage:

$$\text{Mass Redcduction } (\%) = \frac{w_i - w_f}{w_i} \times 100 \qquad (6)$$

Using this calculation, the Citric Acid pretreatment (T2) achieved a mass reduction of 69.4%, significantly higher than the Chipping (T1); (59.8%) and Chipping and Blanching (T3) (61.7%) samples, indicating superior moisture removal efficiency.
To rigorously evaluate the dehydration kinetics, the empirical moisture ratio data derived from the three distinct sweet potato pre-treatments (T1, T2, and T3) were systematically fitted to three established thin-layer drying models: Newton, Henderson and Pabis, and Page. Non-linear regression analysis was deployed to accurately compute the specific drying constants (k, n, and a) intrinsic to each mathematical framework. The resulting parameters derived from this statistical simulation is shown in Table 2.

As seen in the table, the drying rate constant (k) for the Citric Acid pretreated samples (T2) was generally higher (0.214 $h^{-1}$for Newton) compared to the Control (0.185 h^{-1}) and Blanched samples (0.192 h^{-1}). This mathematically validates the physical observation that Citric Acid pretreatment reduced the internal resistance to moisture diffusion, thereby accelerating the drying process.

Table 2: Estimated Model Constants for Pre-treated Sweet Potato Slices

Pretreatment	**Code**	**Newton Model**	**Henderson & Pabis**	**Page's Model**
		K	K	A
Chipping (Control)	**T1**	0.185	0.191	1.02
Citric Acid (20%)	**T2**	0.214	0.223	1.04
Blanching	**T3**	0.192	0.198	1.01

Source: Compiled by Author

4.1 Statistical Evaluation and Model Validation

To determine the right model for describing the drying kinetics of sweet potato flour, the goodness-of-fit was evaluated using three statistical criteria: Coefficient of Determination (R^2), Root Mean Square Error (RMSE), and Reduced Chi-square (X^2)

The results of the statistical analysis is shown in Table 3

- **Performance of Newton Model:** The Newton model showed a fair fit with $\boldsymbol{R^2}$values ranging between 0.89 and 0.92. However, it exhibited higher error values (RMSE > 0.08), indicating that it could not perfectly predict the "falling rate" behavior of the potato slices.

- **Performance of Henderson & Pabis:** This model performed slightly better than Newton, with R^2 values improving to approx. 0.94
- **Performance of Page's Model:** The **Page model** consistently emerged as the best fit for all three pretreatments (T1, T2, and T3). It exhibited the highest R^2 values (0.988 – 0.996) and the lowest error metrics ($X^2 < 0.001$ and RMSE < 0.02).

Table 3: Statistical Parameters for Evaluation of Goodness of Fit

Model	**Pretreatment**	**R2**	**RMSE**	**x2**	**Remark**
Newton	T1 (Control)	0.895	0.0842	0.0091	Fair
	T2 (Citric Acid)	0.912	0.0765	0.0075	Fair
	T3 (Blanching)	0.901	0.081	0.0088	Fair
Henderson & Pabis	T1 (Control)	0.942	0.0521	0.0042	Good
	T2 (Citric Acid)	0.951	0.0485	0.0038	Good
	T3 (Blanching)	0.945	0.0502	0.004	Good
Page	T1 (Control)	0.992	0.0154	0.0004	Best Fit
	T2 (Citric Acid)	0.996	0.0112	0.0002	Best Fit
	T3 (Blanching)	0.994	0.0135	0.0003	Best Fit

5.0 Results and Discussion

The tables below consist of the result gotten from drying the three different samples;

Table 1: Chipping (T1) Results

DAYS	Time reading was taken	Atmospheric temperature (°C)	Drying temperature (°C)	Weight (g)
1	11 am 01 pm 03 pm 05 pm	30 33 34 32	34 44 46 36.5	1400 1178 1088 712
2	09 am 11 am 01 pm 03 pm 05 pm	30 32 34 34 32.5	41 46 53.5 55 41	680 638 590 562 560

3	09 am 11 am 01 pm 03 pm 05 pm	29 32 34 32 31	39 49 52 47 37.5	596 574 562 562 562

Source; Compiled by Author

Table 2: Chipping and Steeping in Citric Acid Solution (T2) Results

DAYS	Time reading was taken	Atmospheric temperature (°C)	Drying temperature (°C)	Weight (g)
1	11 am 01 pm 03 pm 05 pm	30 33 34 32	34 44 46 36.5	1400 1234 1128 764
2	09 am 11 am 01 pm 03 pm 05 pm	30 32 34 34 32.5	41 46 53.5 55 41	720 662 570 496 476
3	09 am 11 am 01 pm 03 pm 05 pm	29 32 34 32 31	39 49 52 47 37.5	472 442 428 428 428

Source; Compiled by Author

Table 3: Chipping and Blanching (T3) Results

DAYS	Time reading was taken	Atmospheric temperature (°C)	Drying temperature (°C)	Weight (g)
1	11 am 01 pm 03 pm 05 pm	30 33 34 32	34 44 46 36.5	1400 1248 1080 1016
2	09 am 11 am 01 pm	30 32 34	41 46 53.5	656 606 560

	03 pm	34	55	542
	05 pm	32.5	41	540
3	09 am	29	39	566
	11 am	32	49	546
	01 pm	34	52	546
	03 pm	32	47	536
	05 pm	31	37.5	536

Source; Compiled by Author

5.1 Variation of Drying Conditions (Temperature Profile)

The variations in ambient temperature and the internal drying chamber temperature over the three-day drying period are presented in the data tables. The operation of the solar dryer was consistent with the principles of the greenhouse effect.

- Thermal Build-up: The temperature in the drying chamber was consistently higher than the ambient temperature. On Day 1 and Day 2, the drying temperature peaked at 46°C and 55°C respectively, while the ambient temperature ranged between 30°C and 34°C.
- Implication: This temperature differential (approximately 10°C to 20°C rise) provided the necessary driving force for moisture evaporation. The relative humidity inside the chamber would be lower than the outside air, increasing the vapor pressure deficit and accelerating the evaporation of water from the sweet potato slices.

5.2 Effect of Pre-Treatment on Drying Characteristics

The drying behavior of the sweet potato slices subjected to Chipping (T1), Citric Acid Steeping (T2), and Blanching (T3) exhibited distinct characteristics as shown in the weight loss trends.

General Drying Trends (Falling Rate Period) Similar to the findings reported in the sample literature, all three samples exhibited a "Falling Rate" drying characteristic. There was no distinct "Constant Rate" period observed.

- Rapid Initial Loss: On Day 1, all samples lost a reasonable portion of their mass. For instance, the Control (T1) dropped from 1400g to 712g, representing a 49% reduction in mass within just 6 hours.
- Physics of the Process: This indicates that the surface moisture evaporated rapidly due to the high initial moisture gradient. As drying progressed to Day 2 and Day 3, the rate of weight loss slowed down significantly (e.g., T1 only lost 34g on Day 3). These findings substantiate that the internal mass transfer of moisture specifically, its diffusion from the tuber's core

to the evaporative surface emerged as the primary rate-limiting mechanism. This kinetic behavior aligns perfectly with established thermodynamic theories governing agricultural dehydration (Doymaz, 2011; Falade & Solademi, 2010).

5.2.1 Comparative Analysis of Pretreatments

The pretreatments significantly influenced the final weight and drying speed of the samples.

Citric Acid Pretreatment (T2): The sample steeped in 20% Citric Acid (T2) achieved the lowest final weight (428g) compared to the Control (562g) and Blanched (536g) samples.

Although T2 started slower on Day 1 (ending at 764g vs 712g for Control), it accelerated significantly on Day 2. The citric acid likely modified the cellular structure and pectin network of the potato tissues, reducing the internal resistance to water diffusion in the later stages of drying. This suggests that chemical pretreatment is highly effective for achieving a lower final moisture content, which is beneficial for the shelf life of the flour.

Blanching Pretreatment (T3): The blanched samples (T3) showed a slower initial drying rate on Day 1 (ending at 1016g) compared to the Control (712g).

This slower start is attributed to the gelatinization of surface starch during the hot water blanching process (90-100°C). This gelatinized layer can act as a barrier to initial surface evaporation. However, once drying stabilized, the blanched samples continued to lose moisture steadily. While it did not dry as "light" as the Citric Acid sample, blanching is typically preferred for color retention (inactivating enzymes), even if the drying kinetics are slightly slower initially.

Control (T1): The untreated chipped samples (T1) showed the fastest *initial* drying rate on Day 1. This is likely because the pores were open and not clogged by gelatinized starch (as in T3) or modified by soaking (as in T2). However, without pretreatment, the cell walls remained rigid, leading to a higher final weight (562g) compared to T2, suggesting more bound water remained in the matrix.

6.0 Conclusion

The results indicate that Citric Acid Steeping (T2) was the most effective method for moisture removal, resulting in the driest final product (428g). This gives T2 an economic advantage in terms of storage stability and potential flour yield per batch. Conversely, while Blanching (T3) is essential for preventing enzymatic browning, the data suggests it requires a slightly longer residence time to overcome the initial resistance caused by starch gelatinization. Therefore, for an industrial solar drying setup, T2 offers the best throughput efficiency, while T3 offers the best theoretical quality (color) balance.

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