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Original Research Article

Influence of Drying Temperature and Osmotic Pretreatment on Heat and Mass Transfer, Drying Kinetics and Quality of Dried Sweet Potato

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KEYWORDS
Sweet potato,
Drying kinetics,
Mass transfer,
Heat transfer,
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Rehydration.

ABSTRACT
The study investigated the effects of osmotic pretreatment and drying temperature on drying kinetics, heat and mass transfer and quality attributes of sweet potato slices. Mature sweet potato were sliced into 2, 4 and 6 mm thicknesses and subjected to osmotic pretreatment using NaCl, $CaCl_2$ and $C_6H_8O_6$ solutions at concentration of 5, 10 and 15% (w/v) for 4, 6, and 8 hours. Drying experiments were conducted in a hot air oven dryer at 50, 60 and 70°C. The results showed that moisture reduction during osmotic pretreatment significantly increased ($p<0.005$) with increasing solution concentration, soaking time, and drying temperature, ranging from 12.84 ± 0.31% in the control sample to 43.54 ± 0.67% in treated samples, whereas thinner slices recorded faster moisture migration. Samples pretreated with 15% NaCl recorded the highest moisture loss (27.48 ± 0.41% to 44.73 ± 0.66 %) and fastest drying rate, whereas untreated samples showed slower moisture reduction. Effective moisture diffusivity ranged from (1.12 ± 0.05) × 10^{-8} to (4.21 ± 0.14) × 10^{-8} m^2/s in NaCl-treated samples at 70°C and increased with temperature and pretreatment intensity. The Midilli et al. model best described the drying behavior, producing the highest coefficient of determination (R^2= 0.997) and lowest root mean square error (RMSE= 0.008). Drying at 60°C provided an optimal balance between drying efficiency, energy utilization, and sweet potato quality.

CITATION
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INTRODUCTION

Sweet potato (*Ipomoea batatas* L.) is an important food crop worldwide. It is considered a nutritious staple and food security crop with a high starch content, low glycemic index, rich in anthocyanins, and essential minerals, all of which contribute to numerous health benefits. The remarkable adaptability of crops to diverse agroecological conditions and their low production costs make them globally sought-after food crops. In light of the continuous rise in food demand, increasing water scarcity, and climate change, sustainable agriculture is progressively shifting focus toward low-carbon crops, such as sweet potato (Dung et al., 2026; Issaka et al., 2026; Roy, Sun, Ma, & Mu, 2026; Yakubu et al., 2026).

Despite its nutritional and agronomic significance, sweet potato storage is susceptible to various post-harvest challenges in tropical climates and during transportation. Given that sweet potatoes contain approximately 70–80% moisture (Guo et al., 2026), they are prone to rapid deterioration if not properly preserved, leading to considerable post-harvest losses, especially in regions lacking adequate storage facilities (Yuan et al., 2026).

Many smallholder farmers in Nigeria and West Africa continue to rely on traditional drying methods, such as sun drying, which is associated with prolonged drying times, contamination, uneven drying, and nutrient loss (Wang et al., 2026). To overcome these limitations, advanced drying techniques based on the fundamental principles of heat and mass transfer are essential.

Heat transfer during drying supplies thermal energy to food product to remove moisture through conduction, convection, or radiation (Hadj-Taieb et al., 2025). In drying, forced convection predominates heated air flows over the food surface, supplying energy and removing the resulting water vapor. Mass transfer describes water movement from sweet potato slices to the surface and surrounding air (Zhu & Jiang, 2014), driven by a moisture concentration or vapor pressure gradient. Heat and mass transfer occur simultaneously and are interdependent: heat transfer to the product controls moisture vaporization, while vapor removal from the surface determines drying efficiency (Mujumdar, 2014). Effective transfer ensures uniform drying, preserves nutritional quality, texture, and flavor, and extends shelf life. Thin-layer drying models of these processes provide a foundation for designing, optimizing, and scaling up drying operations (Mujumdar, 2014; Doymaz, 2012).

Although the individual effects of osmotic pretreatment and drying temperature have been widely reported (Petikirige et al., 2022), the interactive effects of different pretreatments and drying conditions on the drying kinetics and quality parameters of sweet potato slices remain insufficiently studied. According to Ntsowe (2026), properly dried sweet potato products confer numerous health benefits, including improved diet quality, as well as anti-glaucoma, lipid-lowering, antioxidant, anticancer, anti-inflammatory, antibiotic, anti-pathogenic, cardioprotective, and antidiabetic effects. Consequently, selecting an appropriate drying method and parameter is important to minimize quality deterioration (Roy et al., 2026) particularly among Nigerian small-holder farmers. Sensory qualities are important, as they ultimately determine consumer acceptance and the commercial success of dried products (Kudra & Mujumdar, 2009).

Drying temperature and osmotic pretreatment are among the most influential factors affecting drying performance and final product quality. Temperature directly governs heat transfer rates, moisture diffusivity, and drying kinetics. However, excessive heat can induce case hardening, non-enzymatic browning, nutrient degradation, and loss of rehydration capacity. Chemical pretreatments, such as dipping in citric acid (Aboyeji et al., 2020), ascorbic acid, sodium metabisulfite, or salt solution, can modify tissue structure, inactivate oxidative enzymes, reduce browning, and enhance mass transfer by disrupting surface resistance or altering cell wall permeability. Despite the recognized individual effects of temperature and pretreatment, their interactive influence on heat and mass transfer, drying rate, and overall quality of dried sweet potato remains unclear.

Recent studies have shown growing interest in applying advanced drying techniques to extend the shelf life of seasonal and perishable foods while enhancing final product quality (Fathi et al., 2022). However, published data are limited regarding how different temperatures, in combination with chemical pretreatment, affect heat and mass transfer dynamics, drying rates, and the multiple quality dimensions of the sensory, nutritional, and physical attributes of sweet potato (Lagnika et al., 2021; Rashid et al., 2022). Therefore, understanding energy consumption at different drying temperatures is essential for designing energy-efficient drying systems, particularly given the constant rise in energy costs and sustainability concerns.

To address this gap, this study investigated the influence and limitations of drying temperature and osmotic pretreatment on the theoretical energy requirement for mass transfer parameter and the quality of dried sweet potato. The findings are expected to provide a robust scientific basis for optimizing drying processes, reducing post-harvest losses, improving product quality, and enhancing energy efficiency in sweet potato processing, specially within Nigerian and West African context. Therefore, we hypothesized that:

H_0 (Null): There is no significant difference (p>0.05) in effective moisture diffusivity between NaCl, $CaCl_2$, $C_6H_8O_6$, osmotically treated samples, and untreated sweet potato samples during hot air drying.

H_{11} (Alternative): NaCl osmotic treatment significantly increases effective moisture diffusivity of the sweet potato samples compared with $CaCl_2$, ascorbic acid and untreated samples during hot air drying

H_{02} (Null): Increasing drying temperature from 50 to 70 °C does not significantly affect moisture diffusivity or drying performance of pretreated sweet potato

H_{12} (Alternative): Increasing drying temperature from 50 to 70 °C significantly affects moisture diffusivity or drying performance of pretreated sweet potato

H_{03} (Null): There is no significant difference in prediction accuracy among Newton, page, Henderson-Pabis, logarithmic, two term and Midilli et al. models for thin layer drying kinetics of sweet potato.

H_{13} (Alternative): The model proposed by Midilli et al. provides a significantly better fit for the thin-layer drying kinetics of sweet potato than the other tested models.

MATERIALS AND METHODS

Osmotic Pretreatment of Sweet Potato Sample

Sweet potatoes were collected from the Center for Dry Land Agriculture Farm at Bayero University, Kano, Nigeria. They were sorted, cleaned, washed, and peeled using a stainless-steel knife. Potatoes were cut into 2, 4, and 6 mm thick pieces with a circular cutter dimension of (4 mm diameter) to ensure uniform area. The different thickness were used for comparative experiments and subsequent analyses focused on the optimum thickness condition. All experiments were conducted in triplicate (n=3), with results reported as mean ± standard error to reduce random error and ensure reproducibility.

Osmotic Pretreatment

The osmotic pretreatment was carried out using a sample-to-solution ratio of 1:10w/v (100 g sweet potato soaked in 1000 ml of the solution). The treatments included control (distilled water), NaCl (Sigma Aldrich), $CaCl_2$ (Science Company), and $C_6H_8O_6$ (ascorbic acid; Oxford Lab) at concentrations of 5, 10, and 15% w/v. The mixture was then steeped for 4, 6, and 8 hours. Samples were weighed at intervals of 40 minutes until equilibrium was achieved. After pretreatment, the water was drained, and the surface was dried by gently blotting with clean tissue paper.

Drying Experiments

Drying was conducted using a conventional oven dryer (DHG 9248-A JINGHONG, fitted with a thermostat for temperature control and a fan for forced air circulation at a constant velocity of 1. 5 m/v throughout the experiment with relative humidity (RH) ranging between 18 and 20% and was monitored using a digital thermohygrometer (model HTC-1, Shenzhen Technology Co., China). It was positioned inside the drying chamber near the sample tray to provide a representative measurement of the drying conditions surrounding the sweet potato. The dryer was preheated for 1 hour to the target temperature of 50, 60, or 70°C before the samples were loaded.

The sliced potato samples were uniformly arranged on the trays before being introduced into the dryer. Drying was conducted continuously, and the samples were removed at 40-min intervals (0, 40, 80, 120, 160, 200, and 240 minutes). At each interval, the samples were weighed immediately using an analytical weighing balance and returned to the dryer for continued drying.

Moisture Content Determination

The moisture content of the samples at each interval was calculated using Equation (1):

$$moisture\ content\ \% = \frac{w_t - w_f}{w_f} * 100 \qquad (1)$$

Where;

W_t weight at time t and

W_f is the final dry weight after drying weight at constant temperature 105°C for 4 hours

Moisture Diffusivity

The effective moisture diffusivity test was conducted using Fick's second law of diffusion following the method described by Clifford et al., (2014). The sliced potato was assumed to behave as an infinite slab during drying.

The moisture ratio (MR)was expressed using Equation (2):

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

Where;

M_t moisture content at time t

M_o initial moisture content

M_e equilibrium moisture content

The equilibrium moisture content values were small compared with M_t and M_o, especially at the drying temperature used; therefore, M_e was assumed to be negligible. This assumption has been widely adopted in thin-layer drying studies of fruits, vegetables, and tuber crops. Therefore, the moisture ratio was simplified as follows using Equation (3):

$$MR \frac{M_t}{M_0} \qquad (3)$$

Drying continued until the sweet potato attained a constant weight at 240 minutes, which was considered as equilibrium for the purpose of the drying curve analysis.

For a long drying period, Fick's second law was simplified in Equation (4):

$$\text{MR} = \frac{8}{\pi^2} \exp(-\frac{\pi^2 Dt}{4L^2}) \qquad (4)$$

Taking the natural logarithm in Equation (5):

$$\ln(\text{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \frac{-\pi^2 Dt}{4L^2} \qquad (5)$$

Thus, from the plot of ln (MR) vs. drying time (t), the slope was obtained using Equations (6 & 7):

$$\text{Slope} = -\frac{\pi^2 D}{4L^2} \qquad (6)$$

Thus:

$$D = -\text{Slope} \times \frac{4L^2}{\pi^2} \qquad (7)$$

Where;

D effective moisture diffusivity (m^2/s)

L half thickness of potato slice (m)

t drying time (s)

MR moisture ratio

2.6 Osmotic Dehydration

Water loss (WL) and Solid gain (SL) of sweet potatoes were calculated using Equations (8 & 9):

$$WL(\%) = \frac{W_i X_i - W_f X_f}{W_i} * 100 \qquad (8)$$

$$SG(\%) = \frac{W_i(1-X_f) - W_f(1-X_i)}{W_i} * 100 \qquad (9)$$

Where;

W_i initial sample weight

W_f final sample weight

X_i initial moisture fraction

X_f final moisture fraction

Proximate Composition

Moisture Content Determination

The moisture content of the sweet potato was determined according to the method described by AOAC (2010) using the oven drying method. Approximately 2 g of the sweet potato was dried at 105 °C to a constant weight. The weight loss after drying was used to calculate the moisture content using Equation (10):

$$\text{moisture content } (wb) = \frac{w_i - w_f}{w_i} * 100 \quad (10)$$

Where;
WC (wb) moisture content on wet basis (%)
$\boldsymbol{W_i}$ initial weight of the sample (g)
$\boldsymbol{W_f}$ final weight of the sample (g)

Ash Content Determination

Ash content was determined by incineration in a muffle furnace following the procedure of the Association of Official Analytical Chemists (Mortensen & Wallin 1989). The residue remaining after incineration represented the ash content and was expressed as percentage of the original sample weight using the Equation (11):

$$\% \, Ash = \frac{w_3 - w_1}{w_2} * 100 \quad (11)$$

Where;
W_1 empty crucible weight
W_2 Sample weight
W_3 Crucible + ash weight

Crude Protein Determination

The protein content was determined using the Kjeldahl method according to the AOAC International method. Approximately 1 g of dried sweet potato was placed in a digestion flask, and 15 mL of sulfuric acid and a digestion catalyst mixture consisting of potassium sulfate and copper sulfate was added to accelerate digestion and increase the boiling point. The mixture was digested at approximately 420 °C until a clear solution was obtained. After cooling, the digest was diluted with distilled water and transferred into the flask. Ammonia released during distillation was collected in a 40% boric acid solution containing a mixed indicator and titrated against a standardized 0.1 N hydrochloric acid (HCl). The nitrogen content was first calculated and subsequently converted to crude protein using appropriate conversion factor
The percentage nitrogen was calculated using Equation (12):

$$\% \, N = \frac{(T-B)N * 14.007 * V_d * 100}{w_s * V_a * 1000} \quad (12)$$

Where;
T sample titration volume (ml)
$\boldsymbol{B}$ blank titre value (ml)
N normality of acid
$\boldsymbol{V_d}$ total volume of digest (ml)
$\boldsymbol{V_a}$ volume of digest distilled (ml)
$\boldsymbol{W_S}$ weight of sample (g)
The crude protein content was obtained by multiplying the nitrogen value by a conversion factor of 6.25.

Rehydration Capacity Determination

Rehydration capacity was determined using the method described by Kim et al. (2023). One gram of dried sweet potato sample was weighed and marked as (R_1). The weighed sample was soaked in 100 mL distilled water for 60 min at room temperature. The soaking duration was selected based on a pilot trial and previous literature report indicating that most dried root and tuber crops attain near equilibrium water absorption within 60 min under ambient rehydration conditions. After soaking, the samples were drained, gently blot with tissue paper to remove excess surface water, and weighed again. The final weight was recorded as (R_2). The rehydration ratio was calculated using Equation (13):

Rehydration Ratio (%)=R_1R_2*100 (13)

Where;
$\boldsymbol{R_1}$ weight of dried sample before soaking
$\boldsymbol{R_2}$weight of sample after soaking for 60 min

Theoretical Energy Requirement and Mass Transfer Parameter

The theoretical energy associated with moisture evaporation during drying was estimated using the mass of water removed from the sweet potato samples. The energy associated with water evaporation was calculated as Equation (14):

$$Q_e = M_w * h_{fg} \quad (14)$$

Where;
Q_e theoretical evaporation energy (kJ)
M_w mass of water evaporated (kg)
h_{fg} latent heat of vaporization of after drying temperature (kJ/kg)
The latent heat of vaporization was adjusted according to the drying temperature rather than assuming a constant value at 100 °C. Approximate values were used (2383 kJ/kg at 50^{O}C, 2358 kJ/kg at 60^{O}C, 2334 kJ/kg at 70^{o}C)
The sensible heat required to raise temperature of the sweet potato during was calculated using Equation (15):

$$Q_s = mc\Delta T \quad (15)$$

Where;
$\boldsymbol{Q_s}$ heat energy supplied (kJ)
$\boldsymbol{m}$ mass of sample (kg)
$\boldsymbol{c}$ specific heat capacity of sweet potato (3500 J/kg·K)
$\boldsymbol{\Delta T}$ temperature difference between drying temperature and ambient temperature (K)

Thin-Layer Drying Model Fitting

The moisture content data obtained during drying were converted into dimensionless moisture ratios (MR) using Equation (16):

$$MR = \frac{M_t}{M_o} \quad (16)$$

Where;
M_t moisture content at time
M_0 initial moisture content
The drying data was fitted to three thin layer drying models: Newton, Page and Henderson and Pabi's models using nonlinear regeneration analysis using Equations (17- 19).
The models used were:
Newton model

$$MR = e^{-kt} \quad (17)$$

Page model

$$MR = e^{-kt^n} \quad (18)$$

Henderson and Pabi's model

$$MR = ae^{-kt} \quad (19)$$

In addition, the drying data were further fitted to two-term, logarithmic, and Midilli et al. models using Equations (20 - 22):

Logarithmic Model

$$MR = e^{-kt} + C \quad (20)$$

Two-term model

$$MR = ae^{-k_o t} + be^{-k_1 t} \quad (21)$$

Midilli et al. Model

$$MR = a^{-kt^n} + b.t \quad (22)$$

Model suitability was evaluated based on the coefficient of determination (R^2) and root mean square error (RMSE). The best-fitting model was the one with an R^2 value closest to 1 and the lowest RMSE value.

Experimental Design and Statistical Analysis

A randomized complete block design was used to account for potential variability between experimental runs. Data obtained were subjected to statistical analysis using OriginPro software (version 2024; OriginLab Corporation, Northampton, MA, USA). Analysis of variance was performed using a two-way factorial design to evaluate the effects of pretreatment types, osmotic concentration, soaking time, slice thickness, and drying temperature on the measured responses. Mean separation was performed using Duncan's multiple range test at a significant level of $p<0.05$. Drying curves and regression analyses were generated using OriginPro. Thin-layer drying was fitted to experimental data using nonlinear regression analysis. The adequacy of the model fitting was evaluated using the coefficient of determination (R^2) and root mean square error. The model with the highest R^2 value and lowest RMSE value was considered the best model for describing the drying kinetics of the sweet potato slices

The root mean square error (RMSE) was calculated using Equation (23):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2} \quad (23)$$

Where;

MR_{exp}= experimental moisture ratio

MR_{pre}= predicted moisture ratio

N= number of observations

The coefficient of determination (R^2) was used to determine the correlation between the experimental and predicted moisture ratio values.

RESULTS AND DISCUSSION

Influence Of Osmotic Pretreatment on Moisture Loss of Sweet Potato

Moisture loss during osmotic pretreatment of sweet potato was influenced by the type of solution, concentration of solution, soaking duration, and thickness of the slice. Moisture reduction increased with soaking time, and thinner slices exhibited faster moisture migration than thicker slices. Sweet potato treated with 15% NaCl solution showed the highest moisture loss, followed by $CaCl_2$ and ascorbic acid treatments. The control sample showed the least moisture reduction throughout the pretreatment time. The increased moisture loss observed in the osmotic solutions could be attributed to the concentration gradient established between the sweet potato tissue and the surrounding hypertonic solution, leading to water diffusion from the sample into the solution.

Table 1 shows the moisture content of sweet potato slices during pretreatment at a 10% concentration and 4 mm thickness. A decrease in moisture content was recorded during the early stages of osmotic treatment owing to the rapid removal of water from the slice surface. Over time, the rate gradually decreased as equilibrium was approached.

Table 1: Loss of moisture of sweet potato during different osmotic pretreatment time

Time (min)	Control	NaCl	$CaCl_2$	$C_6H_80_6$
0	78.54 ± 0.00[a]	78.54 ± 0.00[a]	78.54 ± 0.00[a]	78.54 ± 0.00[a]
40	76.81 ± 0.42[a]	71.34 ± 0.37[c]	73.52 ± 0.39[d]	74.18 ± 0.41[b]
80	74.92 ± 0.38[a]	66.28 ± 0.34[d]	69.11 ± 0.36[c]	70.35 ± 0.37[b]
120	72.47 ± 0.36[a]	60.74 ± 0.31[d]	64.85 ± 0.33[c]	66.28 ± 0.35[b]
160	69.88 ± 0.34[a]	55.13 ± 0.28[d]	60.22 ± 0.31[c]	62.17 ± 0.34[b]
200	67.44 ± 0.33[a]	50.91 ± 0.26[d]	56.48 ± 0.29[c]	58.92 ± 0.31[b]
240	65.73 ± 0.31[a]	47.62 ± 0.24[d]	52.74 ± 0.27[c]	55.83 ± 0.29[b]
280	64.31 ± 0.29[a]	45.16 ± 0.22[d]	50.41 ± 0.25[c]	53.67 ± 0.27[b]
320	63.54 ± 0.28[a]	43.92 ± 0.21[d]	48.87 ± 0.24[c]	52.44 ± 0.26[b]
360	63.02 ± 0.27[a]	42.73 ± 0.20[d]	47.94 ± 0.23[c]	51.88 ± 0.25[b]

Values are presented as the mean ± standard error of triplicate determinations (n=3). Means with different superscript letters within the same row are significantly different ($p < 0.05$).

Influence of Treatment Concentration and Soaking Period

Increasing the osmotic concentration from 5% to 15% significantly enhanced moisture removal from sweet potatoes. Continuous diffusion from sweet potato tissue was observed with soaking time in the osmotic solution until equilibrium gradually approached. NaCl resulted in the highest water loss of all concentrations, which may be attributed to its strong osmotic effect and high ionic dissociation in solutions. Analysis of variance showed that osmotic concentration significantly affected moisture loss in sweet potato samples [$F(2,24) = 64.38$, $p < 0.001$] (Fig 1a).

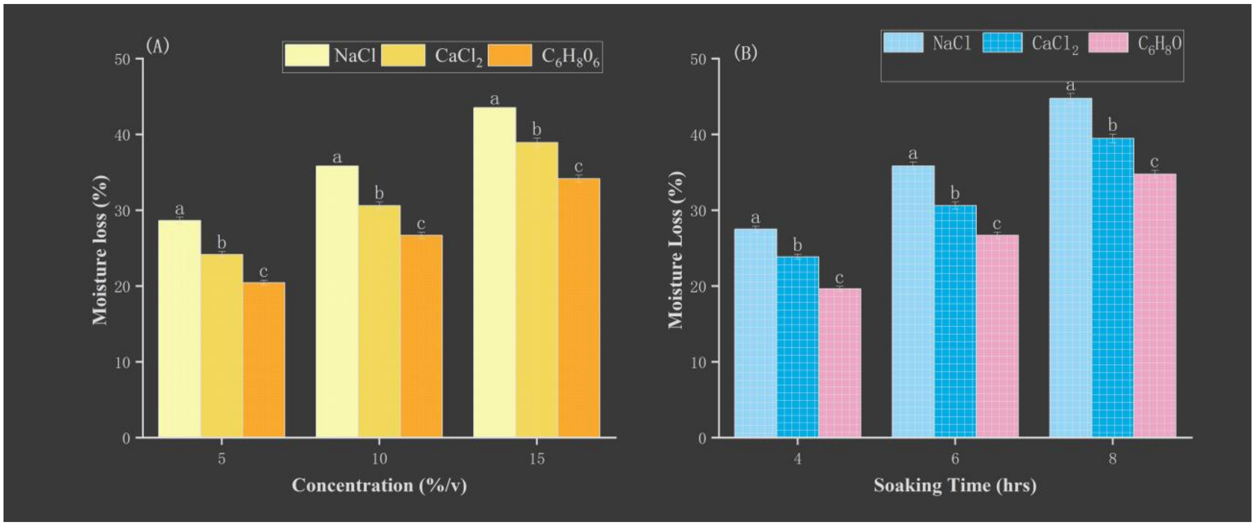

Figure 1: Schematic representation of effect of osmotic pretreatment concentration on moisture reduction of sweet potato samples during hot air drying (A) Effect of osmotic solution concentration on moisture loss of sweet potato sample pretreated with NaCl, $CaCl_2$, and $C_6H_8O_6$. Values are expressed as mean ± SE ($n = 3$). Different superscript letters indicate significant differences among treatments at $p < 0.05$ (B) effect of soaking time on moisture loss of sweet potato sample subjected to different osmotic pretreatments. Values are presented as mean ± SE ($n = 3$). Means with different superscpipt letters are significantly different at $p < 0.05$.

Longer soaking time significantly improves moisture removal. Sweet potato slices soaked for 8 h recorded the greatest reduction in moisture content. Increased moisture loss with respect to time showed continuous diffusion of water from the sweet potato tissue into the osmotic solution until equilibrium was gradually achieved. One-way analysis of variance (ANOVA) revealed that soaking time significantly influenced moisture loss during osmotic pretreatment [$F(2,24) = 71.56$, $p < 0.001$] (Fig 1.b).

Water Loss, Solid Gain, Diffusivity and Rehydration Characteristics

Pretreatment of sweet potatoes resulted in simultaneous water loss and solute uptake by the tissue. NaCl-treated samples showed the highest solid gain owing to the penetration of salt ions into the tissue matrix. Diffusion of moisture increased with drying temperature and osmotic pretreatment concentrations. The values recorded ranged from 1.12 10^{-8} to 4.21 x 10^{-8} m^2/s, which is within the range reported for food products, such as sweet potatoes, carrots, and other root crops. High diffusion was observed in NaCl-treated sweet potato samples, showing improved internal moisture migration. Increasing the drying temperature and enhancing molecular mobility led to fast moisture diffusion from the interior of the sweet potato tissues to the surface.

The rehydration ratio decreased with increasing drying temperature and osmotic concentration. The sample pretreated with $CaCl_2$ recorded better structural integrity and higher rehydration capacity than the NaCl-pretreated sweet potato samples. The lower rehydration ratio observed in NaCl-treated samples may be attributed to tissue shrinkage and structural collapse caused by intense osmotic dehydration, as shown in (Table 2). The uptake of the solute during osmotic dehydration may improve textural stability and reduce enzymatic deterioration during subsequent drying.

Table 2: Water loss, solid gain, effective moisture diffusivity and rehydration characteristics of osmotic pretreated sweet potato samples

Treatment	Water loss (%)	Solid gain (%)	50°C (m^2/s)	60°C (m^2/s)	70°C (m^2/s)	Initial weight (g)	Rehydration weight(g)	Rehydration ratio (%)
Control	12.84 ± 0.31 ^{d}	0.00 ± 0.00 ^{d}	(1.12 ± 0.05)×10^{-8d}	(1.86 ± 0.07)×$10^{-8\,d}$	(2.74 ± 0.09) ×$10^{-8\,d}$	1.00 ± 0.00 ^{a}	3.74 ± 0.06 ^{a}	374 ± 5.82 ^{a}
NaCl (15%)	43.52 ± 0.67 ^{a}	8.61 ± 0.24 ^{a}	(1.84 ± 0.07) ×$10^{-8\,a}$	(2.96 ± 0.10) ×$10^{-8\,a}$	(4.21 ± 0.14) ×$10^{-8\,a}$	1.00 ± 0.00 ^{a}	2.91 ± 0.05^{c}	291 ± 4.73 ^{c}
$CaCl_2$ (15%)	38.91 ± 0.58 ^{b}	6.42 ± 0.19 ^{b}	(1.56 ± 0.06) ×$10^{-8\,b}$	(2.44 ± 0.09) ×$10^{-8\,b}$	(3.62 ± 0.12) ×$10^{-8\,b}$	1.00 ± 0.00 ^{a}	3.28 ± 0.05^{b}	328 ± 5.14^{b}
$C_6H_80_6$ (15%)	34.14 ± 0.49 ^{c}	4.85 ± 0.16 ^{c}	(1.31 ± 0.05) ×$10^{-8\,c}$	(2.12 ± 0.08) ×$10^{-8\,c}$	(3.18 ± 0.11) ×$10^{-8\,c}$	1.00 ± 0.00^{a}	3.11± 0.04 ^{bc}	311± 4.92 ^{bc}

Values are expressed as the mean ± standard error of triplicate determinations (n=3). Mean with different superscript letters within the same column are significantly different at p<0.05

Influence of Thickness on Drying Behavior

The thickness of the slice significantly affects mass transfer during pretreatment. The 2 mm slices showed the highest moisture loss, whereas the 6 mm slice retained more moisture after treatment. High moisture loss observed in the thinner slices may be due to their larger surface area to volume ratio, which enhanced water diffusion during osmotic treatment. One-way ANOVA showed that slice thickness and pretreatment significantly affected the moisture content of sweet potato samples [F (3,32) = 48.72, p , 0.001] (Fig. 2a).

The drying behavior of the pretreated sweet potato was characterized by a continued decrease in moisture content with increasing drying time and temperature. The sweet potato pretreated with osmotic solutions exhibited moisture removal faster than the untreated control sample. The enhanced drying behavior may be linked to partial water removal during pretreatment, resulting in a low quantity of free water remaining within the tissue before drying. The NaCl-treated sample showed the fastest moisture reduction during a longer soaking period and higher concentration. Sample sliced at 2 mm thickness dried faster than 4 and 6mm sweet potato due to internal diffusion paths. The rapid moisture reduction observed in the NaCl treatment may be attributed to increased osmotic dehydration before drying, which results in a lower initial moisture content and enhanced mass transfer during drying. A repeated-measures analysis of variance indicated that drying time and pretreatment significantly influenced moisture reduction during drying [$F(6,56) = 126.44$, $p < 0.0001$] (Fig. 2b).

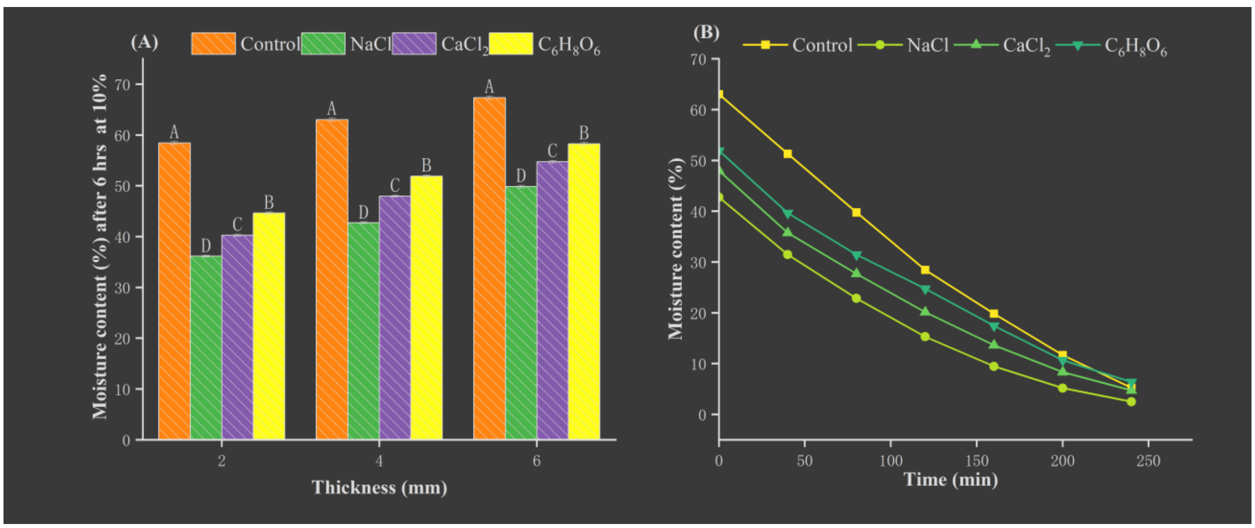

Figure 2: Influence of the thickness of moisture reduction in sweet potato samples under different osmotic pretreatments (A) and effect of slice thickness on the moisture content of osmotically pretreated sweet potato samples after 6 h of soaking in 10% (w/v) osmotic solution. Values are presented as mean ± SE(n=3). Bars with different subscript letters differ significantly at < 0.005, according to Duncan's Multiple Range Test (B). Drying curve of the control and osmotically pretreated sweet potato samples during hot air drying at 70 °C. Values are presented as mean ± SE (n=3).

Proximate Composition

The final moisture content of the dried sweet potato decreased with increasing drying temperature (Table 3). Potatoes treated with NaCl recorded the lowest residual moisture content after drying. Ash content slightly increased after drying, which was attributed to the concentration of mineral components after moisture removal (Table 3). The $CaCl_2$-pretreated samples recorded higher ash contents, which was also attributed to mineral uptake during treatment. Reduction in moisture content in osmotic-treated samples may improve storage stability and reduce microbial spoilage during storage.

Table 3: Proximate composition of dried sweet potato samples subjected to different osmotic pretreatments

Parameters (%)	Control	NaCl (15%)	$CaCl_2$ (15%)	$C_6H_80_6$ (15%)
moisture	5.22 ± 0.14^{b}	2.48 ± 0.16^{d}	4.71 ± 0.16^{c}	6.35 ± 0.16^{a}
ash	2.74 ± 0.05^{d}	3.91 ± 0.16^{c}	4.22 ± 0.16^{a}	3.06 ± 0.16^{b}
Crude protein	4.38 ± 0.16^{d}	4.57 ± 0.16^{b}	4.63 ± 0.16^{a}	4.44 ± 0.16^{c}

Values are presented as the mean standard ± error (n=3). Mean with different superscripts letters within the same rows indicate are significantly different (p<0.05)

Theoretical Evaporation Energy and Effective Moisture Diffusivity

Table 4 presents comparative thermal energy associated with moisture rather than actual dryer efficiency. The theoretical evaporation energy increased with drying temperature because greater moisture removal occurred at high temperatures. Higher temperatures increase the vapor pressure gradient between the surface of the sweet potato and the drying air, thereby speeding up moisture diffusion. Similar data were reported by Kudra and Mujumdar (2009), who observed that increasing the drying temperature aids the heat and mass transfer rate during the convective drying process.

However, the actual thermal efficiency of the laboratory dryer could not be determined because electrical energy consumption and system heat losses were not experimentally measured. Therefore, the calculated values represent the theoretical evaporation energy rather than the true dryer efficiency. Laboratory-scale hot air dryers commonly exhibit relatively low thermal efficiencies because of heat loss through chamber walls and exhaust air. Similar limitations were reported by (Singh & Heldman, 2014) in studies using convective drying systems.

Table 4: Heat and mass transfer attributes of sweet potato samples during hot air drying

Temperature (°C)	Water evaporated (kg)	Latent heat h_{fg} (kJ/kg)	Evaporation Energy Q_e (kj)
50	0.068 ± 0.002^{A}	2383 ± 3.12^{C}	161.04 ± 0.008^{C}
60	0.072 ± 0.002^{A}	2358 ± 3.48^{B}	169.78 ± 0.009^{B}
70	0.076 ± 0.002^{A}	2334 ± 3.76^{A}	177.38 ± 0.0010^{A}

Values are presented as the mean ± standard error of triplicate determinations. Means with different superscript letters differ significantly at ($p<0.05$) between columns. The evaporation energy value reported represents the theoretical thermodynamic minima based on the latent heat of vaporization. Actual dryer energy consumption expected to be higher due to heat losses, fan power and inefficiencies in electrical to thermal conversion

Thin Layer Drying Model Fitting

The drying data model exhibited (R^2 = 0.981–0.997) and relatively low (RMSE 0.008 – 0.028), indicating strong agreement between the experimental and predicted moisture ratios. Among the models, the Newton model showed comparatively poorer performance attributed to its single exponential assumption of that fail to account for internal diffusion resistance prevalent in food materials during falling rate drying. A limitation consistently reported in thin layer drying studies of fruits, vegetables and roots crops. The Page model demonstrated high prediction accuracy, and the inclusion of additional models, such as the Midilli et al. and two-term models, improved the robustness of the model comparison and reduced the likelihood of overfitting risk. (Table 5).

Table 5: Thin-Layer Drying Model Parameters for NaCl Pretreated Sweet Potato (15%, 8 h, 2 mm)

Model	Parameters	95% Confidence Interval	R^2	RMSE
Newton	k = 0.0115	0.0101 ≤ k ≤ 0.0129	0.981	0.028
Page	k = 0.0036, n = 1.32	0.0031 ≤ k ≤ 0.0042; 1.24 ≤ n ≤ 1.39	0.994	0.014
Henderson & Pabis	a = 1.02, k = 0.0108	0.97 ≤ a ≤ 1.06 ; 0.0098 ≤ k ≤ 0.0119	0.988	0.022
Logarithmic	a = 0.96, k = 0.0122, c = 0.041	0.91 ≤ a ≤ 1.01 ; 0.0111 ≤ k ≤ 0.0134 ; 0.033 ≤ c ≤ 0.049	0.995	0.012
Two-Term	a = 0.61, b = 0.39, k_0 = 0.015, k_1 = 0.006	0.56 ≤ a ≤ 0.66 ; 0.34 ≤ b ≤ 0.44 ; 0.0137 ≤ k_0 ≤ 0.0164 ; 0.0052 ≤ k_1 ≤ 0.0068	0.996	0.010
Midilli et al.	a = 0.998, k = 0.0031, n = 1.35, b = -0.00008	0.982 ≤ a ≤ 1.014 ; 0.0027 ≤ k ≤ 0.0036 ; 1.29 ≤ n ≤ 1.41; -0.00011 ≤ b ≤ -0.00005	0.997	0.008

Discussion

Sweet potatoes of 2 mm pretreated with 15% NaCl has exhibited the highest moisture reduction. This observation agrees with the findings of Doymaz (2012), who reported that thinner food materials exhibit faster moisture removal owing to a shorter internal diffusion path and a larger surface area to volume ratio. Krokida and Maroulis (2022) also observed that a longer soaking period and higher osmotic solution concentration enhanced water loss in osmotically treated foods owing to a greater osmotic pressure gradient between the food product tissue and the surrounding solution. The high moisture loss observed in the NaCl-treated samples may be attributed to the strong osmotic effect and high ionic dissociation of NaCl, which promotes the rapid migration of water from the sweet potato tissue into the hypertonic medium. Falade and Oyedele (2010) reported that pretreatment with salt enhanced moisture removal and reduced the drying time. However, excess osmotic concentration and longer soaking time may adversely impact sensory attributes owing to excessive solute uptake and tissue softening. This is in accordance with the report by Torregiani (1993), who observed that excessive osmotic dehydration may adversely affect the texture and taste characteristics of dried foods.

Moderate moisture loss and improved firmness were observed in the $CaCl_2$-pretreated samples, which may be attributed to the calcium-mediated strengthening of the cell wall structure through cross linking with pectic substance in the middle lamella. Similar observations were reported by Lewicki (2006), found that calcium salt enhance the structural rigidity and reduced tissue collapse g fruits and vegetables. The high ash content observed in $CaCl_2$-treated sweet potatoes also supports the possibility of mineral uptake during osmotic pretreatment. However, ascorbic acid pretreatment produced lower moisture loss but may provide antioxidant protection and color retention during drying. This observation suggests that osmotic pretreatment can significantly enhance moisture removal before drying, thereby potentially reducing drying time, improving product stability, and enhancing energy efficiency. Calín-Sánchez et al. (2020) and Chu et al. (2023), reported that ascorbic acid treatment helps minimize oxidative browning and preserve color quality in dried plant materials. The lower dehydration effects of ascorbic acid may be linked to its lower osmotic strength relative to salt solutions.

The increased rate of effective moisture diffusivity with increasing drying temperatures observed in this work is consistent with the general principle that higher temperatures increase molecular mobility and internal moisture migration. The diffusivity obtained (1.12×10^{-8} to 4.21×10^{-8} m^2/s) is within the range reported for biological materials during convective drying. Diffusivity ranges were reported by Zeng et al. (2024) for food materials subjected to hot air drying. NaCl pretreatment enhanced moisture removal and diffusivity, resulting in shorter drying times and lower residual moisture content. However, excessive osmotic dehydration reduced rehydration capacity due to tissue shrinkage. Similar findings were reported by Drosou et al. (2022), who observed that intense drying conditions and excessive moisture removal reduced the water absorption capacity of dried products owing to irreversible cellular damage.

Drying efficiency increased with drying temperature, indicating improved heat and mass transfer at higher temperatures. This is in accordance with the findings of Mujumdar (2014). However, high temperatures may negatively affect the structural and sensory quality of dried products owing to hardening and thermal degradation. The Midilli model showed the best fit with experimental drying data with highest coefficient of determination of (R^2=0.997, RMSE of 0.008), consistent with several previous studies (Akpinar, 2006; Midilli et al., 2002). Poor prediction accuracy of the Newton model at intermediate drying times observed in this study may be because the model assumes a single exponential moisture removal mechanism and does not adequately account for internal diffusion resistance. The Henderson and Pabis model provided a better fit than the Newton model but was less accurate than the Page model. The Midilli model slightly outperformed Page because of the additional linear correction that enhanced the prediction at the later drying stages. The confidence level showed narrow variation, indicating stable nonlinear regression fitting the experimental drying conditions. The Midilli et al. model presented the narrowest residual distribution and highest prediction accuracy, confirming its suitability for explaining the drying kinetics of NaCl-pretreated sweet potato slices at 70 °C. However, the behavior of drying confirms that moisture migration occurs mostly in the falling-rate period, which is a characteristic of diffusion-controlled drying behavior in biological materials. The results obtained support the three hypotheses of the study.

CONCLUSION

This study demonstrated that osmotic pretreatment, particularly 15% NaCl for 8 hours., effectively intensified convective drying of sweet potato slices. Greater moisture reduction under these conditions reflects reduced diffusion path length from thin slicing and a strong osmotic pressure gradient from NaCl dissociation. Together, these mechanisms enhanced effective moisture diffusivity (1.12×10^{-8} to 4.21×10^{-8} m^2/s) and shortened drying, aligning with literature while providing quantitative benchmarks for sweet potato processing. This work also delineated a clear trade-off among pretreatments, showing selection should be guided by drying speed rather than final product quality targets. The Midilli model was the best fit (R^2=0.997, RMSE = 0.008) across treatments and temperatures, confirming robustness for thin-layer drying of root vegetables and providing a reliable tool for process scale-up and optimization. Therefore, 15% NaCl for 8 hours. (2-slices thickness) is recommended. Although theoretical evaporation energy increases with temperature, the actual energy efficiency was not assessed. Therefore, future studies should validate energy consumption claims through direct power monitoring. This research was conducted on a laboratory scale, so industrial-scale validation is necessary. Additionally, the sensory evaluation of the final products was not performed. This method can be adopted for premium food products that need to preserve natural color and antioxidants; ascorbic acid is recommended. Also, $CaCl_2$ is suitable for products that require firmness, crunchiness, or rehydration.

From the hypothesis of the study, (H_{11}, H_{12}, and H_{13}) were accepted and their corresponding null hypothesis (H_{01}, H_{02}, and H_{03}) were rejected based on the experimental evidence; H_{01} (no osmotic pretreatment effect) was rejected. NaCl pretreatment (15%, 8 h) produced a significantly higher effective moisture diffusivity (4.41×10^{-8} m^2/s at 70 °C) than $CaCl_2$ (3.62×10^{-8}), ascorbic acid

(3.18×10^{-8}), and untreated control (2.74×10^{-8}) ($p<0.005$). Thus, H_{11} was accepted, confirming that NaCl enhanced moisture migration during drying. H_{02} (no temperature effect) was rejected. Increasing the drying temperature from 50 to 70 °C increased the moisture diffusivity by approximately 129% in NaCl osmotic-treated samples ($p<0.05$). Thus, H_{12} was accepted, confirming that higher temperatures improve drying. And H_{03} (no difference between drying models) was rejected. The Midilli et al. model achieved the highest R^2 (0.997) and lowest RMSE (0.008), showing a better fit than the Newton (R^2 =0.981, RMSE=0.028), Page (R^2= 0.994, RMSE=0.014) and Hendersons & Pabis (R^2=0.988, RMSE=0.022) models. Thus, H_{13} was accepted, confirming that the Midilli model is the best-fit model for describing the thin-layer drying kinetics of osmotic-pretreated sweet potato slices under the conditions investigated in this study.

Data Availability Statement

Data will be made available on request.

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