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Drying Pandan Leaves Using Step-Down Microwave Power: Approach for Drying Efficiency, Color Quality, and Energy Consumption

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Abstract

This study investigated the application of a step-down microwave (MW) power technique for drying pandan leaves (*Pandanus amaryllifolius*), assessing its performance against constant-power drying across a range of 100–800 W. Key parameters evaluated included drying kinetics, color quality, specific energy consumption, and effective moisture diffusivity. The results indicated that while constant high MW power of 800 W achieved the shortest drying time of 8 min, it caused significant chlorophyll degradation ($a^* = -1.63$) and high energy use. In contrast, the step-down protocol at MW power of 450 W for 10 min, followed by 200 W, effectively combined rapid initial moisture removal with a gentler finishing phase. This approach yielded a competitive drying time of 16 min, significantly better color preservation, and a 54% reduction in specific energy consumption compared to constant MW power drying at 800 W. The maximum effective moisture diffusivity for the step-down method was calculated to be 7.911×10^{-14} m^2/s. The prediction model based on the Arrhenius equation confirmed that effective moisture diffusivity is a temperature-activated process. Therefore, the step-down MW technique is recommended as an efficient, energy-saving, and quality-preserving method for drying pandan leaves.

Introduction

Pandanus amaryllifolius, commonly known as pandan leaf, is an aromatic plant found in tropical regions. It is widely used in Southeast Asian cuisine and traditional medicine for its distinctive flavor. This versatile plant serves multiple purposes, including acting as a natural flavor enhancer and green colorant in foods and beverages, as well as an aromatic wrapper for various dishes. Effective post-harvest preservation, primarily

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through drying, is essential to reduce perishability and ensure longer storage. Conventional drying methods, such as open-sun drying, are typically slow, reliant on environmental conditions, and susceptible to microbial contamination, which can lead to quality loss. Although conventional hot-air drying provides better control, it generally involves high energy consumption and processed heat loss, along with degradation of the aromatic compounds, when the materials are subjected to high temperature drying (Rayaguru & Routray, 2011; Skendi et al., 2023). Microwave drying offers a more advanced alternative by employing dielectric heating that generates heat throughout the product.

This method accelerates moisture removal, reduces processing time, and can enhance energy efficiency. Research on several herbs, such as mint, basil, and drumstick, has shown that microwave drying can decrease processing time compared to hot-air drying as well as preserving essential oils (Dev et al., 2011; Kusuma et al., 2023). However, constant high microwave power can lead to non-uniform heating, causing scorching, discoloration, and structural damage. This issue is particularly a problem for chlorophyll materials such as pandan leaves, where thermal degradation can significantly impact visual quality (Ozkan et al., 2007).

To address these limitations, step-down drying protocols were investigated. This strategy involves an initial high-power phase to rapidly eliminate surface moisture content, followed by a reduced-power phase to gently extract bound water during the falling-rate period. This approach minimizes thermal stress and may enhance energy efficiency (Nathakaranakule et al., 2019). The effectiveness of variable-power techniques has been demonstrated for other products, such as walnuts, durian chips, and mangoes, where step-down drying improved energy consumption and product quality compared to constant-power processes (Chen et al., 2020; Nathakaranakule et al., 2019; Neamtang et al., 2024). For herbs like coriander and ginseng, step-down drying showed superior aroma retention and over 25% reduction in energy consumption (Łyczko et al., 2021; Jiang et al., 2021).

Previous studies have explored microwave and conventional hot-air drying of pandan leaves (Rayaguru & Routray, 2011; Fitri et al., 2023). They primarily focused on constant drying conditions without considering the advantages of power management and step-down drying. However, emerging research on a variety of food products has demonstrated the significant benefits of step-down microwave strategies. For instance, the application of step-down microwave-hot air drying for seasoned anchovies achieved a 69.6% reduction in drying time compared to conventional hot air, while also lowering specific energy consumption and enhancing product crispiness relative to constant microwave power methods (Paengkanya & Nathakaranakule, 2025). Similarly, in the drying of ripe mango slices, a step-down industrial microwave-hot air belt dryer produced superior outcomes over constant power drying, including faster drying rates, improved color retention with higher lightness and lower redness, reduced shrinkage, better texture quality, and a 56.67% reduction of energy consumption (Neamtang et al., 2024). These findings from diverse food matrices underscore the potential of step-down microwave techniques to optimize the balance between drying efficiency, energy consumption, and the final product quality. Therefore, building on the principles of varying microwave-power drying, this study systematically evaluated the drying kinetics, color preservation, specific energy consumption, and effective moisture diffusivity of pandan leaves under both constant and step-down microwave drying protocols. Additionally, the relationship between diffusivity and temperature was modeled to predict drying behavior.

The novelty of this research was in identifying the optimal drying conditions for pandan leaves using a step-down microwave power protocol. This study integrated a thorough evaluation of drying efficiency, color quality, energy consumption, and moisture diffusivity. It demonstrated how a two-stage power strategy effectively balances rapid drying with the preservation of quality, while also significantly reducing energy consumption. These findings offer valuable insights for both household and small-scale industrial applications.

Materials and methods

1. Sample preparation

Fresh pandan leaves were sourced in a single batch from a local market. Samples were selected for uniformity in size, maturity, and color, discarding any that were damaged. The selected leaves were stored in sealed plastic bags at 4–8°C for no more than 48 h in order to minimize quality degradation before the experiments. The chosen leaves were then cut into approximately 1×1 cm pieces. Before drying, the researchers determined the initial moisture content of the fresh leaves using the

oven-drying method described in the following section.

2. Drying equipment and procedures

Drying experiments were conducted using a domestic microwave oven (MS23F300EEK/ST, Samsung Electronics Co., Ltd., Thailand), which had a maximum output power of 800 W and adjustable power settings. For each experiment, a 0.5 kg sample of fresh pandan leaves was arranged in a single layer on a PTFE sieve (approximately 25 cm in diameter) placed on the glass plate, while the pandan leaf pieces were arranged in a single layer, which corresponded to a thickness of approximately 4–5 mm. The drying procedures are detailed in Table 1. The weight of the samples was recorded at 1-min intervals to monitor moisture loss and develop drying curves. The moisture content of the samples was determined by drying them in an oven (UF75, Memmert, Germany) at a temperature of 103°C for 72 h. Each determination of moisture content was performed in triplicate, and the average value was reported.

The constant MW power levels (100–800 W) were selected to encompass the full range of the microwave oven's capabilities. For the initial phase of step-down drying, a power level of 450 W was chosen based on preliminary trials, which showed efficient drying without immediate scorching. The transition to lower power levels (100 W or 200 W) was intended to gently remove bound water during the falling-rate period. The durations for the initial phase were set at 5 and 10 min to quickly eliminate surface moisture before stepping down the MW power. The drying process was terminated when the sample's moisture content reached a safe level for storage, defined as less than 10% (d.b.).

Table 1 Details of the operating parameters for the drying tests

Drying procedure	Microwave power level
Constant MW power	100, 200, 300, 450, 600, 800 W
Step-down MW power	450 W for 5 min followed by 200 W (SD1)
	450 W for 10 min followed by 100 W (SD2)
	450 W for 10 min followed by 200 W (SD3)

3. Color measurement

The color of the pandan leaf samples was analyzed using a spectrophotometer (CM-3500d, Konica Minolta, Inc., Japan) equipped with a D65 illuminant and a 10° observer angle. The color analysis was based on the CIE color system. Before each measurement, the spectrophotometer was calibrated with a standard white plate, which had the following values: L^* = 93.19, a^* = 1.12, and b^* = 1.33. In this system, L^* represents lightness or darkness, a^* indicates redness or greenness, and b^* reflects yellowness or blueness of the sample. Approximately 20 leaf samples were placed into a cup designed for the spectrophotometer. Three measurements were taken by slightly rotating the cup and the average values were reported.

To quantify the overall color change caused by drying, the total color difference (ΔE) between fresh and dried pandan leaf was calculated using the following equation (1):

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (1)$$

In this equation, L_0^*, a_0^*, b_0^* and represent the color values of the fresh leaf, while L^*, a^*, and b^* represent the color values of the dried leaves. A higher ΔE value indicates a greater color deviation from the fresh sample, reflecting a significant pigment degradation that occurs during the drying process.

4. Energy consumption determination

A kWh meter (DD28, DAI-ICHI, Thailand) was used to measure the total energy consumption for each drying treatment. The energy consumption was calculated based on the total energy used during the drying process in relation to the total amount of moisture evaporated. This relationship can be expressed with the following equation (2):

$$SEC = \frac{2.6(E_{MW})}{M_w} \quad (2)$$

where SEC represents the Specific Energy Consumption (MJ/kg $_{\text{evaporated water}}$), E_{MW} is the electrical energy used by the microwave magnetron to heat the samples (MJ), and M_w is the total amount of evaporated water (kg). A conversion factor of 2.6 accounts for losses in electricity generation, transmission, and distribution. This allows for a meaningful comparison of the total primary energy benefits for industrial application and facilitates the comparison of energy usage across different energy sources. This approach offers a more comprehensive view of overall energy consumption (Balaras et al., 2023; Wilby et al., 2014).

5. Diffusion coefficient determination

The effective moisture diffusivity (D_{eff}) is a crucial parameter that characterizes the movement of moisture within materials during the drying process. For biological materials, this moisture movement is often driven by liquid diffusion, which can be explained by Fick's second law. Assuming that the pandan leaf samples can be treated as an infinite slab with a uniform initial moisture

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distribution, with negligible external resistance, and constant diffusivity, we can simplify the solution to Fick's law. The time dependency of the effective moisture diffusivity and the moisture ratio can be calculated using the equation (3) provided by Crank (1975).

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{L^2}\right) \quad (3)$$

Here MR is the moisture ratio (proportion), M_t is the moisture content at the specific time ($g_{water}/g_{dry\ solid}$), M_0 is the initial moisture content ($g_{water}/g_{dry\ solid}$), and M_e is the equilibrium moisture content ($g_{water}/g_{dry\ solid}$). For microwave drying, it is assumed that the equilibrium moisture content (M_e) is zero when the final moisture content of the samples is below 0.1 $g_{water}/g_{dry\ solid}$. (Akpinar, 2006; Maskan, 2000; Soysal, 2004). D_{eff} is the effective moisture diffusivity (m^2/s), t represents the drying time (s), and L is the full thickness of the leaf slab (m). The average thickness of the pandan leaves was measured to be 0.25 mm using a micrometer (There were 20 leaves collected through random sampling). For longer drying times, the equation (4) can be further simplified to a linear form by taking the natural logarithm.

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{L^2} \quad (4)$$

The effective moisture diffusivity for each drying condition was determined from the slope (k) of the linear plot of ln (MR) versus time (t), where $k = (-\pi^2\ _{Deff})/(L^2)$.

The temperature dependence of effective moisture diffusivity was modeled using the Arrhenius equation (5) (Crank, 1975), which is expressed as follows:

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad (5)$$

Here D_0 is the pre-exponential factor (m^2/s), Ea is the activation energy for moisture diffusion (J/mol), R is the universal gas constant (8.314×10^{-3} J/mol·K), and T is the absolute temperature of the sample (K).

During the drying process, the sample temperature was monitored at two-minute intervals using an infrared thermometer (62 MAX, Fluke Corporation, Malaysia). To ensure accurate measurements and avoid interference from the microwave field, the microwave oven was briefly paused (for less than 5 sec) at each measurement interval to stop the magnetron. The door was then opened, and the temperature of the sample surface was measured immediately. The average temperature for each drying condition was used in the analysis. It is important to note that a domestic microwave oven may cause non-uniform heating effects, which could result in greater temperature variation in the samples. This is a limitation of this study. To determine the activation energy (E_a), the relationship between ln (D_{eff}) and the reciprocal temperature ($1/T$) was plotted, and E_a was obtained from the slope of the resulting line.

Results and discussion

1. Drying kinetics

The drying kinetics of pandan leaves were significantly influenced by the applied microwave power, as illustrated in Fig. 1 and 2. Under constant power conditions, a strong inverse relationship was observed between the microwave power level and total drying time. The 800 W setting achieved the fastest dehydration, completing the process in approximately 8 min. In contrast, the 100 W setting required around 40 min, which is more than five times longer for total drying. This substantial difference highlights the efficiency of higher microwave power in facilitating rapid moisture removal through intense volumetric heating (Makul et al., 2018). The step-down microwave (MW) power drying protocols effectively combined the rapid drying of high power with the gentle finish of lower power settings. All step-down methods began with a MW power of 450 W, which quickly removed over 60% of the initial moisture within the first 5 to 10 min. After this initial phase, the transition to lower powers (100 W or 200 W) allowed for the careful removal of bound water during the falling rate period, minimizing thermal stress on the leaf material. This two-stage approach ensured that the temperature gradient of the sample was uniform.

Comparative analyses confirmed the efficiency of the step-down MW drying strategy. The SD3 protocol, which involves 450 W for 10 min followed by 200 W, achieved complete drying in just 16 min. This duration was 57.51% faster than drying at a constant 200 W and is comparable to drying at a constant 450 W, despite the gentler finishing phase. Although the 800 W setting remained the fastest overall, the SD3 method effectively avoided extreme thermal conditions and reduced energy consumption during the drying process.

To better understand drying behavior and the rationale behind the step-down approach, Fig. 3 shows the plotting of the drying rate against moisture content. At a constant power of 200 W, the drying process was characterized by an extended falling-rate period, indicating that

moisture removal was consistently limited by internal diffusion. In contrast, at 450 W, a significantly higher drying rate was observed during the initial stage, where free surface water was removed quickly, followed by a falling-rate period. Using the step-down SD3 protocol, the initial phase at 450 W effectively removed free water during the early stages, achieving high drying rates similar to those observed with constant 450 W drying. When the MW power was subsequently reduced to 200 W, the drying rate remained comparable to that of constant 450 W. This indicates that the step-down drying approach is beneficial for energy savings. The strategic adjustment of microwave power input to align with the moisture removal mechanism demonstrates that the step-down approach achieves higher drying efficiency compared to constant high-power drying.

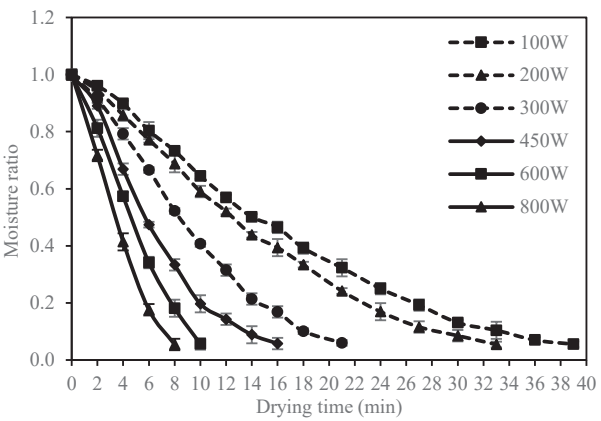


Fig. 1 Changes in the moisture ratio of pandan leaves during MW drying

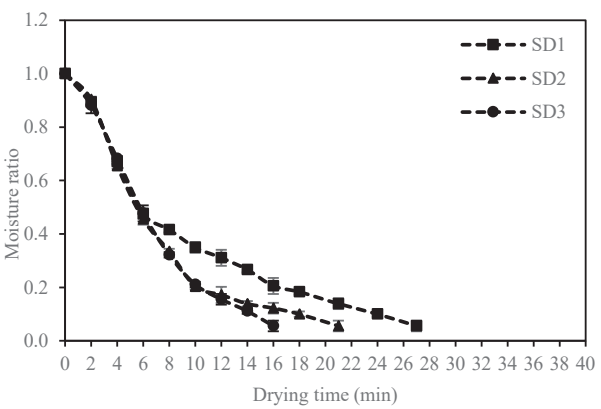


Fig. 2 Changes in the moisture ratio of pandan leaves during step-down MW drying

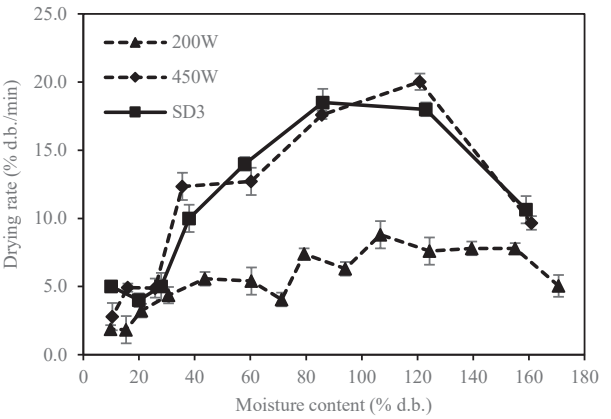


Fig. 3 Drying rate as a function of moisture content for selected drying conditions

2. Color analysis

The color parameters of the pandan leaves subjected to various drying conditions are summarized statistically in Table 2. Fresh leaves displayed a characteristic dark green coloration, indicated by low lightness ($L^* = 27.56$) and a highly negative a^* value (–8.18). Drying treatments significantly altered these characteristics, with all processed samples showing a notable increase in L^* values, signifying substantial lightening. Additionally, a general decrease in a^* values across most treatments suggested chlorophyll degradation and a shift toward redness (Van Loey et al., 1999).

The statistical analysis of a^* values revealed distinct groupings in color preservation. Fresh leaves maintained significantly superior greenness ($a^* = –8.18$) compared to all dried samples. Among the drying treatments, constant 300, 450 W, and all step-down protocols (SD1, SD2, SD3) formed a statistical group with better color retention, showing a^* values ranging from -3.93 to -3.67. In contrast, leaves dried at 600 and 800 W exhibited the poorest color preservation ($a^* = –1.15$ and –1.63), indicating severe chlorophyll degradation. The 100 and 200 W treatments exhibited an intermediate performance.

The step-down microwave approach demonstrated particular effectiveness in maintaining color quality. The protocols SD1, SD2, and SD3 achieved a^* values that were statistically superior to those from the high-power 600 and 800 W treatments. Although the constant 300 W method produced the best a^* value (–3.71b) among the dried samples, the step-down methods provided comparable color preservation while potentially offering advantages in drying efficiency. This confirms that the step-down strategy effectively mitigates color degradation associated with high-temperature exposure, making it a

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viable approach for quality-conscious drying processes (Nathakaranakule et al., 2019).

The *ΔE* values are presented in Table 2. The statistical analysis of *ΔE* revealed that the step-down protocols SD1, SD2 and SD3 (*ΔE* = 10.52, 9.27 and 11.16, respectively) were not statistically different from the constant 300 and 450 W treatments (*ΔE* = 10.16 and 11.18), which exhibited the highest total color difference. Interestingly, the constant high-power treatments at 600 and 800 W (*ΔE* = 9.43 and 8.77) showed significantly lower *ΔE* values compared to the step-down protocols. This apparent contradiction can be explained by the fact that *ΔE* represents the Euclidean distance from the fresh sample in three-dimensional color space. The MW power drying at 600 and 800 W resulted in severe greenness loss (less negative *a** values) but also showed lower lightness (*L**) values, bringing them closer to the fresh sample. For pandan leaves, the green color (*a** value) is the primary quality attribute, as it directly relates to the visual appeal and chlorophyll content. Therefore, while *ΔE* provides a useful overall metric, the *a** value remains the most critical parameter for assessing the quality of dried pandan leaves. The step-down protocols successfully preserved greenness with higher *a** values comparable to the constant MW power drying at 100–450 W.

Table 2 Colors of dried pandan leaves under different drying conditions

Drying condition	*L**	*a**	*b**	*ΔE*
Fresh pandan leaf	27.56±1.66^{c}	–8.18±0.75^{d}	15.33±1.48^{b}	NA
MW 100 W	30.36±3.37^{bc}	–3.35±1.13^{bc}	15.32±2.37^{b}	5.58±1.07^{d}
MW 200 W	35.09±2.86^{a}	–3.57±0.55^{bc}	16.93±1.56^{ab}	8.97±2.34^{c}
MW 300 W	36.15±3.26^{a}	–3.71±1.01^{c}	18.41±0.94^{a}	10.16±1.89^{bc}
MW 450 W	37.22±4.92^{a}	–3.85±1.73^{c}	18.94±1.45^{a}	11.18±1.76^{ab}
MW 600 W	33.12±2.8^{ab}	–1.15±0.52^{a}	18.27±3.46^{a}	9.43±2.11^{c}
MW 800 W	33.23±2.66^{ab}	–1.63±0.58^{a}	16.69±1.68^{ab}	8.77±1.98^{c}
SD1	36.62±2.18^{ab}	–3.67±1.14^{b}	18.19±2.83^{a}	10.52±1.65^{bc}
SD2	35.38±2.26^{a}	–3.93±1.07^{bc}	17.92±2.49^{ab}	9.27±1.42^{c}
SD3	37.17±2.09^{ab}	–3.72±0.61^{b}	18.85±1.75^{a}	11.16±1.53^{ab}

Remark: Different superscript letters in the same column indicate statistical difference ($p<0.05$), NA indicates that the data is not applicable.

3. Specific energy consumption

The evaluation of the Specific energy consumption (SEC) across different drying conditions, as presented in Fig. 4, provides crucial insights into process efficiency. The drying process with a constant microwave (MW) power of 800 W exhibited the most rapid moisture removal. However, it paradoxically demonstrated a higher SEC compared to the 300, 450, and 600 W settings. This apparent contradiction can be explained by the thermodynamic inefficiency associated with maintaining high power levels during the falling rate period, which requires substantially more energy to remove bound moisture. In contrast, the 100 W drying process avoided the risks of thermal degradation, but its prolonged duration of over 39 min resulted in the highest total SEC, consuming approximately 67% more energy than the 800 W method. This finding quantitatively confirms that excessively long drying times fundamentally undermine energy efficiency, regardless of the low instantaneous power applied.

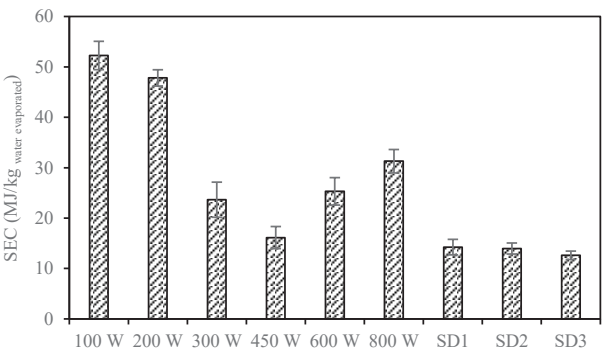


Fig. 4 Specific energy consumption of the drying process under different drying conditions

Analysis of the mid-power constant treatments (200 to 450 W) further clarifies this energy-time relationship. The 450 W setting reduced drying time by approximately 59% and achieved a lower SEC of 69% less than the 100 W process. When compared with the 800 W process, the SEC for the drying process at 450 W was still 48% lower, although the drying time was longer. This indicates that high-power drying offers a speed advantage but consumes more energy.

The step-down protocols, particularly SD3 (using 450 W for 10 min followed by 200 W), successfully decoupled the trade-off between drying rate and energy consumption, achieving the lowest energy consumption of 12.62 MJ/kg $_{\text{evaporated water}}$. This value represents the primary energy consumption, calculated by converting the measured electrical energy, using a factor of 2.6 to account for generation and transmission losses (Balaras et al., 2023). By aligning MW power application with moisture transport mechanisms, using high power for rapid free water removal during the constant rate period and then reducing MW power for the diffusion-controlled falling rate period, this approach proved effective. Although the SD3 method resulted in longer drying times than the 800 W process, it could reduce the SEC by 59% compared to the latter. This strategic step-down in MW

power demonstrates that intelligent power management, rather than simply relying on high or low power outputs, is key to optimizing both temporal and economic efficiency in microwave drying operations (Chen et al., 2020).

4. Effective moisture diffusivity

The effective moisture diffusivity (D_{eff}), calculated using Fick's second law, provides valuable insights into the internal mechanisms of moisture transport during microwave drying. It is important to note that the D_{eff} values presented here are apparent or model-based diffusivities. These values are derived from the Fickian model under the assumptions of constant diffusivity, negligible shrinkage, and uniform moisture distribution. While these values are not intrinsic material properties, they are useful parameters for comparing drying behaviors under different conditions. Table 3 summarizes the D_{eff} values along with the sample temperatures for all drying conditions. Additionally, Fig. 5–7 illustrate the model's fit with the experimental drying data. A clear and expected trend was observed under constant power conditions. The D_{eff} increased significantly with rising microwave power, from 3.323×10^{-14} m^2/s at 100 W to 15.913×10^{-14} m^2/s at 800 W. This represented an increase of nearly 4.8 times, which can be attributed to the intense volumetric heating generated by higher microwave power (An et al., 2024). For the step-down protocols, the effective diffusivity reflected the combined influence of both power stages. The SD3 protocol yielded a D_{eff} of 7.911×10^{-14} m^2/s. This value was significantly higher than that of the constant 200 W process and was comparable to the constant 450 W process. This suggests that the initial high-power phase established an efficient and rapid drying kinetic regime that persisted into the lower-power phase.

In comparison to previous research, Sultana and Ghosh (2021) reported Deff values for the thin-layer convective drying of amaranth leaves ranging from -11.770×10^{-7} to -3.245×10^{-7} m^2/s at drying temperatures of 50–80°C. They found that D_{eff} increased with rising drying temperatures. Kadam et al. (2011) studied the thin-layer convective drying of mint leaves and reported that D_{eff} varied from 1.2325×10^{-10} to 2.6568×10^{-10} m^2/s for a temperature range of 45 to 65°C. Additionally, Darvishi et al. (2016) reported the moisture diffusivity of dill leaves to be between 3.92×10^{-7} and 7.42×10^{-7} m^2/s for a temperature range of 40 to 70°C. The D_{eff} values reported for conventional hot-air drying ranging from 10^{-7} to 10^{-10} m^2/s for amaranth, mint, and dill leaves are several orders of magnitude higher than those found in the current study. This discrepancy arises primarily from the different drying mechanisms and time scales involved. Conventional hot-air drying relies on slower, conduction-based heat transfer over several hours, which allows for

Table 3 Parameters for calculating effective moisture diffusivity

Drying condition	Sample temperature (K)	Slope	D_{eff} (m^2/s×10^{-14})	Drying time (min)
100W	369.8	–0.0755	3.323	36
200W	378.2	–0.0875	3.851	30
300W	388.3	–0.1352	5.951	18
450W	394.1	–0.1858	8.179	14
600W	408.6	–0.2771	12.198	10
800W	413.4	–0.3615	15.913	8
SD1	389.3	–0.0993	4.371	24
SD2	386.7	–0.1394	6.136	18
SD3	391.5	–0.1797	7.911	14

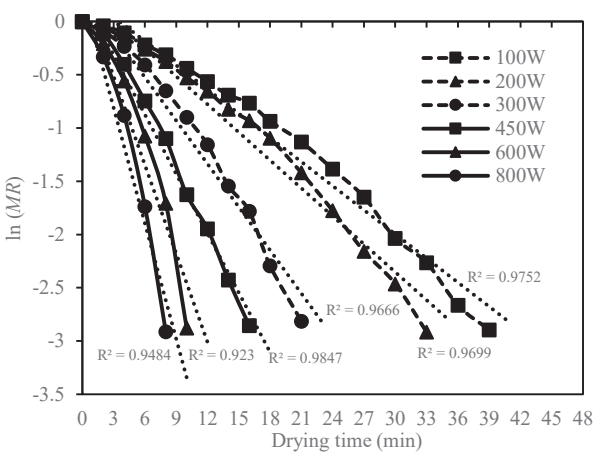


Fig. 5 Moisture ratio forecast from Fick's second law of diffusion representative of the effective diffusion coefficient, depending on the drying time at constant MW power drying

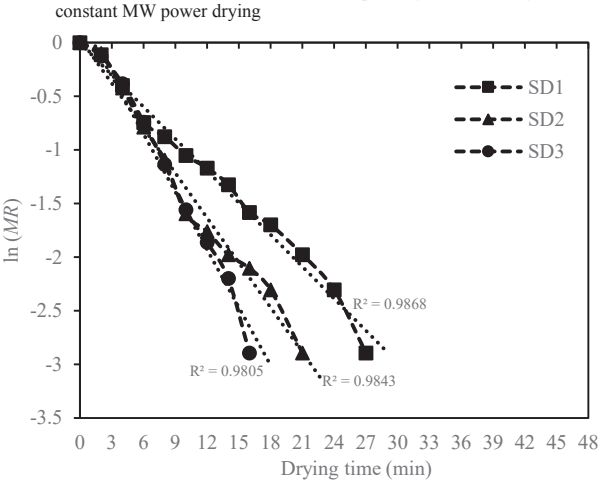


Fig. 6 Moisture ratio forecast from Fick's second law of diffusion representative of the effective diffusion coefficient, depending on the drying time at step-down MW power drying

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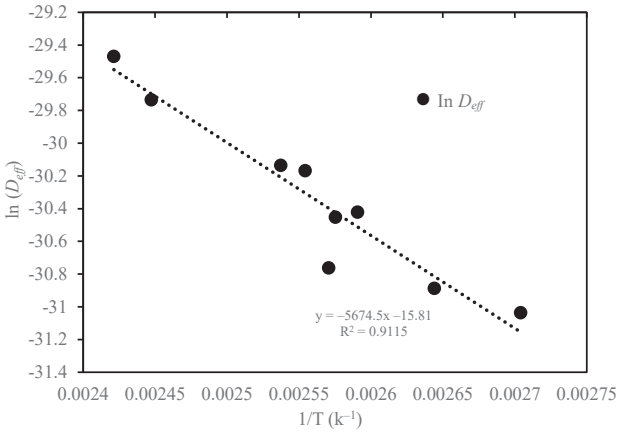


Fig. 7 Arrhenius representing the effective diffusion coefficient, dependent on the pandan leaf temperaturere

extended molecular diffusion. In contrast, microwave drying uses rapid volumetric heating to complete the process in just min. When applying the Fickian model, which assumes diffusion as the primary mechanism, a shorter overall processing time mathematically yields a lower calculated diffusivity. Consequently, the D_{eff} values reported here should be interpreted as apparent parameters for comparative analysis within this study, rather than as absolute measures of moisture mobility.

The strong linear relationship between the natural logarithm of the effective moisture diffusivity and the inverse of absolute temperature, as depicted in Fig. 7, confirms that the diffusion process is thermally activated. The slope of this line is used to calculate the activation energy for moisture diffusion. The predictive model for the diffusion coefficient in pandan leaf drying, derived from the data presented in Table 3 and matched to the experimental data illustrated in Fig. 5 to 7, can be expressed by the following equation (6):

$$D_{eff} = 0.9115 \exp\left(\frac{-47{,}117}{RT}\right) \quad (6)$$

The activation energy (E_a) for moisture diffusion, which represents the energy barrier that water molecules must overcome to diffuse through the leaf matrix, was calculated from the slope of the Arrhenius plot line. The E_a value obtained from the Arrhenius plot line, as illustrated in Fig. 7, is 47.117 kJ/mol. This value falls comfortably within the typical range for the drying of fruits and vegetables, which is generally reported to be between 14 and 60 kJ/mol (Adus & Wisdom, 2024; Haq et al., 2018). The prediction model presented in equation (6) accurately describes the relationship between the diffusion coefficient and temperature. It is a reliable tool for forecasting drying behavior under different microwave conditions. Additionally, this model can be used to predict drying protocols for leafy materials in microwave drying.

Conclusion

The step-down microwave power technique is an effective method for drying pandan leaves, balancing drying time, product quality, and energy efficiency. The optimal SD3 protocol (450 W for 10 min followed by 200 W) achieved a drying time of 16 min, preserved the green color, and reduced energy consumption by 54% compared to constant 800 W drying. Effective moisture diffusivity (D_{eff} = 7.911×10–14 m2/s) indicates a high rate of internal moisture movement, while the Arrhenius-based model effectively predicts drying behavior. For small-scale processors and households, the SD3 protocol offers significant benefits, including lower energy use, faster processing, and better color retention, all without needing specialized equipment. Future research should explore volatile aromatic compounds to assess the impact on pandan leaves' flavor profile and consider scaling up the process for commercial use.

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Conflicts of interest

The authors declare no conflicts of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

In order to assure clarity, the authors have revised the paper's grammar and sentence syntax as necessary using Generative AI (Grammarly) and takes full responsibility for the claims, references, and overall content.

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