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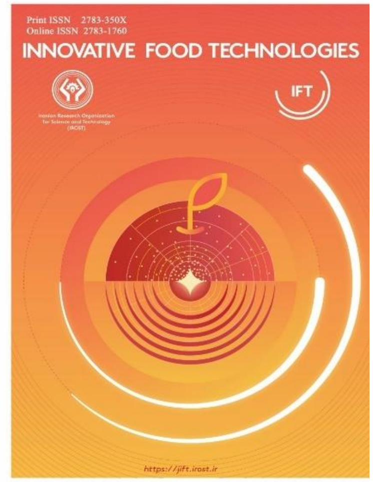

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Microwave Drying Kinetics and Mass Transfer Parameters of Turnip Slices Using Fick and Dincer–Dost Models at Different Power Levels

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Abstract
Turnip (*Brassica rapa* L.) is a nutritionally valuable root vegetable, and preserving its quality during postharvest processing is of considerable importance. In this study, microwave drying behavior of turnip slices was experimentally investigated at three microwave power levels (550, 770, and 990 W), and moisture transfer characteristics were analyzed using the classical Fick diffusion model and the Dincer–Dost model. Drying kinetics, effective moisture diffusivity, surface mass transfer coefficient, Biot number, and activation energy were determined from experimental data.The results showed that increasing microwave power significantly reduced drying time and enhanced moisture removal. Effective moisture diffusivity increased with power in both models, ranging from 3.83×10^{-9} to 1.78×10^{-8} m^2/s for the Fick model (with a correlation coefficient R^2 of the higher power, respectively: 0.98, 0.98 and 0.96) and from 1.16×10^{-9} to 8.74×10^{-8} m^2/s for the Dinser–Dost model. The calculated Biot numbers (0.88–1.30) indicated a mixed control regime, where both internal diffusion and surface mass transfer resistances are significant. The Dincer-Dost model provided a more realistic physical interpretation of mass transfer by explicitly distinguishing between internal moisture diffusion and surface mass transfer resistance, and by using the Biot number calculation.These findings contribute to improved modeling, optimization, and scale-up of microwave drying processes for agricultural products.
Keywords: Microwave drying, Turnip, Moisture diffusivity, Fick diffusion model, Dincer–Dost model, Mass transfer coefficient

1. Introduction
Turnip (Brassica rapa L.) is a root vegetable with high nutritional and functional value, widely consumed due to its rich content of vitamins, minerals, antioxidants, and bioactive compounds. Recent studies have highlighted its potential health benefits, including anti-inflammatory and antidiabetic properties, which have increased interest in its processing and preservation (Kong et al., 2021). However, the high moisture content of fresh turnip makes it highly susceptible to microbial spoilage and quality deterioration, necessitating the application of effective post-harvest preservation techniques.
Drying is one of the most common and practical methods for extending the shelf life of agricultural products by reducing moisture content and water activity. In addition to improving storage stability, drying reduces packaging requirements and transportation costs while limiting undesirable biochemical and microbial reactions (Bissaro et al., 2022; Ambawat et al., 2022). Nevertheless, conventional drying techniques are often associated with long drying times, high energy consumption, and adverse effects on color, texture, and nutritional quality. These limitations have driven continuous research toward more efficient and advanced drying technologies.

Microwave drying (MW) has emerged as an energy-efficient alternative to conventional drying methods due to its volumetric heating mechanism. In microwave drying, electromagnetic waves penetrate the material and interact with polar molecules, particularly water, generating heat internally throughout the product. This internal heat generation accelerates moisture evaporation, significantly reduces drying time, and can improve overall energy efficiency compared to surface-heating methods (Agbede et al., 2020; Kouhila et al., 2020; Zadhossein et al., 2021). Depending on product characteristics and operating conditions, microwave drying has been reported to reduce drying time by up to 50% (Zadhossein et al., 2021).

The efficiency and quality outcomes of microwave drying are strongly influenced by operating parameters such as microwave power level and drying duration. These parameters directly affect drying rate, moisture removal behavior, energy consumption, and final product quality (Zadhossein et al., 2021). Therefore, understanding drying kinetics and moisture transport mechanisms is essential for the design, control, and optimization of microwave drying processes.

Mathematical modeling of drying kinetics provides valuable insight into moisture migration behavior and allows prediction of drying performance under different conditions. Thin-layer drying models have been widely applied to various agricultural products and drying methods, including turnip slices dried using convective, infrared, solar, and microwave-based systems (Gharehbeglou et al., 2014; Kaveh & Amiri Chayjan, 2017; Taghinezhad et al., 2021; Wang et al., 2022). Among these approaches, Fick's second law of diffusion has been extensively used to describe moisture transfer in biological materials. The effective moisture diffusivity (D_{eff}) derived from the Fick model is considered a key parameter in drying analysis, analogous to thermal conductivity in heat transfer, and is commonly estimated from experimental drying curves (Doymaz & İsmail, 2011).

In addition to moisture diffusivity, activation energy (E_a) is another critical drying parameter that reflects the energy barrier associated with moisture diffusion and evaporation. The Arrhenius-type relationship is typically employed to describe the dependence of moisture diffusivity on temperature. However, direct measurement of sample temperature during microwave drying is challenging; therefore, a modified Arrhenius equation based on microwave power density has been widely adopted to estimate activation energy under microwave conditions (Alibas, 2014).

Several studies have investigated the drying behavior and modeling of turnip under different drying technologies. Gharehbeglou et al. (2014) evaluated the drying kinetics and thin-layer modeling of turnip, while Kaveh and Amiri Chayjan (2017) modeled thin-layer drying of turnip slices using a semi-industrial continuous band dryer. Kong et al. (2021) analyzed drying kinetics, energy consumption, and microstructural changes of turnip in a solar drying system. Taghinezhad et al. (2021) optimized the drying and quality of turnip slices using a convective–infrared dryer under various pretreatments, and Wang et al. (2022) investigated microwave power control during drying of green turnip.

Although these studies provide valuable kinetic data and model fitting results, most of them rely primarily on empirical or semi-empirical models and focus on estimating drying parameters rather than interpreting the underlying physical mechanisms of moisture transport. In particular, the classical Fick diffusion model assumes negligible external mass transfer resistance and uniform surface conditions, assumptions that may not be fully valid under microwave drying due to rapid internal heating and intensified moisture flux at the product surface.

The Dincer–Dost diffusion model offers a more physically representative description of moisture transport by explicitly accounting for surface mass transfer resistance and transient moisture movement. This model enables simultaneous estimation of moisture diffusivity (D_m), surface mass transfer coefficient (K_m), and Biot number (Bi), allowing identification of the dominant moisture transfer regime as internal, external, or mixed control. Despite its potential advantages, the application of the Dincer–Dost model to microwave drying of turnip slices and its systematic comparison with the classical Fick model have received limited attention in the literature.

Although the classical Fick diffusion model has been widely applied in drying studies, its underlying assumption of negligible surface mass transfer resistance is seldom questioned, particularly under microwave drying conditions. Microwave drying is inherently governed by volumetric heating, rapid internal vapor generation, and intensified evaporation at the material surface. As a result, internal moisture diffusion and surface mass transfer may occur with comparable resistances, rather than one clearly dominating the process. Nevertheless, most previous studies have focused solely on reporting effective moisture diffusivity, without critically examining the physical validity of this assumption. Accordingly, a comparative modeling approach that explicitly considers both internal diffusion and surface mass transfer resistance is required to provide a more physically meaningful and reliable interpretation of microwave drying behavior.

Therefore, the objective of the present study is to investigate the microwave drying behavior of thin turnip slices at different microwave power levels and to comparatively analyze moisture transport using both the Fick diffusion model and the Dincer–Dost model. The comparison of the two Fick diffusion model and the Dinser and dost model is not simply a mathematical comparison, but rather a comparison of two different analytical perspectives on the mass transfer phenomenon, while this point has been rarely mentioned in previous studies. In previous studies, no research has been conducted to simultaneously evaluate internal and external mass transfer mechanisms in the microwave drying process of turnip by comparing the two mentioned models; so that, in addition to selecting the more appropriate model for predicting drying kinetics, the dominant mass transfer mechanism and the engineering parameters required to optimize the drying process can be examined Special emphasis is placed on evaluating the physical significance of the estimated parameters, analyzing the role of surface mass transfer resistance through Biot number assessment, and clarifying the reasons for discrepancies between D_{eff} and D_m. The findings of this study aim to move beyond purely numerical parameter estimation and provide a more physically grounded understanding of microwave drying mechanisms in agricultural products.

2. Materials and Methods

2.1. Sample Preparation

Fresh turnips were procured from Kerman city, Iran. The samples were stored in a refrigerator at +4°C prior to experimentation. Before drying experiments, the turnips were kept at ambient temperature for 1 h to equilibrate. The ambient temperature and relative humidity were reported as 25°C and 65%, respectively, using an Indoor Room Electronic Temperature and Humidity Meter (Xiaomi, MJWSD05MMC). The samples were then sliced into thin layers with a uniform thickness of 3 mm using a slicer (Arshia, model ES270 1744). The initial moisture of the samples was determined at 9.89% (d.b.) using an oven (RADLAB, SL-908F) at 70 ◦C for 24 h.

2.2. Microwave Drying Procedure

Drying experiments were conducted using a domestic microwave oven (Gplus, model GMW M452s) operating at a frequency of 2450 MHz with a maximum output power of 1100 W. During microwave drying, samples were selected and arranged uniformly to ensure homogeneous exposure to microwave energy (Figure. 1).

Figure. 1 Using a microwave oven to dry turnip slices

Three microwave power levels—50%, 70%, and 90% of the nominal power—corresponding to 550, 770, and 990 W, respectively, were applied. The aim of this study was to determine the activation energy within the operating range of the microwave device (550–990 W), not for all microwave powers; therefore, the results should be interpreted within the power range studied. Also, in several studies, three microwave power levels have been used to estimate the activation energy using Arrhenius analysis (Ahmed et al., 2023; Zhao et al., 2019). The sample mass (sample average initial mass of 40±0.2 g) was recorded at 30 s intervals using a digital balance (TASH Balance, model TD4001) with an accuracy of 0.1 g. Drying was continued until the moisture content of the samples reached approximately 0.2 of the initial moisture content on a dry basis (Hashemi et al., 2022; Zojaji et al., 2016). All experiments were performed in triplicate at the Physical Properties of Agricultural Products Laboratory, Department of Biosystems Mechanical Engineering, Shahid Bahonar University of Kerman, Iran.

2.3. Mathematical Modeling

2.3.1. Fick's Diffusion Model

The moisture ratio (MR) during the drying process was calculated using Eq. (1) (Horuz et al., 2020):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where M_t is the moisture content at time t, M_0 is the initial moisture content, and M_e is the equilibrium moisture content. Since M_e is negligible compared with M_t or M_0, particularly in microwave drying, Eq. (1) can be simplified as follows (Zhao et al., 2019):

$$MR = \frac{M_t}{M_0} \quad (2)$$

The drying rate (DR), defined as the amount of moisture removed from the sample per unit time, was calculated using Eq. (3) (Horuz et al., 2020):

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (3)$$

where $M_{t+\Delta t}$ is the moisture content at time t+Δt (kg water/kg dry matter) and t is the drying time (min).

2.3.2. Effective Moisture Diffusivity

Fick's second law of diffusion was employed to describe moisture transport during the falling-rate period of drying. Since the entire drying process occurred in the falling-rate regime, the diffusion model was applied to analyze moisture migration. The one-dimensional form of Fick's second law is given by Eq. (4) (Taghinezhad et al., 2021):

$$\frac{\partial X}{\partial t} = D_{eff} \frac{\partial^2 X}{\partial x^2} \quad (4)$$

The analytical solution of Fick's second law for slab geometry can be expressed as Eq. (5):

$$MR = \frac{(X - X_e)}{(X_0 - X_e)} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left[-(2n+1)^2 \left(\frac{\pi^2 D_{eff} t}{4L^2}\right)\right] \quad (5)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), L is half the sample thickness (m), X_e, X_0, and X are the equilibrium, initial, and instantaneous moisture contents on a dry basis, respectively, and t is the drying time (Gharehbeglou et al., 2014).

For long drying times, only the first term of Eq. (5) is significant, resulting in Eq. (6) (Zadhossein et al., 2021):

$$MR = \frac{8}{\pi^2} \, exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (6)$$

Taking the natural logarithm of Eq. (6) yields:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (7)$$

The effective moisture diffusivity was determined by plotting ln(MR) versus drying time. The slope of the fitted straight line was then used to calculate D_{eff} according to Eq. (8) (Zadhossein et al., 2021):

$$\text{slope} = \left(\frac{\pi^2 D_{eff}}{4L^2}\right) \quad (8)$$

The application of Fick's second law in the present study is based on several simplifying assumptions, including constant effective moisture diffusivity, negligible shrinkage, and approximately uniform temperature distribution within the sample. It should be noted that the present diffusion analysis is based on simplified assumptions commonly adopted in thin-layer drying studies. During microwave drying, deviations from these assumptions may occur due to volumetric heating, moisture-dependent diffusivity, and structural changes such as shrinkage.

Although the use of thin (3 mm) turnip slices is expected to reduce the magnitude of these effects, they cannot be completely neglected. Consequently, the estimated effective moisture diffusivity should be regarded as an apparent parameter representing the average moisture transport behavior under the studied drying conditions. Future studies incorporating variable diffusivity, shrinkage, and coupled heat and mass transfer models may provide a more comprehensive description of microwave drying.

2.3.3. Dincer–Dost Model

Moisture transfer during drying is governed predominantly by diffusion mechanisms. The Dincer–Dost model was developed to describe mass transfer during drying of products with regular geometries, such as slabs and cylinders, under the assumption of a constant moisture diffusivity throughout the drying process. Compared with the classical Fick-based model, the Dincer–Dost model provides a simpler analytical framework while enabling estimation of physically meaningful parameters for drying analysis and optimization.

Two dimensionless numbers, the Fourier number (F_0) and the Biot number (Bi), are defined as:

$$F_0 = \frac{D \times t}{\left(\frac{L}{2}\right)^2}$$

(9)

$$Bi = \frac{k_m \times \left(\frac{L}{2}\right)}{D_m}$$

(10)

where D_m is the moisture diffusivity (m^2/s), k_m is the surface mass transfer coefficient (m/s), L is the slice thickness (m), and t is time (s) (Boy et al., 2020).

For slab geometry, the transient moisture diffusion equation is given by (Bezerra et al., 2015):

$$\frac{\partial}{\partial x}\left(D_m \frac{\partial M}{\partial x}\right) = \frac{\partial M}{\partial t}$$

(11)

with the following initial and boundary conditions:

$$M(x, 0) = M_0$$

(12)

$$\frac{\partial M}{\partial x}(0, t) = 0$$

(13)

$$-D_m \frac{\partial M\left(\frac{L}{2}, t\right)}{\partial x} = K_m \left[M\left(\frac{L}{2}, t\right) - M_e\right]$$

(14)

The dimensionless moisture ratio is obtained by solving Eq. (11) as (Darvishi et al., 2018):

$$MR = \sum_{n=1}^{\infty} A_n B_n$$

(15)

where the coefficients A_n and B_n are defined as:

$$\begin{cases} A_n = \frac{2 \sin(\mu_n)}{\mu_n + \sin(\mu_n) \cos(\mu_n)} & 0.1 < Bi < 100 \\ A_n = \frac{2 (-1)^{n+1}}{\mu_n} & Bi > 100 \end{cases}$$

(16)

$$B_n = exp(-{\mu_n}^2 F_0) \qquad Bi > 100$$

(17)

For small Fourier numbers, Eq. (15) can be approximated using only the first term:

$$MR = A_1 B_1$$
(18)

For slab geometry, the coefficients can be simplified as follows (Santos et al., 2022):

$$A_1 = G = exp\left(\frac{0.2533\, Bi}{1.3 + Bi}\right) \quad (19)$$

$$B_1 = exp(-\mu_1^2\, F_0) \quad (20)$$

Based on the exponential decay behavior of drying curves, Dincer and Dost (1996) proposed the following empirical relationship:

$$MR = G\, exp(-st)$$
(21)

where G is the lag factor (dimensionless), representing internal resistance to moisture transfer, and *s* is the drying coefficient (s^{-1}), which indicates the drying capability of the material.

By equating Eqs. (18) and (21), the moisture diffusivity for slab geometry can be calculated as:

$$D_m = \left(\frac{s \times \left(\frac{L}{2}\right)^2}{\mu_1^2}\right)$$
(22)

The first root of the characteristic equation, μ_1, can be approximated as a function of the Biot number for slab geometry:

$$\mu_1 = \tan^{-1}(0.64044 Bi + 0.38039)$$
(23)

Finally, the surface mass transfer coefficient is obtained from:

$$k_m = \frac{Bi \times D_m}{\left(\frac{L}{2}\right)}$$
(24)

2.4. Activation Energy

According to the Arrhenius relationship, the activation energy (E_a) is temperature dependent. However, direct temperature measurement during microwave drying is impractical. Therefore, a modified Arrhenius-type equation proposed by Dadali et al. (2007) was employed, in which microwave power per unit sample mass replaces temperature (Zhao et al., 2019):

$$D_{eff} = D_0 exp\left(-\frac{E_a m}{P}\right) \quad (25)$$

where D_0 is the pre-exponential factor (m^2/s), E_a is the activation energy (W/kg), P is the microwave power (W), and m is the sample mass (kg). The activation energy was determined by fitting an exponential curve to the plot of D_{eff} versus m/P.

2.5. Measurement uncertainty and experimental error analysis

Uncertainty analysis is particularly relevant in drying kinetics and transport modeling, where calculated parameters such as D_{eff}, D_m, K_m and activation energy depend on the measured mass, time, sample dimensions and operating conditions. Sources of uncertainty can include the accuracy of mass measurement, possible variability in slice thickness, time intervals and fluctuations in nominal microwave power. These uncertainties may affect the estimation of mass transfer parameters and therefore should be taken into account when interpreting small differences between model outputs. As mentioned in various sections, experimental measurements were performed in triplicate and all reported values represent the average of three independent experiments for each microwave power level. The variability of the experimental data was assessed using the standard deviation. In addition, the precision of the measurement devices is explicitly reported. The electronic balance had an accuracy of ±0.1 g, while both temperature and relative humidity sensors had an accuracy of ±0.01 (degrees Celsius and percent relative humidity, respectively). These uncertainties were minimized by calibrating the instruments before the experiments and by maintaining the same operating conditions for all replicates .

3. Results and Discussion

3.1. Moisture Ratio Behavior under Microwave Drying

Figure 2 illustrates the variation of moisture ratio (MR) of turnip slices during microwave drying at different power levels. As expected for most agricultural products, the moisture ratio continuously decreased with drying time. However, a pronounced dependence on microwave power was observed. Increasing microwave power significantly accelerated moisture removal, leading to substantially shorter drying times. The total drying time required to reach the final moisture content was reduced from 600 s at 550 W to 360 s at 770 W and further to 240 s at 990 W.

This behavior can be attributed to the volumetric heating nature of microwave energy, which directly interacts with polar water molecules inside the product. As microwave power increased from 550 to 990 W, the average drying rate increased by approximately 2.5 times. Higher microwave power results in greater internal heat generation, which raises the sample temperature, enhances vapor pressure gradients, and intensifies internal moisture migration. Consequently, moisture evaporation occurs more rapidly, leading to a reduction in drying time. Similar power-dependent drying trends have been reported for turnip (Kaveh & Amiri Chayjan, 2017), raw rice (Nasrnia et al., 2024), pistachio (Mokhtarian et al., 2021), thyme (Karami & Lorestani, 2021), and kiwi (Darvishi et al., 2018), confirming the general applicability of these findings.

Figure. 2. Moisture ratio experimental data for different microwave drying powers of turnip slices

3.2. Drying Rate Characteristics and Mass Transfer Regime

The drying rate profiles as a function of drying time at different microwave powers are shown in Fig. 3. Microwave drying exhibited a short initial heating or activation phase, during which the drying rate slightly increased. This stage corresponds to rapid temperature rise and activation of moisture diffusion mechanisms within the product. Subsequently, the drying process entered a falling-rate period for all investigated power levels.

The absence of a constant-rate period indicates that moisture transport was predominantly governed by internal diffusion rather than surface evaporation. The drying rate was highest at the early stage of drying and gradually decreased as moisture content declined. This reduction can be explained by increased internal resistance caused by sample shrinkage and reduced porosity, which hinder moisture migration from the interior to the surface.

Furthermore, as drying proceeds and moisture content decreases, the ability of the material to absorb microwave energy diminishes, resulting in lower internal heat generation and, consequently, reduced drying rates. The observed increase in drying rate with increasing microwave power highlights the enhancement of both heat and mass transfer processes at higher power levels. These results are consistent with previously reported findings for various agricultural products (Al‐Ali & Parthasarathy, 2019; Gull et al., 2017; Karami & Lorestani, 2021; Kaveh & Amiri Chayjan, 2017; Kaveh et al., 2018).

Figure.3 Turnip drying rate versus drying time at different powers

3.3. Effective Moisture Diffusivity Based on the Fick Model

The effective moisture diffusivity (D_{eff}) was determined from the slope of the linear relationship between ln(MR) and drying time (Figure. 4). The obtained values ranged from 3.829×10−9 m²/s at 550 W to 8.845×10−9 m²/s at 990 W using curve fitting in MATLAB software (R2018b) and were reported in Table 1, which clearly shows the increase in diffusivity with increasing microwave power. The effective moisture diffusivity (D_{eff}) was obtained from the slope of the linear plot of $\ln(MR)$ versus drying time, in line with Fick's second law. Microwave power was used only as the experimental condition for comparison, and the higher D_{eff} values at greater power levels were mainly attributed to faster internal heating and improved molecular mobility.The obtained values ranged from 3.829×10^{-9} m²/s at 550 W to 8.845×10^{-9} m²/s at 990 W (Table 1), clearly indicating an increase in diffusivity with microwave power. Similar trends have been reported for turnip, with effective moisture diffusivity values in the range of 10^{-10} to 10^{-9} m^2/s (Gharehbeglou et al., 2014; Kaveh & Amiri Chayjan, 2017; Taghinezhad et al., 2021). Comparable ranges have also been reported for other agricultural products, such as banana (Laskar et al., 2023), beetroot (Ahmed et al., 2023), red pepper (Horuz et al., 2020), and celery (Alibas, 2014).
This trend is primarily associated with the higher heating rates achieved at elevated microwave powers, which increase molecular mobility and reduce internal resistance to moisture diffusion. However, it should be noted that the classical Fick model assumes negligible external resistance and purely diffusion-controlled moisture transport. As a result, although the Fick model provides reasonable estimates of D_{eff}, it does not explicitly account for surface mass transfer effects, which may become significant under microwave drying conditions.

Figure. 4 Effect of ln(MR) and drying time at different microwave powers

Table 1. Effective moisture diffusivity values at different microwave powers using the Fick model

Analysis of variance (ANOVA) was performed to determine the significance of the effect of microwave power on the effective humidity coefficient using SPSS software (statisitcs 22), and the null hypothesis of equal means among different powers was rejected. The significance value (sig) was less than 0.05.

3.4. Physical Superiority of the Dincer–Dost Model: Role of Biot Number and Surface Mass Transfer

In the Dincer–Dost model, the lag factor (G) and drying coefficient (s) were determined using Eq. (21). Subsequently, the Biot number (Bi) and the first root of the characteristic equation (μ_1) were calculated using Eqs. (10) and (23), respectively. Based on these parameters, the moisture diffusivity (D_m) and surface mass transfer coefficient (K_m) were determined using Eqs. (22) and (24). The calculated parameters are presented in Table 2.

Table 2. Effective moisture diffusivity coefficient and parameters obtained from the Dincer and Dost model

Unlike the Fick model, the Dincer–Dost model incorporates both internal diffusion resistance and external surface mass transfer resistance through the Biot number (Bi) and the surface mass transfer coefficient (K_m). The calculated Bi values ranged from 1.30 at 550 W to 0.88 at 990 W (Table 2), indicating that microwave drying of turnip slices occurred under a mixed control regime, where internal and external resistances are comparable. In the Dinser–Dost model, the lag factor (G) and the drying coefficient (s) were first determined using Eq. (21). Subsequently, the Biot number (Bi) and the first root of the characteristic equation (μ_1) were calculated using Eqs. (10) and (23), respectively. Using these parameters, the moisture diffusivity (D_m) and the surface mass transfer coefficient (K_m) were obtained from Eqs. (22) and (24). The calculated values are summarized in Table 3. Unlike the classical Fick model, the Dinser–Dost model accounts for both internal diffusion resistance and external surface mass transfer resistance through the Biot number (Bi) and the surface mass transfer coefficient (K_m). The calculated Bi values ranged from 1.30 at 550 W to 0.88 at 990 W, indicating that the microwave drying of turnip slices occurred under a mixed control regime in which both internal diffusion and surface mass transfer contribute to moisture transport. The decrease in the Biot number with increasing microwave power can be explained by the nature of microwave heating. As microwave power increased, volumetric heating within the material intensified, leading to stronger internal vapor pressure gradients and faster moisture migration from the interior toward the surface. This effect reduces internal resistance more rapidly than surface resistance. Consequently, although the overall drying rate increased, the relative contribution of surface mass transfer became more noticeable at higher microwave power levels, which is reflected by the decreasing Bi values.

These observations highlight the advantage of the Dinser–Dost model in describing microwave drying processes. By explicitly accounting for both internal diffusion and surface mass transfer mechanisms, the model provides a more physically representative interpretation of the drying behavior compared with the simplified Fick model, which implicitly assumes negligible external resistance. Therefore, the decreasing Biot number does not imply the disappearance of internal resistance; rather, it reflects a change in the relative balance between internal diffusion and surface evaporation under stronger microwave heating.

This finding has important physical implications. When Bi≈1, neglecting surface resistance—as implicitly assumed in the Fick model—introduces systematic bias in the estimation of moisture diffusivity. The Dincer–Dost model overcomes this limitation by explicitly accounting for surface mass transfer, leading to more physically realistic predictions.

As microwave power increased, K_m increased by more than one order of magnitude, reflecting enhanced moisture removal at the product surface due to higher vapor pressure gradients. At the same time, the decrease in Bi with increasing power suggests that although overall mass transfer rates increased, internal resistance remained the dominant limiting factor(Darvishi et al., 2018). This behavior is characteristic of microwave drying, where volumetric heating intensifies internal diffusion while surface evaporation remains comparatively less restrictive.

The results presented in Table 2 show that the surface mass transfer coefficient (Km) increased markedly with increasing microwave power. The values rose from 1.887×10^{-8} m/s at 550 W to 2.008×10^{-7} m/s at 990 W, indicating that moisture removal from the surface became progressively easier at higher power levels. This behavior is consistent with the stronger temperature gradients and higher vapor pressure developed at the product surface during microwave heating, which promote faster evaporation.

At the same time, the Biot number decreased from 1.30 at 550 W to 0.88 at 990 W. Such a trend suggests a gradual shift in the relative contribution of internal and external mass transfer resistances. As microwave power increased, volumetric heating intensified within the material, accelerating moisture migration from the interior. As a consequence, internal resistance decreased more rapidly than surface resistance. Although the drying process remained within the mixed control regime, surface mass transfer became relatively more influential at higher power levels.

The diffusivity values obtained from the two models are compared in Table 3. At the lowest microwave power (550 W), the effective moisture diffusivity predicted by the Fick model (D_{eff} = 3.829×10^{-9} m^2s^{-1}) was higher than the diffusivity estimated by the Dinser–Dost model (D_m = 1.176×10^{-9} m^2s^{-1}). This difference is associated with the mixed control condition observed at this power level (Bi = 1.30). Since the classical Fick model assumes that moisture movement is governed solely by internal diffusion and does not explicitly consider surface resistance, the calculated diffusivity may become inflated in order to represent the overall drying rate.

At higher microwave powers (770 and 990 W), however, the relationship between the two diffusivities changed, and the values of D_m exceeded those of D_{eff}. Under stronger microwave heating, the development of higher internal vapor pressure gradients enhances moisture transport from the interior of the material toward the surface. The Dinser–Dost model is able to represent this behavior more realistically because it accounts for both internal diffusion and external mass transfer resistance. In contrast, the simplified diffusion framework of the Fick model cannot fully capture the contribution of pressure-driven moisture movement, which explains the lower diffusivity values obtained from this model at higher power levels. These observations indicate that the Dinser–Dost model provides a more physically representative description of the drying process across the investigated microwave power range (Motevali & Hashemi, 2018; Susanti et al., 2022).

Table 3 effective moisture diffusivity values in the two Fick and Dincer and Dost models

3.5. Activation Energy

Activation energy (E_a) is a key parameter governing process kinetics and mass transfer properties. It reflects the sensitivity of effective moisture diffusivity to microwave power and represents the minimum energy required to initiate moisture diffusion from the interior of a material to its surface. In drying process modeling and optimization, activation energy plays a critical role and is strongly dependent on thermal energy and moisture content (Laskar et al., 2023).

During moisture migration, water molecules must overcome an energy barrier. Higher moisture removal rates occur at lower activation energy levels (Ahmed et al., 2023), indicating easier moisture diffusion (Zhao et al., 2019). To determine the activation energy, a plot of D_{eff} versus m/P was constructed (Figure. 5). Based on the modified Arrhenius equation (Eq. 25), an exponential regression was fitted to the experimental data. In Eq. (25), m refers to the sample mass and P to the microwave power. Since the analysis was based on only three power levels, the calculated E_a should be regarded as an approximate value within the tested range

Figure. 5 Relationship between effective moisture diffusivity and sample weight/microwave power for turnip layers

From the fitted equation, the activation energy and pre-exponential factor were determined as E_a =20.869 W/g and D_0=2.0×10^{-8} m^2/s, with a coefficient of determination of R^2=0.9986:

$$D_{eff} = 2.0 \times 10^{-8}\, exp\left(-20.869\,\frac{m}{P}\right) \qquad R^2 = 0.9986 \qquad (26)$$

As observed, the activation energy decreased with increasing microwave power. Lower activation energy corresponds to higher moisture diffusivity during drying. In general, higher activation energy values are associated with materials in which water is strongly bound to the structure, making moisture removal more difficult (Darvishi et al., 2018). The relatively moderate activation energy obtained in this study suggests that microwave drying effectively weakens these interactions through rapid internal heating.

Reported activation energy values for food materials typically range from 8.12 to 110 W/g (Ahmed et al., 2023), and the results of the present study fall well within the reported ranges (Dadalı et al., 2007; Guemouni et al., 2022; Laskar et al., 2023).

3.6. Scientific Contribution and Physical Significance

The principal scientific contribution of this study is the presentation of a physically meaningful comparison between the classical Fick diffusion model and the Dincer–Dost model for describing microwave drying of turnip slices. The Fick model simplifies moisture transport by assuming negligible surface mass transfer resistance and representing the entire process with a single effective diffusivity. In contrast, the Dincer–Dost model explicitly distinguishes between internal moisture diffusion (D_m) and surface mass transfer resistance (K_m) through the Biot number (Bi), allowing a more realistic representation of the underlying transport mechanisms.

The experimentally obtained Biot numbers (0.88–1.30) clearly indicate that microwave drying of turnip slices occurs under a mixed control regime, in which internal diffusion and surface mass transfer resistances are of comparable importance. Under such conditions, the fundamental assumption of the Fick model ($Bi \rightarrow \infty$) is no longer valid. This explains why the Fick approach tends to underestimate the true internal moisture diffusivity when applied to microwave drying processes.

Beyond providing higher and more physically realistic diffusivity values, the Dincer–Dost model also revealed a pronounced increase in the surface mass transfer coefficient with increasing microwave power. This behavior offers direct mechanistic insight into the effects of volumetric heating and intensified vapor pressure gradients at the product surface during microwave drying. From a practical standpoint, the availability of two independent transport parameters (D_m and K_m) enables more reliable process optimization, equipment design, and scale-up than is possible with the single-parameter Fick model.

Overall, this study moves microwave drying modeling beyond the simple reporting of effective diffusivity values and toward a physically interpretable mass transfer framework, bridging empirical drying kinetics with the actual transport mechanisms governing moisture removal in agricultural products.

4. Conclusions

This study presented a detailed physical and mathematical investigation of microwave drying behavior in turnip (*Brassica rapa* L.) slices by applying both the classical Fick diffusion model and the Dincer–Dost model. The experimental findings clearly showed that increasing microwave power from 550 to 990 W substantially shortened the drying time from 600 s to 240 s and significantly enhanced the drying rate, mainly due to stronger volumetric heating and faster internal moisture movement.

In both modeling approaches, effective moisture diffusivity increased with microwave power, which can be attributed to the higher mobility of water molecules at elevated internal temperatures. Nevertheless, the Dincer–Dost model provided a more realistic physical interpretation by explicitly distinguishing between internal moisture diffusion and surface mass transfer resistance. The calculated Biot numbers, ranging from 0.88 to 1.30, clearly revealed that microwave drying occurred under a mixed internal–external mass transfer control regime. This observation indicates that neither internal diffusion nor surface resistance can be ignored and highlights the limitations of the fundamental assumption underlying the Fick model.

Consequently, the observed differences between D_{eff} and D_m are not numerical artifacts, but rather reflect the actual physics of moisture transport during microwave drying.

The surface mass transfer coefficient (K_m) increased by more than one order of magnitude as microwave power increased, emphasizing the role of intensified vapor pressure gradients and enhanced evaporation at the product surface. At the same time, the reduction in the Biot number with increasing power suggests that internal resistance remains the dominant limiting factor, even under conditions of accelerated surface moisture removal. In addition, the relatively low activation energy (20.869 W/g) confirms that moisture removal becomes energetically more favorable at higher microwave powers, facilitating faster diffusion and improved drying efficiency. Although the estimated activation energy is reliable within the studied operating range, future studies including additional microwave power levels could further improve the statistical robustness and generalizability of the Arrhenius parameters.

Overall, while the Fick model can still be useful for obtaining preliminary estimates of moisture diffusivity, the Dincer–Dost model offers a physically consistent and mechanistically interpretable framework for describing microwave drying processes. By simultaneously accounting for internal diffusivity (D_m) and surface mass transfer (K_m), this model provides a more reliable basis for process optimization, scale-up, and microwave dryer design. The findings of this study therefore contribute to moving microwave drying research beyond purely empirical kinetics toward a more physically grounded understanding of mass transfer in agricultural products.

Conflict of Interest

The authors declare that they have no conflict of interest.

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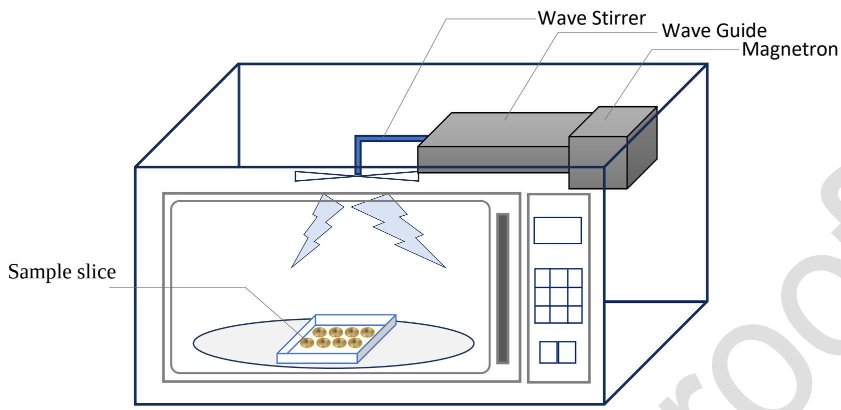

Figure. 1 Using a microwave oven to dry turnip slices

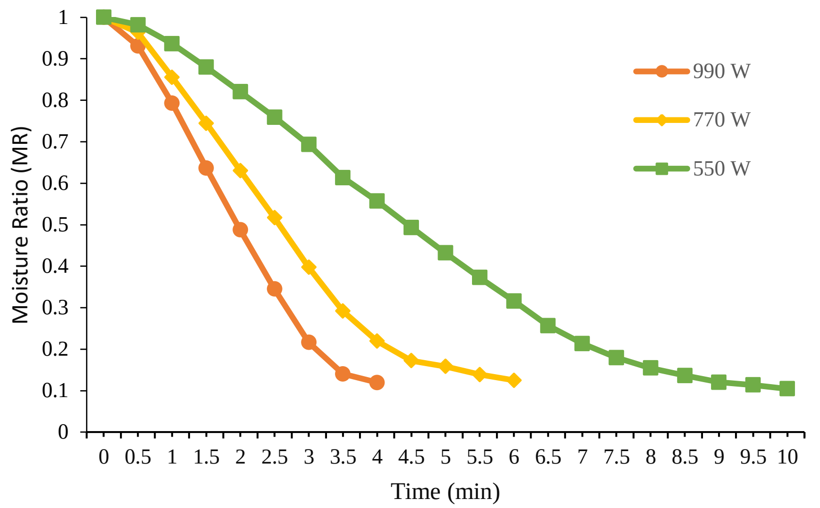

Figure. 2. Moisture ratio experimental data for different microwave drying powers of turnip slices.

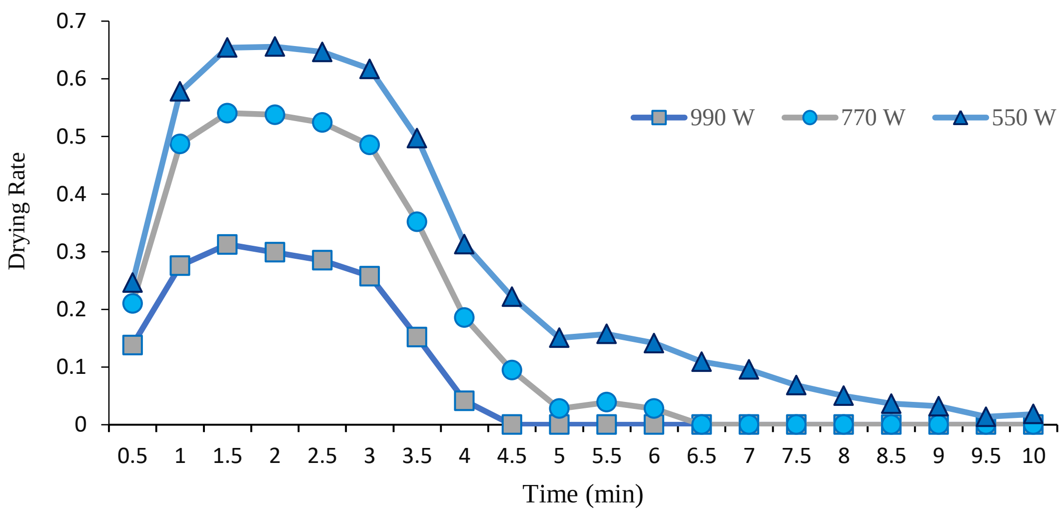

Figure.3 Turnip drying rate versus drying time at different powers

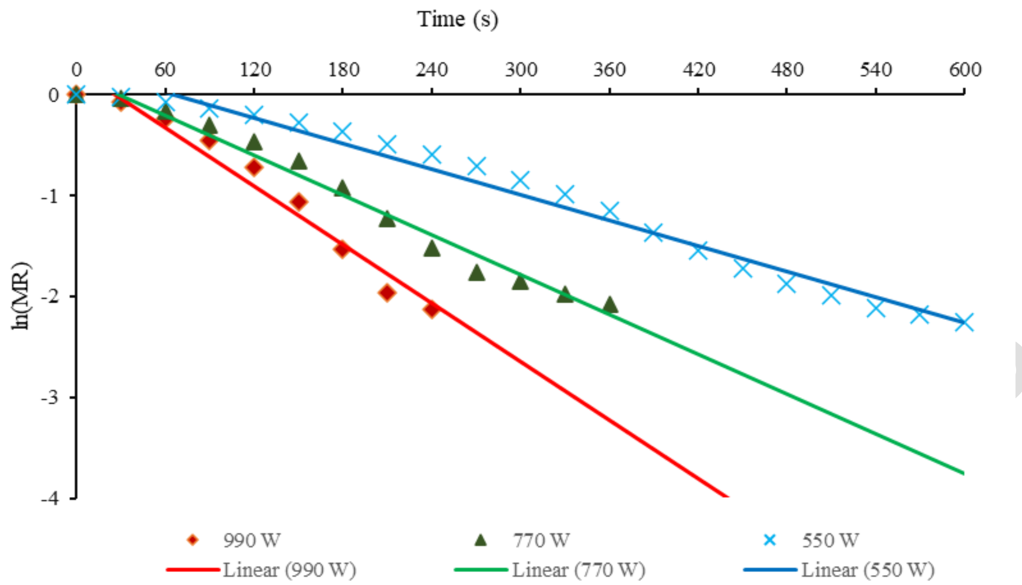

Figure. 4 Effect of ln(MR) and drying time at different microwave powers

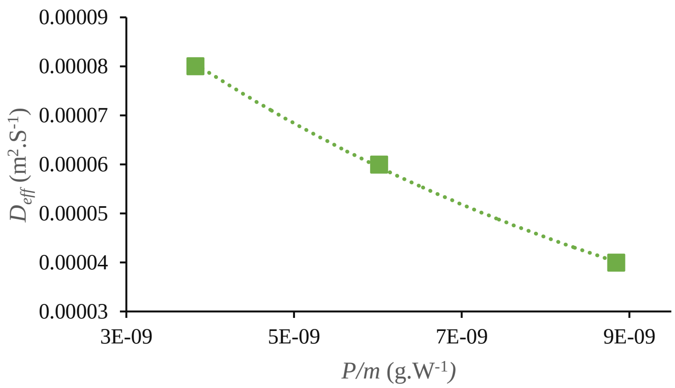

Figure. 5 Relationship between effective moisture diffusivity and sample weight/microwave power for turnip layers

Table 2. Effective moisture diffusivity values at different microwave powers using the Fick model

power (W)	*Line equation*	*SSE*	R^2	*Adj R-sq*	*RMSE*	D_{eff} (m^2/s)
550	y = -0.0042X + 0.2725	0.297	0.976	0.975	0.125	3.829×10^{-9}
770	y = -0.0066X + 0.1912	0.155	0.978	0.977	0.118	6.018×10^{-9}
990	y = -0.0097X + 0.2528	0.195	0.963	0.957	0.167	1.778×10^{-8}

Table 2. Effective moisture diffusivity coefficient and parameters obtained from the Dincer and Dost model

power(W)	G(dimensionless)	*s* (s^{-1})	*Bi*(dimensionless)	μ_1(dimensionless)	K_m (m/s)	D_m (m^2/s)
550	1.14	0.0034	1.30	0.86	0.0000030	1.15E-09
770	1.12	0.0057	0.98	0.77	0.0000142	2.17E-08
990	1.11	0.0077	0.88	0.74	0.0000309	8.74E-08

Table 3 effective moisture diffusivity values in the two Fick and Dincer and Dost models

	Fick Model	**Dincer & Dost Model**
***Power* (W)**	D_{eff} (m^2/s)	D_m (m^2/s)
550	3.83E-09	1.15479E-09
770	6.02E-09	2.17227E-08
990	1.78E-08	8.74152E-08