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# Kinetics of heat and mass transfer in moringa leaves drying in a cabinet dryer

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ABSTRACT

This research focuses on kinetic modeling and investigating heat and mass transport dynamics while drying moringa oleifera leaves in a cabinet dryer. Moringa leaves possess nutritional and pharmacological value, but maintaining these properties after drying has been challenging. An investigation was performed to evaluate the drying kinetics and maximize the quality. The trials were carried out at 40 °C, 50 °C, and 60 °C to examine the variation in moisture removal rates and drying timeframes. The moisture content was recorded periodically till an equilibrium occurred, and the collected data was incorporated into five drying kinetic models, including Midilli and Kucuk, Newton, Page, Henderson and Pabis, and Wang and Singh models, to determine the one with the most accurate representation of the drying behavior. The effective moisture diffusivity was determined using Fick's second law of diffusion. Moisture diffusion activation energy was calculated using the Arrhenius equation. The findings indicated that the rate of drying increased as the temperature rose. The Page model demonstrated an excellent fit, having a large coefficient of determination ($R^2$) and decreased error levels. Drying at 1.5 m/s resulted in Deff values ranging from $4.06 \times 10^{-11}$ m$^2$ s$^{-1}$ to $1.40 \times 10^{-10}$ m$^2$ s$^{-1}$, while drying at 1.7 m/s resulted in values ranging from $6.74 \times 10^{-11}$ m$^2$ s$^{-1}$ to $6.48 \times 10^{-10}$ m$^2$ s$^{-1}$. The study gives an insight into the drying characteristics of moringa leaves, which will serve as a basis for developing ideal drying characteristics.

## 1. Introduction

Moringa has attracted considerable attention as it has nutritional and medicinal values owing to considerable post-harvest practices like drying that enhances the quality of dry products as well as extends its shelf life. The capsules of Moringa Oleifera are especially rich in vitamins as well as are popular because they have anti diabetic, anti inflammatory and blood cholesterol lowering effects among others [1–2]. However, in order to retain these beneficial components in the moringa leaves, the process of drying has to be done carefully since various conventional methods may expose the leaves to adversely high temperatures [3]. Given the variety of conventional techniques of drying, the concern among nutritionists is whether they will be able to retain most of the valuable components that are intrinsic in the leaves of the plant [4].

Reducing moisture content involves mass and heat transfer within the material, this process is complicated [5]. In this regard, it becomes necessary to control the drying parameters so that proper drying of moringa occurs alongside its nutritional profile. In regard to the ease of application, cost-effectiveness and flexibility of handling different operating conditions, cabinet drying is one of the most widely used systems in drying leafy crops such as moringa [6–7].

Generally, the fall in a cabinet drying process of moringa leaf follows a normal falling rate drying phase; however, it is highly dominated by a diffusion-controlled moisture removal method [8]. Considering nutrient retention and energy efficiency for moringa drying, an investigation into drying kinetics regarding heat and mass transport in a cabinet drier is warranted. However, kinetic modeling of the drying process is crucial in that it describes heat and mass transport behavior and, hence, makes it possible to predict drying performance under varied conditions [5,9].

Several empirical and semi-empirical models exist that have described the drying kinetics, such as the Newton, Two terms, Hii et al., Verma et al., Logarithmic, Page, and Henderson-Pabis models, among others [10–11]. These models can be used to predict the drying rate and time for any temperature, as well as to determine optimum drying

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factors that guarantee product quality [12] (Minaei et al. 2012). Kinetic modeling is useful not only for drying processes but also for inventing and optimizing drying equipment to improve total drying efficiency [13–14].

Another important characteristic that controls the moisture movement within plant material during drying is effective moisture diffusivity (Deff) [15]. This metric basically shows the ability of the material to retain moisture content though moisture content is affected by clauses such as temperature, humidity, and even the structure of the material, It has been noted by Tavakoli and Mojaverian [16]. The second rule of Fick's diffusion is most widely used as a formula for calculating effective moisture diffusivity in moringa leaves. It assists to understand the rate of moisture movement and how the conditions of drying differ in relation to the dynamics of the drying process [17]. Besides, the temperature dependence of the moisture diffusivity could also be described using the Arrhenius equation, which defines the effective diffusivity and drying temperature relationship, providing important information for energy-effective drying as stated by Tian et al. [18].

Several studies have investigated the drying behavior of leaves, water solubility, activation energy using the Arrhenius equation, energy consumption, and evaluation of different drying conditions in thin layer drying of different agricultural products such as pomace [19], apricot [20], berries [21], figs [22], grapes [23], freeze-dried [24], organic apples [25], red pepper [26], M. oleifera leaves [2,27–28], leaves of other plants [29–30], tomatoes [31], dried onions [32], microwave drying [33], Moldavian dragon leaves[34], pepper leaves [35], olive leaves [13], fruits [36–37], and vegetables [38–40].

This paper, therefore, recognizing the importance of drying in preserving moringa's nutritional and functional qualities, investigates heat and mass transport dynamics during moringa leaf drying in a cabinet drier. This study is intended to investigate the drying kinetics of moringa leaves at various temperature ranges, find the best-fitted kinetic model that describes the drying process, evaluate the effective moisture diffusivity, and estimate the activation energy using the Arrhenius equation. This drying behavior of moringa leaves can be used in future research directed toward optimizing drying parameters for improved quality and efficiency.

## 2. Materials and methods

### 2.1. Materials

To maintain both integrity and standard, fresh Moringa leaves were obtained from the Landmark University Moringa Farm. The leaves were subjected to cleaning processes to remove debris such as broken leaves and stems, and this led to the collection of intact and high-quality leaves only for the drying experiments. Cleaning removed visible impurities, and the leaves were washed with clean water followed by air drying to eliminate liquids in them. The moisture content of the leaves was evaluated using AOAC [41] specification which involves drying samples of the leaves at 105 Degrees Celsius for 24 h or a period that ensures uniformity of weight.

### 2.2. Drying equipment

The drying experiments were performed in a cabinet dryer as shown in Fig. 1. This includes the fan that produces constant airflow and the temperature controls. The BioSpec® IM is suitable for stable temperatures between 40 °C to 60 °C and can be changed not only in respect of air velocity but temperature as well. It consists of an electric motor, a blower, an air intake, a top vent, heating elements, a data logger, and sensors for temperature and humidity. To enhance the uniformity of heat distribution inside the drying chamber, two perforated trays were installed inside.

### 2.3. Experimental procedure

#### 2.3.1. Drying process

In the cabinet drier, drying was performed at 40 °C, 50 °C and 60 °C and constant (1.5 m/s and 1.7 m $s^{-1}$) air velocity was maintained to mimic natural convection process that aids to the leaching of moisture. The low-temperature cabinet dryer provides three perforated trays with evenly scattered Moringa leaves for heat convection. Air is sucked in from an inlet duct and is pulled through a heating compartment where it comes in contact with the heating element and is blown back into the drying chamber. Sensors continuously monitor the temperature and humidity level inside the chamber, while the data logger records the drying process and its outcome for completeness of the record. It was

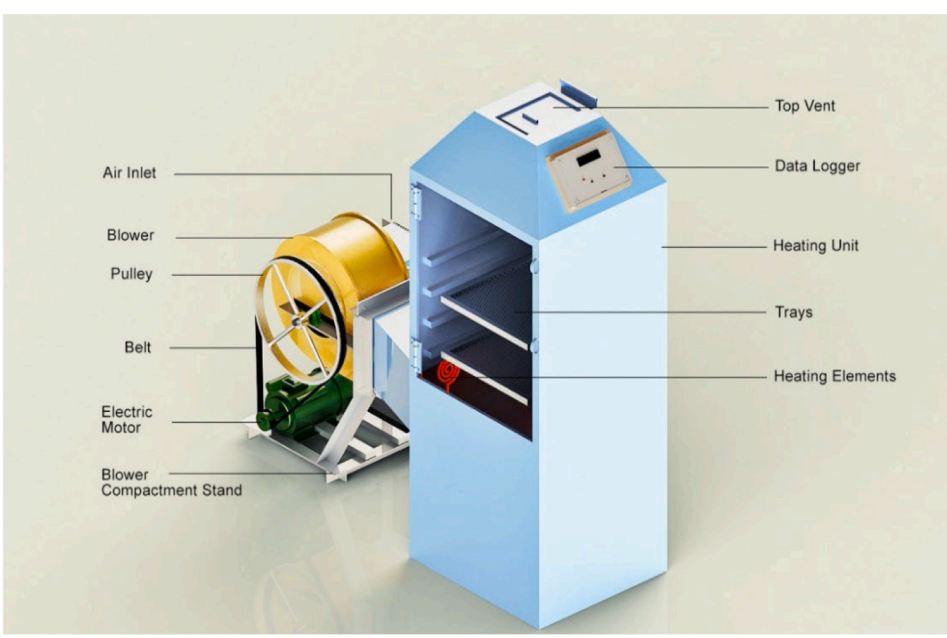


**Fig. 1.** AutoCAD diagram of the drying machine.

dried further until the leaves attained moisture equilibrium.

#### 2.3.2. Moisture content measurement

The moisture content was determined intermittently during the drying process. Samples were taken from the dryer at every interval of time, weighed in a digital balance with a readability of ±0.01 g, and then put back into the dryer as quickly as possible to keep drying conditions. The moisture content (M) at any time (t) can be calculated by the following Eq. (1):

$$Mt = \frac{W_t - W_{dry}}{W_{dry}} \tag{1}$$

Where Wt is the weight of the sample at time t, and Wdry is the final dry weight of the sample.

The data was utilized to establish moisture ratio (MR) curves, defined in Eq. (2):

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{2}$$

Where Mi is the starting moisture content and Me is the equilibrium moisture content, which is set to zero for simplicity in the thin-layer drying model provided.

#### 2.3.3. Drying kinetic modeling

A set of five thin-layer drying models was used to describe the drying behavior of Moringa leaves. This study has incorporated the following models:

1. Wang & Singh ($MR = 1 + at + bt^2$)
2. Midilli and Kucuk Model: ($MR = a \times \exp(-kt^n) + b$
3. Newton Model: ($MR = \exp(-kt)$
4. Page Model: ($MR = \exp(-kt^n)$)
5. Henderson-Pabis Model: ($MR = a \exp(-kt)$

Where k is the drying constant, time is t (drying), empirical value in the Page model and Henderson–Pabis equivalent for "n" and associating with a. Each model was tested using non-linear regression for parameters k, a, and n. To determine the accuracy of the models, we examined their coefficient of determination ($R^2$) and root mean square error (RMSE). Models whose values were at least below average (RMSE) had the highest $R^2$.

#### 2.3.4. Effective moisture diffusivity (Deff)

The constant of moisture diffusivity (Deff) was obtained by using Fick's second law of diffusion for the thin-layer drying model, in this case, a slab. This computation was conducted based on Eq. (3):

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2\, Deff^t}{4L^2} \tag{3}$$

Here, L signifies the thickness of each Moringa leaf layer. The gradient of the linear plot (ln(MR) at different drying times (t)) was employed for the determination of Deff for each drying temperature.

#### 2.3.5. Determination of activation energy (Ea)

The activation energy for moisture diffusion, Ea, was estimated by applying the Arrhenius equation on the temperature dependence of effective diffusivity as:

$$Deff = D0\ exp\left\{-\frac{E_a}{RT}\right\} \tag{4}$$

Where; $D_0$ is the pre-exponential factor, R is the universal gas constant (8.314 J/mol K), and T is the absolute temperature (in Kelvin). By plotting ln(Deff) against (1/T), the slope of the linear relationship provided (Ea/R), from which (Ea) was calculated.

#### 2.3.6. Statistical analysis

To ensure the accuracy and reproducibility of the tests, all tests were repeated three times. The SPSS program (Version XX, SPSS Inc., Chicago, IL, USA) was used for the statistical analysis. The ANOVA was used to investigate the effect of temperature on drying rate, effective moisture diffusivity, and kinetic parameters. The critical level of significance was set as 95 % ($p < 0.05$). Data were matched with the model of kinematics of the system and with the use of the software product MATLAB the fit was achieved. By making use of $R^2$, RMSE, and the $\chi^2$ test we determined the best model.

#### 2.3.7. Quality analysis of dried moringa leaves

Moringa leaves were dried and subjected to coloring tests and nutrient analysis. Dry samples were put on the table and a colorimeter was used to measure their L (lightness), a (green-red), and b (blue-yellow). In addition, the study involved high performance liquid chromatography (HPLC) analysis for which the effect of drying temperature on nutritional value was observed through the level of ascorbic acid as a food quality preservation status [42]. The colorimeter was employed to gauge moringa leaves' freshness and dried them at three different temperatures. The colorimeter was calibrated at the beginning of each reading. First, taking a reading from a black standard plate and then from a white standard plate. Each sample had ten random measurements taken and the average value as well as the standard deviation was obtained. A measurement of the amount of white in a sample is indicated using the symbol L which starts from nothing-black at zero to full-white at one hundred. According to Zhang et al. [43], b represents blue, that is when negative, and yellow when positive, while a represents green when negative and red when positive.

## 3. Results and discussion

### 3.1. Drying kinetics of moringa leaves

Fig. 2 presents the drying curves depicting Moringa leaves at, namely, 40, 50, and 60oC, which depict a standard falling-rate drying phase. i.e., during this phase, the moisture removal rate continuously decreased over time as the leaves approached equilibrium moisture content. Just as anticipated, higher drying temperatures sped up the process, more effectively removing the moisture and shortening the drying period. The drying procedure took almost 6 h at 40 °C, yet at 60 °C, it only took around 3.5 h. This specific temperature dependence is similar to the previous research results far and wide, which demonstrate that higher temperatures greatly promote moisture transport in plant materials, hence the drying time is shortened [11,24,44–47].

As can be seen in Table 1, it can therefore be concluded that the drying kinetics of Moringa leaves in this study is best described by the Page Model. This conclusion is supported by its excellent statistical power, which includes high $R^2$ values at all temperatures (40 °C, 50 °C, and 60 °C) as well as values of 0.998 or higher which indicate that the model fitted well with the experimental data. Moreover, the model possesses the lowest RMSE values of 0.003 to 0.006 which suggests that the predicted moisture content is very consistent with the actual moisture content. A numeric constant (n) in the Page model, which accounts for various drying phenomena, changed with temperature, demonstrating the model's applicability in dealing with the dynamics of drying activities on moringa leaves under different conditions [48–49].

The introduction of the constant n relaxation into the model enables it to capture the nonlinear drying phenomena which is applicable in intricate drying operations. The Midilli & Kucuk Model emerges as a strong competitor with an $R^2$ value of above 0.99 and low values of RMSE, although the Midilli & Kucuk model is not as good as the Page model. On the other hand, the models by Wang, Singh, and Newton exhibited lower $R^2$ values and a greater root mean square error which means they have the lower fitness level. Such findings support the viability of the Page model for modeling the drying of Moringa leaves

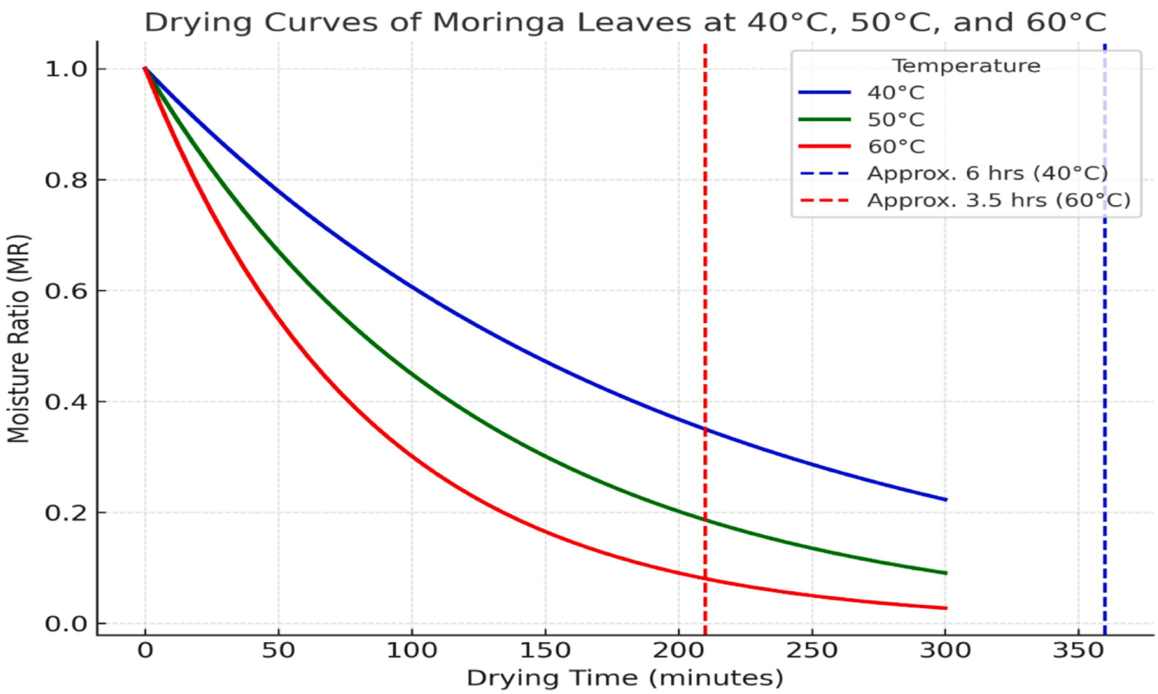


**Fig. 2.** Drying curves of moringa leaves at various temperatures.

**Table 1**
Model parameters and fitting statistics for the drying kinetics.

| Model | Temperature ( °C) | Empirical Constant (k) | Empirical Constant (n) | $R^2$ | RMSE |
|---|---|---|---|---|---|
| Wang & Singh | 40 | −0.002 | – | 0.953 | 0.014 |
| | 50 | −0.003 | – | 0.960 | 0.012 |
| | 60 | −0.004 | – | 0.968 | 0.010 |
| Midilli & Kucuk Model | 0 | 0.005 | 1.2 | 0.990 | 0.010 |
| | 50 | 0.007 | 1.3 | 0.994 | 0.008 |
| | 60 | 0.010 | 1.5 | 0.996 | 0.006 |
| Newton Model | 40 | 0.003 | – | 0.948 | 0.016 |
| | 50 | 0.005 | – | 0.955 | 0.014 |
| | 60 | 0.007 | – | 0.964 | 0.012 |
| Page Model | 40 | 0.004 | 1.1 | 0.998 | 0.006 |
| | 50 | 0.006 | 1.2 | 0.999 | 0.004 |
| | 60 | 0.009 | 1.3 | 0.999 | 0.003 |
| Henderson-Pabis Model | 40 | 0.004 | – | 0.925 | 0.018 |
| | 50 | 0.005 | – | 0.935 | 0.016 |
| | 60 | 0.007 | – | 0.945 | 0.014 |

**Table 2**
Effective Moisture Diffusivity ($D_{eff}$).

| Temperature ( °C) | velocity (m $s^{-1}$) | $D_{eff}$ |
|---|---|---|
| 40 | 1.5 | $4.06 \times 10^{-11}$ |
| | 1.7 | $6.74 \times 10^{-11}$ |
| 50 | 1.5 | $5.17 \times 10^{-11}$ |
| | 1.7 | $6.48 \times 10^{-11}$ |
| 60 | 1.5 | $1.04 \times 10^{-10}$ |
| | 1.7 | $1.38 \times 10^{-10}$ |

and are in agreement with results from [46,47].

### 3.2. Effective moisture diffusivity (Deff)

The results in Table 2 show values of effective moisture diffusivity (Deff) for Moringa leaves, which were dried in a cabinet dryer. The Deff parameters obtained ranged from $4.06 \times 10^{-11}$ $m^2$ $s^{-1}$ to $1.40 \times 10^{-10}$ $m^2$ $s^{-1}$ for the different temperatures maintained with an air velocity of 1.5 m/s. Drying at 1.7 m/s led to the values of Deff ranging from $6.74 \times 10^{-11}$ $m^2$ $s^{-1}$ to $6.48 \times 10^{-10}$ $m^2$ $s^{-1}$. For food materials, these values are in the range of $10^{-11}$ $m^2$ $s^{-1}$ to $10^{-9}$ $m^2$ $s^{-1}$ [15,48,49]. In addition, in most instances when the temperature is raised, there was a corresponding rise in Deff values except for the samples dried at 40 and 50 °C at 1.7 m/s where a very low Deff was recorded. This discrepancy is certainly associated with increased thermal energy at higher temperatures which augment the interactions of water molecules in the sample and also increases vapor pressure and therefore, the rate of movement of water [50].

### 3.3. Activation energy (Ea) for moisture diffusion

The water diffusion activation energy (Ea) calculated using the Arrhenius equation is 27.6 kJ $mol^{-1}$, which falls within the range reported for green vegetables and medicinal plants (25 - 50 kJ/mol) [30,38]. The tree exhibits a strong barrier to water movement within the Moringa leaves and shows how thermal energy affects propagation. Activation energy (Ea) indicates a strong response to temperature changes. The lower Ea, the smaller the temperature dependence. The activity energy (Ea) was similar to previous studies, with the Ea of quinoa being 37.98 kJ $mol^{-1}$, the Ea of andrographis paniculata being 33.4 kJ $mol^{-1}$, and the Ea of moringa leaves being 32.74 kJ $mol^{-1}$.

### 3.4. Quality evaluation of dried moringa leaves

Table 3 shows the influence of drying temperature on color parameters (L*, a*, b*), total color difference (ΔE*), and hue angle (h*) in Moringa leaves. Lightness (L*) values point to variations in the specimen's brightness. The control sample had a L* value of 37.568, but

**Table 3**
The L*, a*, b*, ΔE* values and hue angles of dried moringa leaves.

| Temperature (°C) | L* | a* | b* | ΔE* | h* |
|---|---|---|---|---|---|
| Control | 37.568 | −3.216 | 4.493 | – | - 45.8611 |
| 40 | 38.22 | −2.346 | 9.079 | 4.8074 | −60.2924 |
| 50 | 41.632 | −2.251 | 8.404 | 4.1033 | −62.5091 |
| 60 | 36.039 | 2.625 | 7.098 | 8.1652 | 59.7631 |

drying at 50 °C produced the lightest leaves (L* = 41.632). However, at 60 °C, the L* value dropped to 36.039, indicating darkening caused by heat degradation or browning processes. This trend illustrates how greater temperatures affect the visual qualities of the dried product.

The chromatic coordinates (a* and b*) demonstrate the effect of temperature on color. The a* values were negative for the control and samples dried at 40 °C and 50 °C, showing greenish tones, but increased to a positive value (2.625) at 60 °C, indicating a switch to reddish colors due to heat impacts. For b*, all samples showed positive values, indicating a yellowish tone, with increased yellowness at 40 °C and 50 °C. These variations indicate changes in pigment stability, such as chlorophyll *b*reakdown, which are impacted by heat exposure.

The total color difference (ΔE*) measures perceptual color changes vs the control. The lowest ΔE* was detected at 50 °C (4.1033), suggesting minor color modification, while the largest ΔE* occurred at 60 °C (8.1652), showing considerable alterations due to greater thermal effect. This implies that moderate drying temperatures help to retain Moringa leaves' inherent color qualities.

The hue angle (h*) represents alterations in the overall color tone. Negative h* values for the control and samples dried at 40 °C and 50 °C indicate greenish-yellow tones. At 60 °C, h* became positive (59.7631), indicating a shift to reddish-yellow tones due to heat-induced pigment changes.

## 4. Conclusions

The drying of Moringa leaves in a cabinet drier was examined in this work using kinetic modeling, heat and mass transfer dynamics, drying behavior, activation energy, effective moisture diffusivity, and quality retention. The Page model outperformed other models considered in this study in accurately characterizing moringa leaf drying behavior at all temperatures evaluated (40 °C, 50 °C, and 60 °C), with higher $R^2$ and RMSE. This study suggests that the Page model is capable of properly forecasting drying behavior, allowing for greater process control.

Drying at 1.5 m/s resulted in Deff values ranging from $4.06 \times 10^{-11}$ $m^2$ $s^{-1}$ to $1.40 \times 10^{-10}$ $m^2$ $s^{-1}$, while drying at 1.7 m/s resulted in values ranging from $6.74 \times 10^{-11}$ $m^2$ $s^{-1}$ to $6.48 \times 10^{-10}$ $m^2$ $s^{-1}$. The Arrhenius connection revealed a positive association between drying temperature and moisture diffusivity, emphasizing the necessity of temperature management in optimizing drying time and energy consumption. The activation energy for moisture diffusion was found to be 27.6 kJ $mol^{-1}$, indicating how much heat energy is required to speed up moisture flow inside moringa leaves. The color of Moringa leaves is significantly affected by drying temperature. Lower temperatures (40 °C and 50 °C) result in better color stability and less visible changes, but higher temperatures (60 °C) cause greater color distortion and damage. This highlights the need to control drying conditions to find a balance between color retention and efficiency. This study provides useful insights into improving the drying of Moringa leaves by highlighting the need to balance drying efficiency and quality maintenance. The results help improve the drying process for highly nutritious crops such as Moringa and support more sustainable agricultural practices.

### CRediT authorship contribution statement

**Timothy Adekanye:** Conceptualization, Methodology, Writing – original draft. **Elijah Alhassan:** Methodology, Project administration, Supervision. **Matthew Amodu:** Methodology, Resources, Supervision. **Taofiq Olanrewaju:** Data curation, Formal analysis, Funding acquisition. **Murtala Iyanda:** Data curation, Validation, Writing – review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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