International Journal of Agricultural Technology 2025 Vol. 21(5):1687-1702
DOI: https://doi.org/10.63369/ijat.2025.21.5.1687-1702
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

# Production of chlorophyll-rich powder from *Moringa oleifera* leaves using dehumidification and intermittent drying: impact on drying characteristics and chlorophyll retention

**Djaeni, M.**[*]**, Hadiyanto, H., Suherman, S., Handayani, N. A. and Utari, F. D.**

Department of Chemical Engineering, Diponegoro University, Semarang, Indonesia.

Djaeni, M., Hadiyanto, H., Suherman, S. and Handayani, N. A. (2025). Production of chlorophyll-rich powder from *Moringa oleifera* leaves using dehumidification and intermittent drying: impact on drying characteristics and chlorophyll retention. International Journal of Agricultural Technology 21(5):1687-1702.

**Abstract** Results demonstrated that zeolite enhanced moisture removal efficiency, with significant reductions in moisture ratios which observed at higher temperatures. Specifically, at 40°C, the moisture ratio improved from 0.9175 to 0.8924, while at 80°C, it decreased from 0.8039 to 0.6275. Intermittent tempering further optimized moisture removal, achieving a moisture ratio of 0.4199 with a 20-minute tempering period at 60°C. The study employed the Henderson & Pabis model which achieved high predictive accuracy for drying characteristics. Notably, chlorophyll retention was maximized at lower temperatures and optimal tempering durations. Overall, this research underscored the potential of combining zeolite and intermittent drying techniques to enhance moisture removal and preserve chlorophyll, offering a practical solution for producing high-quality Moringa leaf powder in both small-scale and industrial settings.

**Keywords:** Chlorophyll retention, Intermittent drying, *Moringa oleifera*, Zeolite-assisted drying

## Introduction

Known as the "miracle tree," *Moringa oleifera* has attracted a lot of attention because of its remarkable nutritional profile and several uses. Bioactive substances such as flavonoids, tannins, saponins, and phenolic acids, which have been demonstrated to have antibacterial, anti-inflammatory, and antioxidant qualities, are abundant in moringa leaves (Mallenakuppe *et al.*, 2019; Pareek *et al.*, 2023). Because of its nutritional and bioactive qualities, moringa leaves are highly sought after in a variety of businesses, including medicines, nutraceuticals, and functional foods, as well as in the fight against hunger, especially in underdeveloped nations (Singh *et al.*, 2018).

Despite its vast potential, the perishable nature of Moringa leaves presents a major challenge. Freshly harvested leaves are prone to rapid nutrient degradation due to their high moisture content and susceptibility to

[*] **Corresponding Author:** Djaeni, M..; **Email:** moh.djaeni@live.undip.ac.id

environmental factors such as heat, light, and humidity (Aznury *et al.*, 2021; Hasizah *et al.*, 2022). Post-harvest deterioration can lead to significant losses in both the nutritional quality and bioactive components of the leaves, particularly chlorophyll and vitamins, which are highly sensitive to external conditions (Ademiluyi *et al.*, 2018; Hasizah *et al.*, 2022).This makes preservation methods essential to extend the shelf life of Moringa leaves while retaining their quality.

Drying is a commonly used method to preserve Moringa leaves by reducing moisture content and inhibiting microbial growth, but the effectiveness of different drying methods in retaining nutritional and bioactive properties varies widely (Sasongko *et al.*, 2020). Traditional techniques like sun drying and air drying are popular in rural, resource-limited settings due to low costs and simplicity; however, they have drawbacks, such as long drying times, exposure to dust and insects, and nutrient losses from prolonged sun exposure and inconsistent conditions (Asiah *et al.*, 2017; A'yuni *et al.*, 2022).In contrast, industrial techniques like freeze drying and spray drying offer controlled environments that minimize nutrient loss but are energy-intensive and require substantial capital investment, making them less accessible for small-scale producers (Agnieszka and Lenart, 2011; Díaz-Bandera *et al.*, 2015).

To overcome the limitations of both traditional and industrial drying methods, researchers have been exploring alternative techniques that strike a balance between efficiency, cost, and nutrient retention. One such promising approach is the combination of intermittent drying and dehumidification drying using zeolite, a natural mineral with high moisture adsorption capacity (Djaeni *et al.*, 2021). Intermittent drying involves periodic pauses in the drying process, which allows for more uniform moisture and heat distribution within the material, leading to shorter drying times and enhanced energy efficiency (Golmohammadi *et al.*, 2016; Pereira *et al.*, 2020). This technique is particularly advantageous for preserving chlorophylls as it reduces the risk of thermal damage by allowing the material to cool intermittently (Md Saleh *et al.*, 2020).

The combination of intermittent drying and dehumidification using zeolite offers a novel and efficient drying solution that addresses many of the limitations posed by traditional and industrial methods. This combined approach leverages the strengths of both techniques—intermittent drying's ability to promote uniform moisture removal and dehumidification drying's capacity to reduce energy consumption—resulting in a more effective and sustainable drying process. Furthermore, this method is expected to have a positive impact on the retention of critical chlorophylls, particularly chlorophyll, which is responsible for Moringa's vibrant green color and a key indicator of its nutritional quality.

Chlorophyll plays an essential role in the health benefits associated with Moringa leaves (Oyeyinka and Oyeyinka, 2018). It is not only a vital pigment in photosynthesis but also possesses antioxidant and detoxifying properties (Abdulkadir *et al*., 2015). The preservation of chlorophyll during the drying process is therefore critical for maintaining the functional and commercial value of Moringa leaf powder. Traditional drying methods often result in significant chlorophyll degradation, leading to a loss of both color and bioactivity (Arslan and Musa Özcan, 2010; Asiah *et al.*, 2017; A'yuni *et al.*, 2022). However, by maintaining a lower drying temperature and reducing the exposure to oxidative stress, the combination of intermittent and zeolite-based dehumidification drying is expected to enhance chlorophyll retention, thus preserving the nutritional integrity of the dried leaves.

The aim of this study was to investigate the effects of intermittent and dehumidification drying using zeolite on the production of *Moringa oleifera* leaf powder, particularly in terms of drying characteristics and chlorophyll retentionincluding moisture reduction, effective moisture diffusivity, color changes, and chlorophyll retention, and to develop a drying method to improve the quality of Moringa leaf powder and to minimize energy usage, making it a practical and sustainable solution for both small-scale and industrial applications.

## Materials and methods

### *Plant material preparation*

The *Moringa oleifera* leaves were gathered from a local farm in (Semarang, Indonesia). Harvest was done in the early hours of the day to minimize water stress and maintain the natural chlorophyll. To cleanse the dirt, the selected leaves were washed in distilled water. Before drying process, the leaves were exposed to air circulation at room temperature for 30 minutes to eliminate any remaining surface moisture.

### *Experimental setup for drying techniques*

The drying setup and equipment are shown in Figure 1. About 0.25 kgs of fresh moringa leaves were evenly spread on aluminum trays and placed inside a food dehydrator (ARD-PM99, Maksindo, Indonesia). The drying process was conducted at three different temperatures: 40°C, 60°C, and 80°C. The drying was carried out for 120 minutes for each temperature setting. During this time, the dehydrator was kept closed to maintain consistent drying conditions. Every 5 minutes, a sample of the drying leaves was taken out for moisture content analysis. The moisture content was determined using a gravimetric method, by weighing a small portion of the leaves and calculating the weight loss due to water evaporation (A'yuni *et al.*, 2022)

The experiments utilized two drying methods: zeolite-assisted dehumidification and intermittent drying. Once the drying process was completed, the *Moringa oleifera* leaves were ground and sieved to obtain particles of 80 mesh size. The resulting powder was then analyzed for its properties.

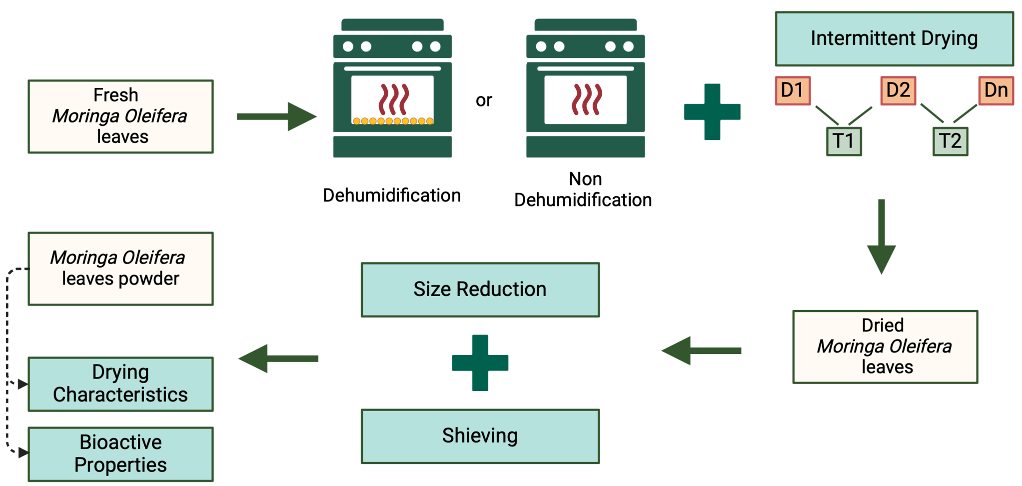


**Figure 1.** Drying setup and equipment

***Dehumidification drying using zeolite***

The setup consisted of a zeolite bed placed inside a food dehydrator, with Moringa leaves arranged on trays above the zeolite bed, as shown in Figure 1. Zeolite was used as a desiccant in the dehumidification drying process to reduce the relative humidity of the air inside the chamber (Sasongko *et al.*, 2020). Before the drying process, the zeolite bed was pre-treated by heating it at 150°C for 2 hours to enhance its moisture adsorption capacity (Djaeni *et al.*, 2021). Dehumidified air was then circulated through the drying chamber at a controlled temperature (40°C, 60°C, and 80°C), with the relative humidity and temperature continuously monitored and maintained throughout the process. The process was also done without dehumidification using zeolite as the control (Table 1).

**Table 1.** The process variable of moringa leaves drying

| Run | Drying temperature (°C) | Intermittent Drying | | Dehumidification |
|---|---|---|---|---|
| | | Drying Periods (Minutes) | Tempering Periods (Minutes) | |
| 1 | 40 | 10 | 20 | Zeolit |
| 2 | 40 | 20 | 10 | Zeolit |
| 3 | 60 | 10 | 20 | Zeolit |
| 4 | 60 | 20 | 10 | Zeolit |
| 5 | 80 | 10 | 20 | Zeolit |
| 6 | 80 | 20 | 10 | Zeolit |
| 7 | 40 | 10 | 20 | Non zeolit |
| 8 | 40 | 20 | 10 | Non zeolit |
| 9 | 60 | 10 | 20 | Non zeolit |
| 10 | 60 | 20 | 10 | Non zeolit |
| 11 | 80 | 10 | 20 | Non zeolit |
| 12 | 80 | 20 | 10 | Non zeolit |

***Intermittent drying process***

The intermittent drying process consisted of alternating drying and tempering periods (Golmohammadi *et al.*, 2016; Pereira *et al.*, 2020). Moringa leaves were arranged on aluminum trays and placed inside a food dehydrator, with the air temperature initially set at 40°C. Each drying period lasted for 10 minutes, followed by a 20-minute tempering period in a desiccator to allow for moisture redistribution within the leaves. The drying experiments were conducted at varying air temperatures and intermittent periods, as detailed in Table 1.

***Drying characteristics***

Moisture ratios were calculated on the rasio of the moisture content of moringa leaves at t time and moisture content of moringa leaves before drying.

$$\text{Moisture Ratio (MR)} = \frac{M_t}{M_0} \tag{1}$$

An empirical drying kinetics model, namely Henderson and Pabis (Equation 2), was used to determine the equation or model that best fits the drying process by showing the direct relationship between moisture ratio (MR) and drying time (Turan and Firatligil, 2019).

$$MR = a\exp(-bt) \tag{2}$$

Where a and b are the model parameters. The drying kinetics were analyzed by recording the reduction along the drying. The effective moisture diffusivity, Deff, is determined using Fick's second law of diffusion, assuming a slap for the Moringa leaves. The equation used to calculate Deff as follows:

$$\ln MR = \ln\frac{6}{\pi^2} - \left(\frac{D_{eff}.\pi^2}{r^2}\right)t \quad (3)$$

Where (r) is the characteristic length of the leaves, and (t) was the drying time.

### *Chlorophyll content determination*

Chlorophyll content was determined using a spectrophotometric method. A UV-visible spectrophotometer (U-2900, Hitachi Ltd., Japan) was employed to measure the chlorophyll concentration. Absorbance readings of the samples were taken at wavelengths of 663 nm and 645 nm. The total chlorophyll concentration, Cc, in mg/L, was then calculated using Equation 5, following the previous method (Zhang *et al.*, 2009). Then the total chlorophyll concentration of each sample was converted into chlorophyll retention (%).

$$\mathbf{C_C = 20.31(A_{645}) + 8.05(A_{663})} \quad (5)$$

## Results

### *Effect of dehumidification on moisture ratio reduction*

The addition of zeolite in the drying process, particularly for Moringa leaves, demonstrated a significant impact on the efficiency of moisture removal. The relationship between zeolite use and the reduction of moisture ratio during intermittent drying with drying period of 10 minutes and tempering period of 20 minutes at temperatures of 40°C and 80°C is shown in Figure 2.

It is clearly compared between drying processes with and without zeolite at different temperatures (Figure 2). The moisture ratio of Moringa leaveswas significantly reduced in the presence of zeolite, especially at higher temperatures. For instance, at 40°C, the moisture ratio in the absence of zeolite was 0.9175 after 120 minutes, whereas with zeolite, it was reduced to 0.8924. This 3 % difference may seem modest but is an indication of the effectiveness of zeolite even at lower temperatures.

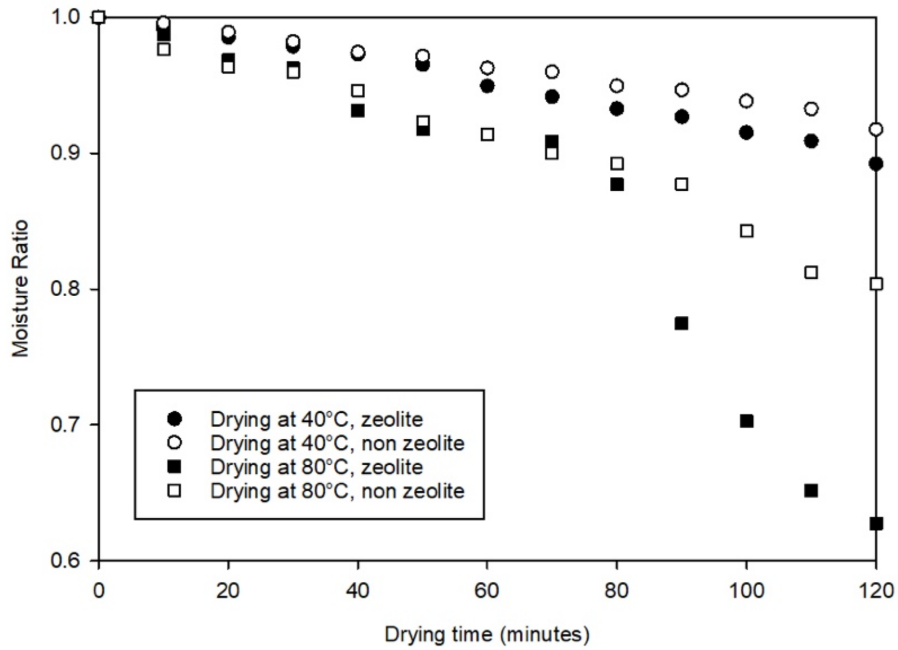


**Figure 2.** Moisture ratio reduction during moringa leaves drying using drying periods of 10 minutes and tempering periods of 20 minutes

The impact of zeolite becomes more pronounced at higher temperatures. At 80°C, the difference was more significant, with the moisture ratio falling from 0.8039 (non-zeolite) to 0.6275 (zeolite), a 22% reduction. These results clearly indicated that the higher the temperature, the more pronounced the effect of zeolite on moisture ratio removal.

***Effect of intermittent tempering periods on moisture ratio reeduction***

The relationship between intermittent tempering periodsand moisture ratio at drying temperatures of 60°C, with tempering periods of 10 and 20 minutes is shown in Figure 3. Intermittent tempering is allowed for periodic paused in the drying process, which can help to reduce thermal stress on the product and enhanced the drying efficiency by promoting better water diffusion. The experimental data revealed a clear trend to decrease moisture ratio over the drying time, with variations depending on the tempering periods of 10 and 20 minutes. The moisture ratio for drying periods of 10 minutes and tempering periods of 20 minutes after 120 minutes drying was 0.4199. While the moisture ratio for drying periods of 20 minutes and tempering periods of 10 minutes after

120 minutes drying was 0.8205. It is evident that the moisture ratio decreased more effectively at a tempering time of 20 minutes.

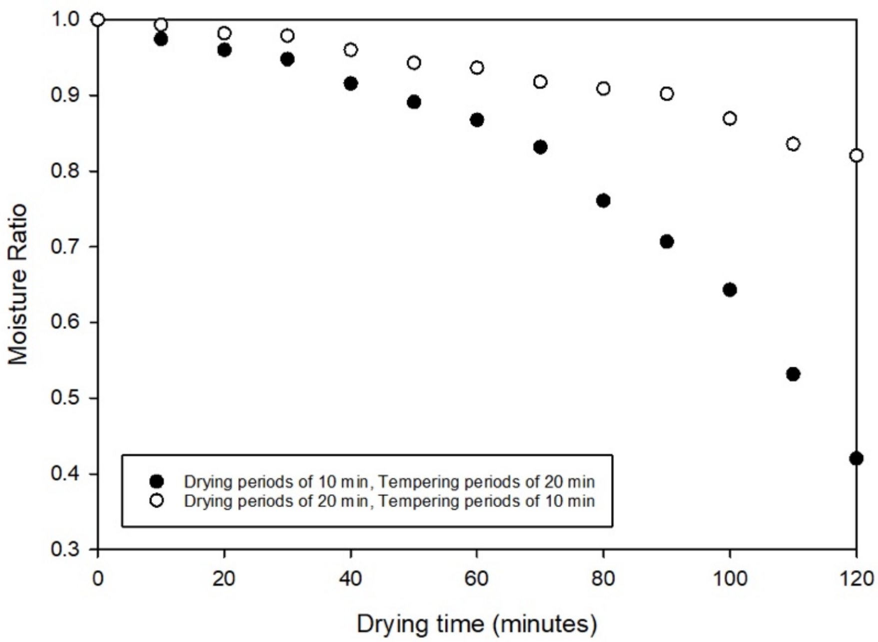


**Figure 3.** Moisture ratio reduction during moringa leaves drying using dehumidification with zeolite at 60°C

***Drying model***

The modeling constants and statistical parameters for drying Moringa leaves at temperatures of 40°C, 60°C, and 80°C are summarized in Table 3. The results indicated that the Henderson and Pabis model provided the best fit for the experimental data, as evidenced by the highest $R^2$ values across the various drying conditions. Specifically, the $R^2$ values for zeolite-assisted intermittent drying ranged from 0.9972 to 1.0000, demonstrating excellent predictive accuracy, with the highest values observed at both 40°C and 60°C with different drying and tempering periods. In the case of non-zeolite drying, the $R^2$ values also remained high, ranging from 0.9982 to 1.0000, confirming the reliability of the model across different conditions.

The model constants for the zeolite-assisted drying process showed a consistent increase in the drying rate constant (k) with increasing temperature, reflecting enhanced moisture removal efficiency. For instance, the k value for intermittent drying at 60°C (0.0061) was significantly higher than that at 40°C (0.0009), indicating a direct correlation between drying temperature and moisture removal rates. Conversely, while non-zeolite drying exhibited similar trends, the k values were generally lower, suggesting that zeolite enhances drying performance. Overall, the findings confirmed that both the drying method and temperature significantly influenced the drying characteristics of Moringa leaves, validating the use of the Henderson and Pabis model for predicting moisture content reduction during the drying process.

**Table 3.** Model constants and statistical parameters for moringa leaves drying

| Run | Drying temperature (°C) | Intermittent Drying | | Dehumidification | Model constant | | $R^2$ |
|---|---|---|---|---|---|---|---|
| | | Drying Periods (Minutes) | Tempering Periods (Minutes) | | k | a | |
| 1 | 40 | 10 | 20 | Zeolite | 0.0009 | 1.0046 | 1.0000 |
| 2 | 40 | 20 | 10 | Zeolite | 0.0032 | 1.0445 | 0.9993 |
| 3 | 60 | 10 | 20 | Zeolite | 0.0061 | 1.1285 | 0.9972 |
| 4 | 60 | 20 | 10 | Zeolite | 0.0011 | 1.0041 | 1.0000 |
| 5 | 80 | 10 | 20 | Zeolite | 0.0017 | 1.0068 | 0.9999 |
| 6 | 80 | 20 | 10 | Zeolite | 0.0038 | 1.0558 | 0.9984 |
| 7 | 40 | 10 | 20 | Non zeolite | 0.0007 | 1.0027 | 1.0000 |
| 8 | 40 | 20 | 10 | Non zeolite | 0.0031 | 1.0330 | 0.9999 |
| 9 | 60 | 10 | 20 | Non zeolite | 0.0057 | 1.1133 | 0.9982 |
| 10 | 60 | 20 | 10 | Non zeolite | 0.0016 | 1.0184 | 0.9999 |
| 11 | 80 | 10 | 20 | Non zeolite | 0.0038 | 1.0729 | 0.9986 |
| 12 | 80 | 20 | 10 | Non zeolite | 0.0174 | 1.4039 | 1.0000 |

***Moisture diffusivity***

The drying experiments investigated the effects of temperature, intermittent tempering periods, and the inclusion of zeolite on the effective moisture diffusivity (Table 4). The use of dehumidification with zeolite generally showed a higher Deff and efficient moisture removal across different drying temperatures, with enhanced the results at higher temperatures. For drying at 40°C, the configuration of 20-minute tempering and 10-minute drying intervals (Run 2) produced a significant Deff of $7.31 \times 10^{-8}$ m²/s with an $R^2$ value of 0.8789. Increasing in drying temperature to 60°C under similar intermittent conditions (Run 3) achieved the highest diffusivity among all tests with a Deff of $13.98 \times 10^{-8}$ m²/s and an $R^2$ of 0.825, indicating that higher temperatures and zeolite facilitate moisture removal more effectively.

At 80°C, the configuration of 10-minute drying periods and 20-minute tempering periods (Run 5) with zeolite reached a Deff of $3.98 \times 10^{-8}$ m²/s, maintaining a high $R^2$ value of 0.9647. When zeolite was excluded, higher diffusivity values were observed only at elevated temperatures, notably in Run

12 (80°C with 20-minute drying and 10-minute tempering), yielding a diffusivity of 39.8 × $10^{-8}$ $m^2/s$ but with a relatively lower $R^2$ value of 0.8543, suggesting a less stable drying pattern.

**Table 4.** Diffusivity values for various variables

| Run | Drying temperature (°C) | Intermittent Drying | | Dehumidification | Deff ($10^{-8}$ $m^2/s$) | $R^2$ |
|---|---|---|---|---|---|---|
| | | Drying Periods (Minutes) | Tempering Periods (Minutes) | | | |
| 1 | 40 | 10 | 20 | Zeolite | 2.11 | 0.9891 |
| 2 | 40 | 20 | 10 | Zeolite | 7.31 | 0.8789 |
| 3 | 60 | 10 | 20 | Zeolite | 13.98 | 0.825 |
| 4 | 60 | 20 | 10 | Zeolite | 2.42 | 0.9742 |
| 5 | 80 | 10 | 20 | Zeolite | 3.98 | 0.9647 |
| 6 | 80 | 20 | 10 | Zeolite | 8.58 | 0.8137 |
| 7 | 40 | 10 | 20 | Non zeolite | 1.54 | 0.9876 |
| 8 | 40 | 20 | 10 | Non zeolite | 6.995 | 0.9636 |
| 9 | 60 | 10 | 20 | Non zeolite | 12.9 | 0.8664 |
| 10 | 60 | 20 | 10 | Non zeolite | 3.65 | 0.949 |
| 11 | 80 | 10 | 20 | Non zeolite | 8.69 | 0.8438 |
| 12 | 80 | 20 | 10 | Non zeolite | 39.8 | 0.8543 |

### *Chlorophyll retention*

The retention of chlorophyll in *Moringa oleifera* leaf powder was significantly influenced by the drying temperature, intermittent tempering periods, and the use of zeolite in the drying process (Figure 4). The data revealed that lower drying temperatures and optimal intermittent drying configurations favor higher chlorophyll retention. At a drying temperature of 40°C, the highest chlorophyll retention was observed, where a 10-minute drying period followed by a 20-minute tempering period with zeolite yielded a retention of 60.58%. In contrast, increasing the drying duration to 20 minutes while maintaining the same temperature resulted in a notable decrease to 51.98% chlorophyll retention.

As the drying temperature increased to 60°C, chlorophyll retention decreased further. Run 3, which utilized a 10-minute drying period and a 20-minute tempering period with zeolite, achieved a retention of 35.57%. This value dropped to 30.97% with longer drying periods (20 minutes) and tempering (10 minutes). At the highest temperature of 80°C, chlorophyll retention plummeted significantly, with recording a retention rate of only 25.09% and Run 6 further declining to 13.86% under the same intermittent drying conditions. This trend clearly indicated that higher drying temperatures, regardless of the intermittent drying configuration, adversely affect chlorophyll retention, highlighting the importance of carefully managing drying conditions to preserve chlorophylls in Moringa leaves.

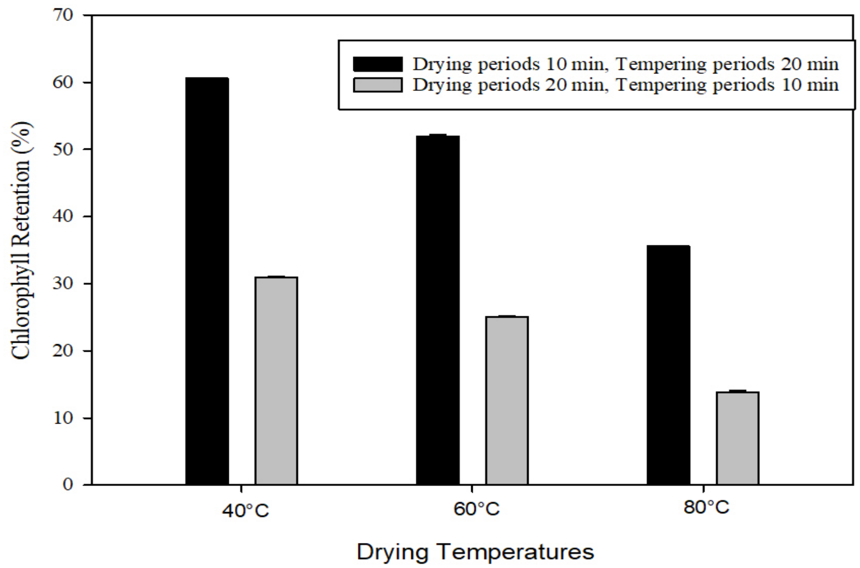


**Figure 4.** Chlorophyll retention during moringa leaves drying using dehumidification with zeolite

## Discussion

Zeolite is a highly porous aluminosilicate mineral known for its superior ability to adsorb water vapor due to its strong affinity for water molecules. This makes it an excellent desiccant for use in drying processes. The adsorption properties of zeolite are linked to its microporous structure, which allows it to capture water vapor during drying (A'yuni *et al.*, 2022). As zeolite adsorbs moisture from the air surrounding the drying material, it lowers the relative humidity within the drying environment (Asiah *et al.*, 2017; A'yuni *et al.*, 2022). The reduction in air humidity creates a higher drying driving force or moisture gradient between the material and the air, which accelerates the evaporation of water from the Moringa leaves. In practical terms, the presence of zeolite during drying leads to faster moisture removal as it prevents the buildup of humidity in the drying chamber. Without zeolite, the water vapor released by the Moringa leaves would remain in the surrounding air, slowing down further moisture evaporation as the air approaches saturation (Atuonwu *et al.*, 2011a; Djaeni *et al.*, 2021). However, with zeolite continuously adsorbing the vapor, the drying air maintains its capacity to absorb more moisture from the leaves, thus enhancing the drying efficiency.

The results indicated that a tempering time of 20 minutes is more effective in reducing moisture content. The underlying mechanism for this effect can be attributed to the longer tempering period, which provided sufficient time for water molecules trapped within the product to migrate toward the surface (Golmohammadi *et al.*, 2015, 2016). During this period, the diffusion of free water is enhanced, which, in turn, accelerates the drying process once the heat is reintroduced. As a result, the thermal gradient within the product decreases, allowing for more efficient heat transfer and a faster drying rate (Pereira *et al.*, 2020). The effectiveness of tempering in intermittent drying can be evaluated using the intermittent ratio (α), which represents the proportion of tempering time relative to the total cycle time (Kumar *et al.*, 2014a). The intermittent ratio is calculated as:

$$\propto = \frac{t\ out}{(t\ out + t\ in)} \tag{6}$$

Based on the experimental data, the most optimal drying condition was found to occur when the intermittent ratio $\alpha = 2/3$. This ratio implies that for every complete drying cycle, two-thirds of the time was spent on tempering. Such a ratio strikes a balance between allowing sufficient time for moisture redistribution and minimizing the overall drying time. This result suggests that intermittent drying with longer tempering times can offer an efficient drying strategy by preventing excessive surface drying, reducing energy consumption, and ensuring uniform moisture content within the product. Additionally, the Henderson & Pabis model was chosen to predict the drying characteristics of moringa leaves drying.

The drying experiments underscored the effectiveness of temperature control, intermittent tempering intervals, and zeolite integration in enhancing moisture diffusivity during moringa leaf drying. Zeolite with high moisture adsorption properties which is helped to maintain low relative humidity, supporting moisture migration from the leaves and optimizing drying efficiency (Atuonwu *et al.*, 2011b; Sasongko *et al.*, 2020). This method showed notable advantages over traditional drying approaches like sun or hot air drying, which often lead to slower moisture removal and less effective moisture diffusivity. The intermittent drying approach, with tempering periods are contributed by allowing internal moisture redistribution, which stabilizes moisture release, reduces thermal stress, and prevents surface hardening—challenges commonly observed in continuous drying methods (Kumar *et al.*, 2014a; Md Saleh *et al.*, 2020). When zeolite is not used, higher temperatures are required for effective diffusivity, often resulting in drying instability. Together, zeolite and intermittent drying improve drying rates and ensure a more stable drying process, presenting an advanced approach for achieving efficient moisture removal in Moringa leaf drying.

The reduction in chlorophyll content during drying indicated its degradation from heat, as elevated temperatures can denature the proteins that form complex bonds with chlorophyll, leading to the release of organic acids (Aryanti and Nafiunisa, 2017; Lípová *et al.*, 2010). Continuous high temperature drying exacerbates this degradation since the outer layer of the leaf loses water faster than the inner part, creating potential temperature differences within the leaf (Kumar *et al.*, 2014b). To mitigate this, a tempering phase is employed, halting heat energy and airflow to ensure that the water exiting the product is less than that diffusing from the inside to the outside, resulting in more uniform moisture content (Dehghannya *et al.*, 2018). By combining drying with tempering, known as intermittent drying, protein denaturation can be minimized, thereby preserving chlorophyll and reducing its degradation.

Moringa leaf powder, rich in chlorophyll, presents a viable alternative to synthetic green food colorants, aligning with the increasing consumer preference for natural ingredients. Beyond its vibrant green hue, chlorophyll offers health benefits, including antioxidant properties that help prevent food oxidation and enhance nutritional profiles (Oyeyinka and Oyeyinka, 2018; Rahmawati *et al.*, 2023). The drying techniques used in this study, especially intermittent drying, effectively preserve chlorophyll's integrity and bioavailability, making it suitable for food applications and health supplements. *Moringa oleifera* leaf powder is valuable for its high chlorophyll, vitamins, minerals, and antioxidants, supporting detoxification, immune function, and skin health while minimizing nutrient degradation and protein denaturation during processing.

In conclusion, the study on producing chlorophyll-rich powder from *Moringa oleifera* leaves using dehumidification and intermittent drying demonstrated that combining zeolite with these drying techniques effectively enhances moisture reduction and chlorophyll retention. Zeolite aids moisture removal by continuously adsorbing water vapor, while intermittent drying improves efficiency by promoting moisture diffusion and reducing thermal stress. This approach is preserved chlorophyll stability, making the powder a valuable natural alternative to synthetic colorants and a potent health supplement due to its retained nutrient bioavailability.

## Acknowledgements

This research was funded by the Faculty of Engineering Diponegoro University by RKAT FT UNDIP Grant 2024.

## Conflicts of interest

The authors declare no conflict of interest.

## References

Abdulkadir, A. R., Jahan, Md. S. and Zawawi, D. D. (2015). Effect of chlorophyll content and maturity on total phenolic, total flavonoidn contents and antioxidant activity of Moringa oleifera leaf (Miracle tree). Journal of Chemical and Pharmaceutical Research, 7:1147-1152.

Ademiluyi, A. O., Aladeselu, O. H., Oboh, G. and Boligon, A. A. (2018). Drying alters the phenolic constituents, antioxidant properties, α-amylase, and α-glucosidase inhibitory properties of Moringa (*Moringa oleifera*) leaf. Food Science and Nutrition, 6:2123-2133.

Agnieszka, C. and Lenart, A. (2011). Freeze-drying – application in food processing and biotechnology – A review. Polish Journal of Food and Nutrition Sciences, 61:165-171.

Arslan, D. and Musa Özcan, M. (2010). Study the effect of sun, oven and microwave drying on quality of onion slices. LWT - Food Science and Technology, 43:1121-1127.

Aryanti, N. and Nafiunisa, A. (2017). Extraction, characterization and degradation of chlorophyll from Suji Leaves *(Pleomele angustifolia).* Oriental Journal of Chemistry, 33:3185-3190.

Asiah, N., Djaeni, M. and Hii, C. L. (2017). Moisture transport mechanism and drying kinetic of fresh harvested red onion bulbs under dehumidified air. International Journal of Food Engineering, 13. https://doi.org/10.1515/ijfe-2016-0401

Atuonwu, J. C., Jin, X., van Straten, G., Deventer Antonius, H. C. van and van Boxtel, J. B. (2011a). Reducing energy consumption in food drying: Opportunities in desiccant adsorption and other dehumidification strategies. Procedia Food Science, 1:1799-1805.

Atuonwu, J. C., Van Straten, G., Van Deventer, H. C. and Van Boxtel, A. J. B. (2011b). Optimizing energy efficiency in low temperature drying by zeolite adsorption and process integration. Chemical Engineering Transactions, 25.

A'yuni, D. Q., Djaeni, M., Asiah, N. and Subagio, A. (2022). Enhancement of onion bulb drying with air dehumidification assisted dryer. AIMS Agriculture and Food, 7:168-183.

Aznury, M., Zikri, A., Saputra, M. F. and Rachmadona, N. (2021). Analyzing effect of temperature on drying Moringa *(Moringa Oleifera)* leaves using photovoltaic tray dryer, 48.

Dehghannya, J., Hosseinlar, S. H. and Heshmati, M. K. (2018). Multi-stage continuous and intermittent microwave drying of quince fruit coupled with osmotic dehydration and low temperature hot air drying. Innovative Food Science & Emerging Technologies, 45:132-151.

Díaz-Bandera, D., Villanueva-Carvajal, A., Dublán-García, O., Quintero-Salazar, B. and Dominguez-Lopez, A. (2015). Assessing release kinetics and dissolution of spray-dried Roselle (*Hibiscus sabdariffa* L.) extract encapsulated with different carrier agents. LWT - Food Science and Technology, 64:693-698.

Djaeni, M., A'yuni, D., Alhanif, M., Hii, C. and Kumoro, A. (2021). Air dehumidification with advance adsorptive materials for food drying: A critical assessment for future prospective. Drying Technology, 39:1-22.

Golmohammadi, M., Assar, M., Rajabi-Hamaneh, M. and Hashemi, S. J. (2015). Energy efficiency investigation of intermittent paddy rice dryer: Modeling and experimental study. Food and Bioproducts Processing, 94:275-283.

Golmohammadi, M., Foroughi-Dahr, M., Rajabi-Hamaneh, M., Shojamoradi, A. R. and Hashemi, S. J. (2016). Study on drying kinetics of paddy rice: Intermittent drying. Iranian Journal of Chemistry and Chemical Engineering, 35:105-117.

Hasizah, A., Djalal, M., Mochtar, A. A. and Salengke, S. (2022). Fluidized bed drying characteristics of moringa leaves and the effects of drying on macronutrients. Food Science and Technology (Brazil), 42:1-11.

Kumar, C., Karim, M. A. and Joardder, M. U. H. (2014a). Intermittent drying of food products: A critical review. Journal of Food Engineering, 121:48-57.

Kumar, S. S., Manoj, P., Shetty, N. P. and Giridhar, P. (2014b). Effect of different drying methods on chlorophyll, ascorbic acid and antioxidant compounds retention of leaves of *Hibiscus sabdariffa* L. Journal of the Science of Food and Agriculture, 95:1812-1820.

Lípová, L., Krchňák, P., Komenda, J. and Ilík, P. (2010). Heat-induced disassembly and degradation of chlorophyll-containing protein complexes in vivo. Biochimica et Biophysica Acta (BBA) - Bioenergetics, 1797:63-70.

Mallenakuppe, R., Homabalegowda, H., Gouri, M. D., Basavaraju, P. S. and Chandrashekharaiah, U. B. (2019). History, Taxonomy and Propagation of Moringa oleifera-A Review. SSR Institute of International Journal of Life Sciences, 5:2322-2327.

Md Saleh, R., Kulig, B., Emiliozzi, A., Hensel, O. and Sturm, B. (2020). Impact of critical control-point based intermittent drying on drying kinetics and quality of carrot *(Daucus carota var. laguna).* Thermal Science and Engineering Progress, 20:100682.

Oyeyinka, A. T. and Oyeyinka, S. A. (2018). Moringa oleifera as a food fortificant: Recent trends and prospects. Journal of the Saudi Society of Agricultural Sciences, 17:127-136.

Pareek, A., Pant, M., Gupta, M. M., Kashania, P., Ratan, Y., Jain, V., Pareek, A. and Chuturgoon, A. A. (2023). Moringa oleifera: An updated comprehensive review of its pharmacological activities, ethnomedicinal, phytopharmaceutical formulation, clinical, phytochemical, and toxicological aspects. International Journal of Molecular Sciences, 24:2098.

Pereira, J. C. A., da Silva, W. P., Gomes, J. P., Queiroz, A. J. de M., de Figueirêdo, R. M. F., de Melo, B. A., Santiago, Â. M., de Lima, A. G. B. and de Macedo, A. D. B. (2020). Continuous and intermittent drying of rough rice: effects on process effective time and effective mass diffusivity. Agriculture (Switzerland), 10:1-13.

Rahmawati, I., Anggraeni, S. D., Bernika, S. O. and Julianti, A. I. (2023). Phenolic content and antioxidant activity of Moringa oleifera leaf infusions and tea. AIP Conference Proceedings, 2572. https://doi.org/10.1063/5.0118400

Sasongko, S. B., Hadiyanto, H., Djaeni, M., Perdanianti, A. M. and Utari, F. D. (2020). Effects of drying temperature and relative humidity on the quality of dried onion slice. Heliyon, 6:e04338.

Singh, V., Arulanantham, A., Parisipogula, V., Arulanantham, S. and Biswas, A. (2018). Moringa olifera: Nutrient dense food source and world's most useful plant to ensure nutritional security, good health and eradication of malnutrition. European Journal of Nutrition & Food Safety, 8:204-214.

Turan, Y. O. and Firatligil, E. F. (2019). Modelling and characteristics of thin layer convective air-drying of thyme *(Thymus vulgaris)* leaves. Czech Journal of Food Sciences, 37:128-134.

Zhang, J., Han, C. and Liu, Z. (2009). Absorption spectrum estimating rice chlorophyll concentration: preliminary investigations. Journal of Plant Breeding and Crop Science, 1:223-229.

(Received: 26 October 2024, Revised: 2 June 2025, Accepted: 29 July 2025)