Journal of Food Measurement and Characterization (2026) 20:2412–2424
https://doi.org/10.1007/s11694-026-04055-w

ORIGINAL PAPER

Investigation of quality characteristics and mathematical modeling of green lentil (*Lens culinaris medik*) and mung bean (*Vigna radiata*) microgreens dried in different dryers

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Received: 22 October 2025 / Accepted: 6 January 2026 / Published online: 27 January 2026
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Abstract
Microgreens have been consumed by different cultures for many years. The main reason for this is that microgreens are additive-free, natural, and can be easily grown even at home. In this research, green lentil and mung bean microgreens were produced, harvested, and finally dried in two different dryers (conventional dryer and microwave). The drying process was carried out at 3 different temperatures in a conventional dryer and at 3 different microwave powers in a microwave oven. It was calculated that the moisture values of dry green lentil microgreens and dry mung bean microgreens varied between 11.97 ± 1.22–12.52 ± 0.13% and 14.61 ± 0.65–18.86 ± 1.21%, respectively. It was found that dried samples had higher L^* and a^* values and lower b^* and C^* values than fresh microgreens. The best drying models for dried green lentil and mung bean microgreens were determined to be the Henderson and Pabis and Modified Page models, respectively. It was determined that both TFM and antioxidant activity values of fresh microgreens were lower than those of dried microgreens. The differences between the groups in terms of water activity, TPC, and antioxidant activity results of dried green lentil microgreens and dried mung bean microgreens were found to be statistically significant ($P < 0.05$). This research not only examines drying technology from a scientific perspective but also hopes that the study data will serve as a guide for people to consume their own microgreens, both fresh and preserved by drying them, in their daily lives. This study will enable consumers to grow green lentil and mung bean microgreens, which are easy to grow at home. Following this, consumers can consume healthy alternatives with these nutritious dried green lentil and mung bean microgreens. The study not only provides consumers with information about growing and drying green lentil or mung bean microgreens but also serves as a guide for those wishing to grow other microgreens.

Keywords Antioxidant · Phenolic · Drying · Microgreens · Modeling

Introduction

The first structure that emerges from a germinating seed is referred to as a "sprout." Sprouts are products that lack true leaves, remain in a bud-like form, and are consumed shortly after germination. The consumption of seed sprouts as food originates from the Far East and has become increasingly widespread in Western countries in recent years, driven by the growing demand for minimally processed, additive-free, natural, nutritious, and healthy foods. Germinating seeds with low moisture content and high nutrient density enhances the bioavailability of proteins, vitamins, and other nutrients, reduces the activity of toxins and enzyme inhibitors, and improves overall digestibility [1].

Building upon the interest in sprouts, microgreens have emerged as another popular group of young plants valued for their nutritional and sensory properties. Microgreens are young greens harvested at the stage when the first true leaves develop following the germination of various vegetable, plant, or grain seeds. These plants, which can be harvested and consumed at different stages of early growth and are generally eaten raw, have gained increasing popularity in recent years. In microgreen production, seeds and grains of grasses and legumes are most commonly

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used. However, microgreens can also be cultivated from the seeds of a wide range of crops, including legumes, cereals, oilseeds, vegetables, and herbs [2, 3]. In recent years, the consumption of microgreens has increased, and these plants are described by many authorities as superfoods or the food of the future [4–6].

Due to their immature developmental stage, microgreens possess concentrated flavors, delicate textures, and vibrant colors. Common commercially available microgreens include broccoli, kale, celery, basil, and radish. Owing to these desirable sensory attributes, microgreens have been increasingly incorporated by chefs into soups, sandwiches, and various culinary applications. At the same time, their functional properties have drawn significant attention from nutrition researchers, resulting in growing scientific interest in their roles in nutrition and health [5, 6]. There are studies in the literature on the health effects of microgreens and their potential phenolic and antioxidant sources [7–9].

Legumes, another group widely used in microgreen production, are considered an important source of nutrition, especially for individuals experiencing economic difficulties, due to the high amounts of protein, carbohydrates, dietary fiber, vitamins, minerals, and phytochemicals they contain [10]. In recent years, numerous studies have investigated the health benefits of germinated legumes. Comparative analyses between germinated and non-germinated grains in terms of vitamin and mineral content, antioxidant capacity, and various bioactive components (such as phenolic acids and isoflavones) consistently demonstrate that germinated seeds exhibit significantly higher levels of these nutrients and functional compounds. Bioactive components that contribute to the functional properties of foods offer a wide range of health benefits, including the prevention or reduction of certain cancers, cardiovascular diseases, osteoporosis, and age-related degeneration, as well as improved glycemic control and enhanced protection against oxidative stress [11].

Eating habits vary across different periods and regions of the world, and among these trends, vegan diets have gained significant popularity in recent years. In this plant-based dietary pattern, microgreens are frequently consumed by individuals. Today, however, microgreens are recognized for their high nutritional value and are now consumed not only by those following a vegan diet but also by a wide range of consumers across society.

Despite their nutritional and sensory advantages, microgreens present significant challenges in terms of postharvest handling. Although cultivating microgreens is relatively simple, their short shelf life necessitates rapid consumption. Consequently, one of the primary challenges in the microgreens industry is storage, specifically, maintaining product quality after harvest. Microgreens are difficult to store due to their high surface-area-to-volume ratio, as well as their high respiration and transpiration rates, all of which accelerate senescence. Factors such as temperature, humidity, microbial load, packaging type, and overall storage conditions can further accelerate quality deterioration, thereby limiting the shelf life of microgreens.

Given these limitations, drying technologies have become an important approach for preserving perishable plant-based foods. The use of drying technologies dates back centuries and continues to play a significant role in the food industry today. One of the primary reasons for the enduring interest in these technologies is their ability to substantially extend the shelf life of foods. By reducing moisture content, drying enables products with inherently short shelf lives to be preserved for much longer periods. Currently, a wide variety of drying systems is available, making it possible to produce high-quality dried products using appropriate drying equipment. In recent years, several conventional dryers, as well as microwave ovens, have gained popularity for home use, enabling consumers to quickly dry fresh and perishable foods in their own kitchens. Because microgreens have a short shelf life and are perishable foods, in this study, they were dried in conventional and microwave ovens that are easily accessible to all consumers.

A careful examination of the mathematical modeling data revealed that no studies have been conducted on the drying behavior of microgreens. Furthermore, no research has addressed the drying of green lentils and mung beans, which are not only rich in protein but also possess significant phenolic and antioxidant potential. The thin-layer drying modeling data of dried microgreens, which have not been previously reported, are therefore expected to contribute valuable insights to the literature.

In this research, freshly harvested green lentil and mung bean microgreens were produced, harvested, and dried in conventional and microwave ovens. Green lentil microgreens were dried in a conventional oven at 50, 60 and 70 °C, and in a microwave oven at 180 W, 300 W and 450 W. On the other hand, mung bean microgreens were dried in a conventional oven at 60, 65 and 70 °C, and in a microwave oven at 600 W, 700 W and 800 W. Subsequently, mathematical modeling of microgreens was conducted, followed by quality analyses and statistical evaluations of both fresh and dried microgreens. This study provides a comprehensive overview of the drying, modeling, and quality characteristics of microgreens; however, further research in this field remains necessary. Future studies are planned to focus on vegetable microgreens. The production and drying of vegetable microgreens, such as radish, cabbage, lettuce, and parsley, containing high levels of bioactive compounds, similar to mung bean and lentil microgreens, are of particular interest, as there is currently no literature on their drying and modeling.

Materials and methods

Cultivating microgreens

In the first step of the study, green lentils and mung beans were purchased from a local market in Turkey. 20 L of peat soil used in microgreen cultivation were supplied by a commercial company. The soil used ensures a slow and steady transfer of water to the plant. Containing organomineral substances, it enriches the soil, aerating the plant's roots and promoting growth. It contains easily soluble minerals. It contains imported peat, coco peat, and perlite in proportions. Its high infiltration properties allow it to quickly drain excess water away from the plant.

Microgreens were planted in disposable plastic containers with lids. Microgreens were grown directly in the home environment (natural light). Microgreens were grown under 1000–10,000 lx of natural light. Before planting, both green lentils and mung beans were placed in a deep container and soaked in pure water for approximately 2 h. Thus, it was determined that legume grains that took some water into their structure germinated more efficiently. Lentil microgreens were harvested on the 7th day, and mung bean microgreens were harvested after 8 days. No regeneration was done in the harvested soil. The soil and disposable plastic containers used for cultivation were not reused in the study. Microgreens that had grown sufficiently for the study were harvested. Harvested microgreens were quickly analyzed to prevent loss of quality. Microgreens that could not be analyzed on the day they were harvested were stored at −18 °C until analysis. Figure 1 shows the cultivation stages of green lentils and mung beans until harvest time.

Chemicals

All chemicals used in this study were of analytical grade and were used without further purification. Methanol (≥99.8% purity, CAS: 67-56-1), acetonitrile (≥99.9%, CAS: 75-05-5), sodium carbonate (≥99.9%, CAS: 497-19-8), sulfuric acid (95–98%, CAS: 7664-93-9), and ethanol (≥99.5%, CAS: 64-17-5) were purchased from Merck (Darmstadt, Germany). Folin–Ciocalteu reagent (CAS: 12111-13-6) and DPPH (2,2-diphenyl-1-picrylhydrazyl, ≥95% purity, CAS: 1898-66-4) were purchased from Sigma-Aldrich (St. Louis, MO, USA).

Drying process

In the second step of the project, harvested green lentil and mung bean microgreens were dried in a microwave (Samsung, Korea) and conventional dryers (Kiwi, Turkey). In this research, conventional drying was preferred because the conventional dryer (home-type fruit dryer) can be easily used in every kitchen, does not take up space, and has low energy consumption. All drying processes were done in 5 replications. Drying times for microgreens were chosen to avoid burning and to ensure similar moisture levels. Burning was particularly common in microgreens grown using microwave ovens. Green lentil microgreens were dried under 180 W, 300 W and 450 W for 20, 12 and 9 min, respectively. Microgreens were dried in a conventional oven at 50, 60, and 70 °C for 420, 240, and 150 min, respectively. Mung bean microgreens were dried at 600 W, 700 W, and 800 W for 16, 14, and 10 min, respectively. Microgreens were dried in a conventional oven at 60, 65, and 70 °C for 240, 210, and 165 min, respectively.

Mathematical calculations and modeling of microgreens

Four drying models were used in the study. The equations for these models are given in Table 1. When the drying behavior of microgreens was examined, the models with the highest R^2, lowest χ^2 and RMSE values among the calculated model equations were the Newton, Henderson and Pabis, Page, and Modified Page models, so the 4 mathematical models specified in the study were used.



Fig. 1 Microgreen production steps from mung beans and green lentils

Table 1 Mathematical models used in drying microgreens [16]

Model name	Model equation
Newton	$MR = \exp(-kt)$
Henderson and Pabis	$MR = a \cdot \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Modified page	$MR = \exp[(-kt)^n]$

Moisture ratio (MR) of fresh and dried microgreens was calculated using the simplified definition given in Eq. (1), where M_t and M_0 represent the moisture content at any drying time and the initial moisture content, respectively [12–14]. The equilibrium moisture content (M_e) was not included in the MR calculation because equilibrium conditions were not experimentally attained and M_e was not explicitly determined under the applied drying conditions. When the MR definition including equilibrium moisture content [$MR=(M_t–M_e)/(M_0–M_e)$] is used, the moisture ratio theoretically approaches zero as M_t approaches M_e; however, since the calculated MR values in this study did not reach zero, the simplified MR formulation excluding M_e was adopted to ensure consistency between the mathematical formulation and the experimental calculations. Therefore, the simplified MR definition was adopted in this study to ensure practical applicability and consistency in the comparison of different drying methods. Modeling the moisture ratio of drying microgreen samples using conventional and microwave dryers can use the mathematical equation shown in Table 1.

$$MR = \frac{M_t}{M_0} \tag{1}$$

Experimental data of dried microgreens were compared with thin-layer models in the literature to determine the most appropriate model. For this purpose, R^2, Chi square (χ^2) and RMSE values of dried microgreens were determined. The R^2 value was determined by applying the SPSS 20.0 package program (Eq. 4), which is also used for statistical analysis of other analyses. χ^2 and RMSE values were calculated in the Excel program using Eq. 2 and Eq. 3 given below, respectively [12, 15].

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp} - MR_{pre})^2}{N - z} \tag{2}$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{pre} - Mr_{exp})^2 \right]^{\frac{1}{2}} \tag{3}$$

$$R^2 = \frac{MSS}{TSS} \tag{4}$$

Moisture determination of microgreens

Moisture content was determined via a gravimetric approach, by loss on drying, in which the microgreen samples were heated and the weight loss due to evaporation of moisture was recorded. For this purpose, the oven-drying method was used in the research. Before moisture determination, the drying containers used for the samples were dried at 105 °C for 1 h and then tared. Approximately 2–3 g of each sample was placed into the pre-dried containers and weighed. The drying process in the oven was continued until a constant weight was achieved. Once constant weight was reached, the samples were transferred to a desiccator to cool. The containers were then weighed, and the final weights were recorded. Moisture content was calculated, and the results were expressed as percentages (%) [17].

Determination of water activity of microgreens

Water activity values of the fresh and dried samples were determined using a Testo water activity device (AG Electronics, Germany, 1999). A total of 4 g of each raw material and powder sample was weighed, and after 30 min the water activity measurement reached equilibrium, at which point the results were recorded.

Protein determination of microgreens

Protein determination was performed according to the Kjeldahl method. For this analysis, 5 g of fresh samples and 2 g of dried samples were used. The analytical procedure consisted of digestion, distillation, and titration steps. The samples were digested with concentrated sulfuric acid in Kjeldahl tubes, distilled with sodium hydroxide, and subsequently titrated using phenolphthalein as an indicator. Protein contents of the fresh and dried microgreens were expressed as percentages (%) [18].

Determination of pH of microgreens

A total of 5 g of shredded wet samples and 1 g of dried samples were placed into a glass beaker. Distilled water was added, and the samples were homogenized. After standing at room temperature for 1 h, the pH values were measured and recorded using a pH meter calibrated with two buffer solutions (pH 4 and pH 7) [17].

Determination of color values of microgreens

The L^* (brightness, darkness), a^* (redness +, greenness -), b^* (yellowness +, blueness -), C^* (Chroma) and h° (hue angle) values of the samples were measured and recorded with the

Minolta CR 400 (Tokyo, Japan) device. L_0*, a_0* and b_0* represent the color values of fresh microgreens, while L*, a* and b* represent the color values of dried microgreens. In addition, the ΔE values of the samples were calculated using Eq. 5 given below. Color measurements were taken on at 5 random points on the stem and leaf sections of fresh and dried microgreens. The averages and standard deviations of the measurements were calculated. While recording the color values, the averages of readings taken from 5 random points were calculated.

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (5)$$

Determination of total phenolic compounds (TPC)

TPC analysis of microgreens was performed by modifying the method reported by Singleton and Rossi [19]. A total of 0.4 mL of the methanolic extract was transferred into a test tube. Subsequently, 2 mL of Folin–Ciocalteu reagent and 1.6 mL of 7% sodium carbonate solution were added. The mixture was left to stand in the dark at room temperature for 1 h. Absorbance was then measured using a spectrophotometer set at 760 nm. The results were expressed as mg GAE/kg DM.

Determination of antioxidant activity

For the analysis of DPPH antioxidant activity of fresh and dried microgreens, the method proposed by Pyo et al. [20] was used with modification. This method is based on the spectrophotometric measurement of the decrease in color caused by the decomposition of the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical, a stable purple compound. In this procedure, 3.6 mL of DPPH solution (0.025 g/L in methanol) was mixed with 0.4 mL of the methanolic extract in a test tube and kept in the dark at room temperature for 60 min. After incubation, the absorbance of the samples was measured at 515 nm to determine the inhibition rate of the DPPH radical. A Trolox standard curve was used for quantification, and the results were expressed as mmol TE/g DM.

Statistical evaluation

All analyses were conducted on fresh and dried samples in triplicate, and the results were expressed as mean ± standard deviation. Differences between groups were determined using analysis of variance (ANOVA) in the SPSS Statistics 20.0 software package (95% confidence interval). Duncan's multiple comparison test was employed to evaluate differences between the means ($P < 0.05$) [21].

Results and discussion

Mathematical modeling

The moisture ratio (MR) and time (min) graphs of green lentil microgreens dried in microwave and conventional dryers are given in Fig. 2. The moisture ratio-time graphs of mung bean microgreens dried in microwave and conventional dryers are given in Fig. 3. Also, R^2, χ^2, RMSE results of green lentil microgreens and mung bean microgreens are given in Tables 2 and 3, respectively. Among the thin-layer drying models, both green lentil microgreens and mung bean microgreens were found to be compatible with the Newton, Henderson and Pabis, Page, and Modified Page models.

The drying kinetics of lentil microgreens exhibited a clear falling-rate drying period across all drying conditions, confirming that internal moisture diffusion was the primary controlling mechanism rather than surface evaporation. During microwave drying, lentil microgreens showed a rapid reduction in MR at the early stage, particularly at 450 W, where the MR dropped sharply from 1.0 to 0.2 within the first 5 min and reached equilibrium (MR < 0.1) within 8–10 min. At 600 W, the drying process extended to 15–18 min, indicating that increased microwave power significantly accelerates internal moisture transport due to volumetric heating effects and pressure-driven flow. In contrast, hot air drying showed a slower and more gradual moisture reduction, with total drying times of 130–150 min at 70 °C, 170–180 min at 60 °C, and over 200 min at 50 °C. The statistical modeling results confirmed that the Henderson and Pabis model provided the best fit for the lentil microgreen. The highest R^2, lowest RMSE and χ^2 values were taken as the basis when determining the most suitable drying model. So, it is seen that the drying curves of green lentil microgreens' groups are in accordance with the literature. In a study where garlic powder was dried in a microwave oven, it was observed that a similar moisture content-time graph was obtained [12]. These findings are in agreement with Doymaz [22], who demonstrated similar drying kinetics for mint leaves, and Midilli et al. [23], who confirmed models in describing moisture diffusion in thin-layer products. The fast internal moisture removal under microwave conditions is linked to localized heating within the cell matrix, which enhances vapor pressure gradients and ruptures microcapillaries, allowing quick release of bound water [24].

Mung bean microgreens exhibited a similar drying trend to lentils but with generally faster moisture removal rates, reflecting their thinner cotyledon structure and lower tissue density. In microwave drying, the MR decreased rapidly at both 600 and 800 W, with drying completion occurring within 7–9 min at 800 W and 13–15 min at 600 W. The initial rapid MR decline (from 1.0 to 0.3 within 4 min at

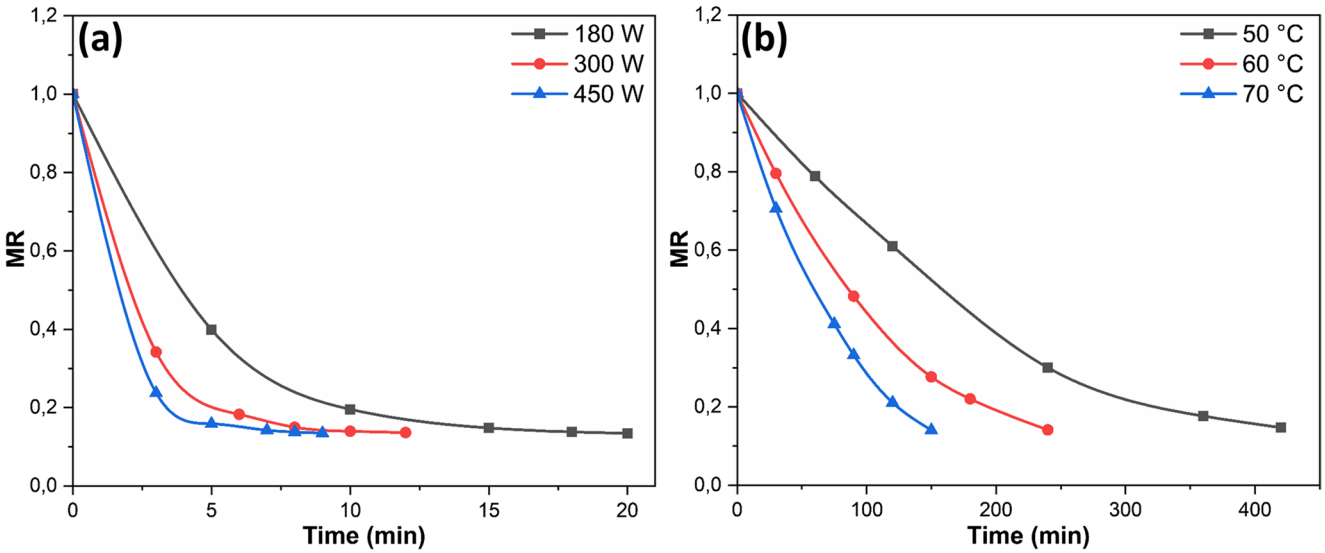


Fig. 2 MR-time graph of green lentil microgreens dried in (**a**) microwave dryer and (**b**) conventional dryer

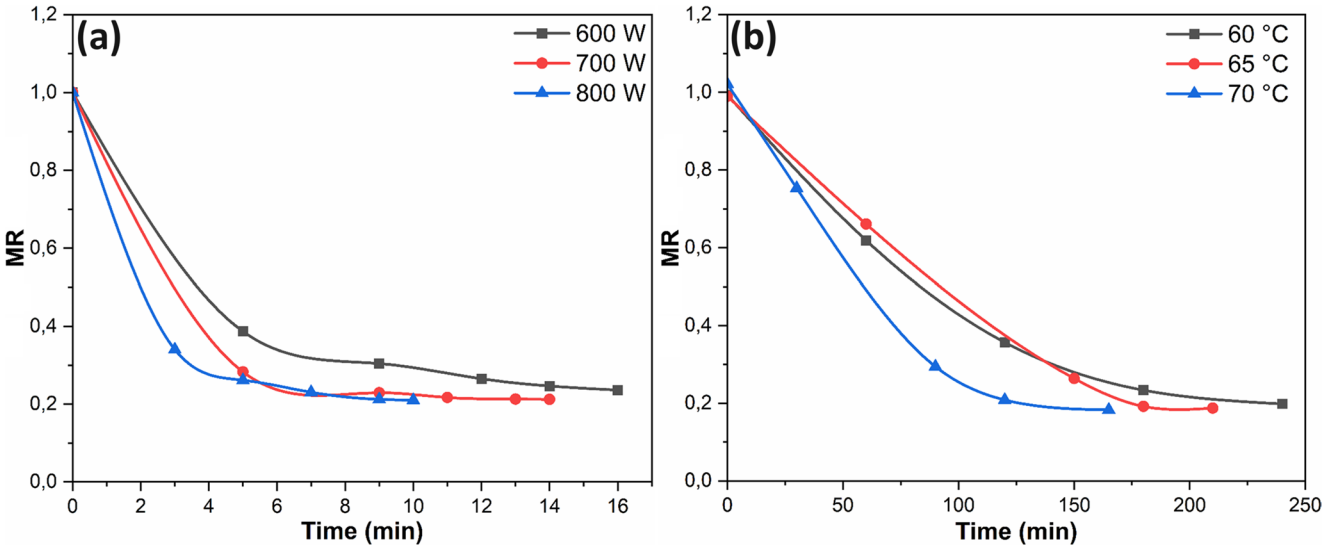


Fig. 3 MR-time graph of mung bean microgreens dried in (**a**) microwave dryer and (**b**) conventional dryer

800 W) reflects intense internal pressure generation, leading to structural expansion and enhanced moisture migration to the surface. Under hot air drying, the process was much slower, taking 110–130 min at 70 °C and exceeding 180 min at 50 °C. The Modified Page model provided the best fit to the mung bean data, with reduced χ^2, consistent with Thamkaew et al. [25], who stated similar model accuracy for kale and basil microgreens. Also, similar findings were reported by Soysal [26] for parsley leaves, where tissue permeability strongly influenced drying kinetics. The dominant mechanisms in mung bean drying involve combined internal vapor diffusion and capillary movement, with microwave energy promoting uniform heating and reducing the resistance of the cellular matrix to moisture flow. Although rapid drying improves process efficiency, extreme microwave powers may cause localized overheating, potentially damaging pigments or bioactive compounds; hence, moderate powers (600–700 W) may offer an optimal balance between efficiency and quality retention, as supported by Nisoa et al. [27] for similar high-moisture microgreen materials.

When directly comparing the drying kinetics of lentil and mung bean microgreens, mung bean microgreens consistently exhibited faster drying under identical conditions, completing microwave drying approximately 15–20% faster and hot air drying roughly 10% faster than lentil. This difference can be attributed to their anatomical and compositional variations. These findings align with the structure–diffusion relationships described by Doymaz [28] and Nisoa

Table 2 R^2, χ^2, RMSE results of dried green lentil microgreens

Model	Drying parameters	Constants and Coefficients		R^2	χ^2	RMSE
Newton	180 W	k = 0.232		0.804	0.0089	0.0913
	300 W	k = 0.243		0.825	0.0015	0.0780
	450 W	k = 0.256		0.858	0.0077	0.0418
	50 °C	k = 0.231		0.806	0.0062	0.0496
	60 °C	k = 0.243		0.825	0.0055	0.0479
	70 °C	k = 0.256		0.858	0.0049	0.0462
Henderson and Pabis	180 W	k = 1.951	a = 2.027	0.993	0.0044	0.0452
	300 W	k = 0.811	a = 2.184	0.985	0.0004	0.0407
	450 W	k = 1.080	a = 2.885	**0.997**	**0.0032**	**0.0400**
	50 °C	k = 0.363	a = 1.512	0.996	0.0053	0.0490
	60 °C	k = 0.385	a = 1.529	0.990	0.0041	0.0472
	70 °C	k = 0.393	a = 1.490	0.994	0.0045	0.0453
Page	180 W	k = 0.174	n = 1.951	0.869	0.0045	0.0866
	300 W	k = 0.160	n = 2.258	0.842	0.0046	0.0454
	450 W	k = 0.000	n = 2.519	0.861	0.1871	0.2884
	50 °C	k = 0.049	n = 2.195	0.982	0.0054	0.0497
	60 °C	k = 0.072	n = 1.971	0.972	0.0045	0.0488
	70 °C	k = 0.107	n = 1.705	0.963	0.0046	0.0468
Modified Page	180 W	k = 1.292	n = 0.297	0.812	0.0079	0.0990
	300 W	k = 0.184	n = 0.217	0.859	0.1871	0.2884
	450 W	k = 1.283	n = 0.339	0.804	0.0036	0.0482
	50 °C	k = 0.138	n = 1.164	0.806	0.0069	0.0598
	60 °C	k = 0.173	n = 1.410	0.825	0.0049	0.0480
	70 °C	k = 0.141	n = 1.821	0.858	0.0050	0.0570

Table 3 R^2, χ^2, RMSE results of dried mung bean microgreens

Model	Drying parameters	Constants and Coefficients		R^2	χ^2	RMSE
Newton	600 W	k = 0.309		0.818	0.0821	0.1911
	700 W	k = 0.363		0.803	0.1123	0.2234
	800 W	k = 0.342		0.812	0.0442	0.1402
	60 °C	k = 0.286		0.829	0.0285	0.0956
	65 °C	k = 0.306		0.827	0.0087	0.0624
	70 °C	k = 0.280		0.811	0.0074	0.0909
Henderson and Pabis	600 W	k = 0.453	a = 1.413	0.819	0.0138	0.0783
	700 W	k = 0.655	a = 1.775	0.828	0.0112	0.0706
	800 W	k = 0.560	a = 1.603	0.828	0.0104	0.0680
	60 °C	k = 0.469	a = 1.578	**0.993**	**0.0166**	**0.0541**
	65 °C	k = 0.525	a = 1.695	0.967	0.0124	0.0624
	70 °C	k = 0.497	a = 1.732	0.955	0.0369	0.0918
Page	600 W	k = 0.261	n = 1.153	0.817	0.0137	0.0780
	700 W	k = 0.000	n = 1.528	0.818	0.1552	0.2626
	800 W	k = 0.272	n = 1.225	0.838	0.0099	0.0665
	60 °C	k = 0.127	n = 1.753	0.945	0.0098	0.0660
	65 °C	k = 0.112	n = 1.976	0.928	0.0089	0.0624
	70 °C	k = 0.750	n = 2.228	0.928	0.0083	0.0509
Modified Page	600 W	k = 1.958	n = 0.158	0.988	0.0130	0.0763
	700 W	k = 1.376	n = 0.264	0.993	0.0105	0.0686
	800 W	k = 1.346	n = 0.254	0.932	0.0078	0.0591
	60 °C	k = 0.168	n = 1.707	0.994	0.0020	0.0178
	65 °C	k = 0.261	n = 1.172	0.987	0.0018	0.0624
	70 °C	k = 0.191	n = 1.468	0.981	0.0026	0.0345

et al. [27]. Under hot air drying, the difference between species was less pronounced because external heat transfer dominated the overall drying process. Mechanistically, lentil microgreens likely retained more bound water within cellular matrices, requiring longer drying durations to overcome the diffusive barrier, while mung bean microgreens allowed easier moisture escape due to their more open morphology.

Color results

L^*, a^*, b^*, C^*, h° and ΔE results of fresh and dried microgreens are given in Table 4. It was determined that dried green lentil and mung bean samples had higher L^* and a^* values, while lower b^* and C^* values compared to fresh green lentils and mung beans. It was determined that as the drying temperature increased, the L^* and b^* values of the samples decreased, while the a^* value increased. It was observed that as the drying temperature or microwave power increased, the h° angle and ΔE values of the samples decreased. It was thought that the increasing a^* and decreasing L^* values as the microwave power and drying temperature increased could be due to the Maillard reaction. Similarly, in a study in which lemon slices were dried, it was recorded that the L^* value decreased and the a^* value increased with increasing drying temperatures [29].

Fresh green lentil microgreens exhibited an L^* value of 44.69, an a^* of −11.43, and a b^* of 26.00, reflecting their natural bright green color due to high chlorophyll content. Upon microwave drying, the L^* values increased, while a^* became less negative, and b^* decreased. Similarly, chroma (C^*) and hue (h°) values decreased, with total color difference (ΔE), showing a moderate but perceptible change compared with the fresh state. The same pattern was observed in air-dried lentil microgreens, though the changes were slightly more pronounced, with L^* values and a^* values increasing and b^* values decreasing. The corresponding C^* and h° values and ΔE values indicate greater pigment degradation and hue loss at higher air-drying temperatures. For mung bean microgreens, fresh samples (L^* = 46.25, a^* = −4.50, b^* = 20.65) also exhibited typical green coloration, which faded upon drying. Microwave-dried samples showed elevated lightness (L^*) and slightly positive a^* values, suggesting chlorophyll breakdown and partial formation of brownish degradation products. The decreases in b^* and C^*, together with reduced h°, confirmed a shift toward duller and less saturated colors, while ΔE values denoted moderate overall deviation from the fresh color. Conversely, air-dried mung bean microgreens showed lower L^* and more substantial reductions in b^* and C^*, with ΔE values of 11.57–13.64, indicating stronger darkening and discoloration under prolonged heat exposure.

These differences between drying techniques can be attributed to the distinct heat and mass transfer mechanisms involved. Microwave drying generates volumetric heating by directly exciting polar water molecules within the plant tissue, resulting in enzymatic oxidation and pigment degradation, allowing better retention of natural green hues [30]. In contrast, conventional hot-air drying relies on external convective heat transfer, where surface moisture must first evaporate before internal moisture diffuses outward. This slower process often leads to higher surface temperatures, longer drying times, and enhanced degradation of chlorophyll to pheophytin, which causes browning and reduced color intensity [31]. Furthermore, previous studies have shown that microwave drying better preserves visual attributes due to the limited oxidation of polyphenols and chlorophylls and less Maillard browning compared with hot air drying. For instance, Vega-Gálvez et al. [32] reported that apples and leafy vegetables subjected to microwave drying exhibited higher L^* and lower ΔE values than those dried by hot air, confirming better color preservation. Microwave

Table 4 Color analysis results of fresh and dried microgreens

Sample	L^*	a^*	b^*	C^*	h°	ΔE
Green lentil micro greens	44.69±3.68	−11.43±0.80	26.00±0.69	35.53±3.23	116.63±0.77	-
180 W	53.80±1.49^a	−11.36±1.23^a	20.68±2.84^a	23.59±3.23^a	118.77±0.86^a	10.54±0.05^a
300 W	52.84±1.08^a	−10.66±0.19^a	19.20±0.80^a	21.03±3.10^a	118.79±0.60^a	10.64±0.78^a
450 W	51.13±1.43^a	−9.06±1.43^a	17.29±2.54^a	18.36±0.79^a	120.05±0.32^a	11.08±0.95^a
50 °C	49.21±1.40^a	−5.96±0.10^a	18.34±1.57^a	18.29±1.52^a	108.84±1.36^b	10.44±0.13^a
60 °C	50.18±2.65^a	−3.87±0.12^b	17.64±0.45^a	17.97±0.51^a	104.23±4.33^{ab}	12.54±0.47^b
70 °C	51.64±1.50^a	−3.11±0.11^{ab}	17.13±0.34^a	17.67±0.36^a	103.77±3.57^a	14.00±0.63^c
Mung bean microgreens	46.25±2.19	−4.50±0.68	23.05±0.62	23.49±0.67	101.27±1.09	-
600 W	54.39±2.17^a	−1.95±0.14^a	18.13±0.85^b	18.2±0.87^b	96.35±0.94^b	9.85±0.39^a
700 W	52.48±0.82^a	0.47±0.09^{ab}	15.26±0.83^a	15.27±0.83^a	90.23±1.89^{ab}	11.14±0.74^a
800 W	52.97±1.27^a	0.48±0.07^b	14.92±1.23^a	14.12±1.06^a	87.95±3.29^a	11.66±0.85^a
60 °C	49.06±0.44^a	−1.78±0.13^a	13.86±0.67^b	14.00±0.77^b	97.60±3.26^b	9.98±0.07^a
65 °C	48.07±1.56^a	0.22±0.02^b	12.65±0.92^{ab}	12.66±0.91^b	89.07±0.37^{ab}	11.57±0.01^b
70 °C	46.98±1.47^a	1.52±0.00^b	10.83±1.35^a	10.1±0.85^a	80.95±6.63^a	13.64±1.10^c

*Superscript letters indicate differences between groups according to Duncan's multiple comparison test ($P<0.05$)

drying maintained higher brightness (L^*), lower ΔE, and better hue retention than hot-air drying, confirming that shorter drying times and uniform internal heating reduce pigment degradation. These findings align with prior literature [33].

The difference between the color values of green lentil microgreens dried in the microwave oven was not found to be statistically significant ($P > 0.05$). The difference between a^* and ΔE values of green lentil microgreens dried in the conventional dryer was found to be statistically significant ($P < 0.05$), while the difference between the groups for other color values was found to be insignificant ($P > 0.05$). The difference between the a^*, b^*, C^*, and hue angle values of mung bean microgreens dried in the microwave oven was found to be statistically significant ($P < 0.05$). The difference between a^*, b^*, C^*, hue angle, and ΔE values of mung bean microgreens dried in the conventional oven was found to be statistically significant ($P < 0.05$). When the color characteristics of green lentil and mung bean microgreens are examined in general, it can be said that the L*(brightness) value decreases with increasing microwave power and conventional temperature, and the characteristic green color of the microgreens decreases a*(-). Additionally, it was determined that the microwave oven preserved the brightness (L*) and characteristic green color (a*) of microgreens better during drying than the conventional oven.

Protein determination results

The protein, TPC, and antioxidant activity analysis results of fresh and dried microgreens are given in Table 5. The protein content of both fresh green lentil and fresh mung bean microgreens was found to be higher than dried microgreens. It is observed that there is a slight decrease in the protein content of microgreens dried in both microwave and conventional dryers due to the effect of drying temperature. It is thought that protein structures are damaged and deteriorated with temperature, and therefore, there may be a slight decrease in protein values. This slight decrease can be explained by denaturation of storage proteins, which causes changes in solubility and potential interaction with polyphenols and carbohydrates during heating [34]. Depending on the drying temperature, the Maillard reaction may have occurred in the microgreens. The Maillard reaction is a non-enzymatic reaction that occurs between the amino groups of proteins and reducing sugars. Maillard reactions between amino groups of proteins and reducing sugars can also contribute to protein loss, particularly at temperatures exceeding 60 °C [35]. Additionally, microwave treatments may induce localized heating ("hot spots"), leading to greater unfolding and aggregation of proteins compared to conventional hot-air drying [36]. Despite these mechanisms of degradation, the overall protein fraction is retained to a considerable extent, highlighting that both lentil and mung bean microgreens are resilient sources of protein even after processing [37]. The difference between the protein amounts of green lentil microgreens dried in both conventional and microwave ovens was found to be statistically significant ($P < 0.05$). While the difference between the protein amounts of mung bean microgreens dried in the microwave oven was not found to be statistically significant ($p > 0.05$), the difference between the protein amounts of conventionally dried microgreens was found to be statistically significant ($P < 0.05$).

Table 5 Results of protein, TPC, and antioxidant activity of fresh and dried microgreens

Sample	Protein (g/100 g)	TPC (mg GAE/100 g)	DPPH (mg TE/100 g)
Green lentil microgreens	2.96 ± 0.02	31.07 ± 1.47	211.08 ± 2.56
180 W	2.28 ± 0.04^{a}	61.28 ± 0.65^{b}	228.13 ± 1.93^{c}
300 W	2.38 ± 0.04^{b}	60.27 ± 1.22^{b}	227.30 ± 2.02^{b}
450 W	2.21 ± 0.04^{a}	51.69 ± 2.01^{a}	218.34 ± 0.24^{a}
50 °C	2.49 ± 0.02^{b}	58.92 ± 0.28^{a}	222.93 ± 0.27^{a}
60 °C	2.30 ± 0.03^{a}	58.82 ± 0.53^{b}	222.91 ± 2.19^{b}
70 °C	2.47 ± 0.03^{b}	57.42 ± 0.99^{c}	220.26 ± 0.73^{a}
Mung bean microgreens	2.87 ± 0.04	35.92 ± 1.21	224.60 ± 3.07
600 W	2.36 ± 0.07^{a}	61.03 ± 0.28^{a}	253.22 ± 3.76^{b}
700 W	2.25 ± 0.05^{a}	58.41 ± 0.58^{b}	250.15 ± 1.66^{b}
800 W	2.23 ± 0.04^{a}	55.68 ± 0.45^{c}	231.03 ± 4.16^{a}
60 °C	2.30 ± 0.03^{ab}	53.295 ± 1.49^{a}	263.45 ± 1.98^{b}
65 °C	2.34 ± 0.04^{b}	50.05 ± 1.00^{b}	261.45 ± 2.43^{b}
70 °C	2.41 ± 0.04^{a}	46.905 ± 0.63^{c}	250.00 ± 1.09^{a}

*Superscript letters indicate differences between groups according to Duncan's multiple comparison test ($P < 0.05$)

TPC results

It was determined that the TPC amount of fresh green lentil microgreens was lower than the dried samples. The drying process released phenolic compounds from the microgreens. There are studies in the literature showing that drying temperatures increase the total phenolic content, as in this study. In a study where leeks were dried in a microwave oven, it was determined that dried leek samples contained higher TPC than fresh leek slices [38]. Furthermore, the reduction in TPC observed with higher temperatures can be attributed to thermal degradation of labile phenolic acids and flavonoids, which are prone to oxidation and polymerization under heat [39]. However, an interestingly moderate heating, particularly under microwave conditions, can disrupt cell wall polysaccharides and protein–polyphenol complexes, thereby releasing bound phenolics and temporarily increasing extractable TPC [40]. This may explain why, in some treatments, microwave-dried samples retained higher

phenolic content compared to conventionally dried samples. The higher TPC in lentil compared with mung bean microgreens may reflect species-specific differences in biosynthetic pathways for phenylpropanoids and flavonoids, which are known to accumulate more strongly in lentil seedlings [41]. Thus, while drying exerts stress on phenolic stability, the balance between degradation and release of bound compounds determines the final extractable content. The difference between the TPC values of green lentil microgreens dried in both a microwave oven and a conventional dryer was found to be statistically significant ($P < 0.05$). The difference between the TPC values of mung bean microgreens dried in both a microwave oven and a conventional dryer was found to be statistically significant ($P < 0.05$).

Antioxidant activity results

It was determined that the antioxidant activity of fresh green lentil microgreens with DPPH was lower than that of dried samples (Table 5). In drying studies, it is expected that the antioxidant activity results of TPC and DPPH will be compatible and parallel to each other. In this study, it was observed that the TPC and antioxidant activity results were parallel; that is, the antioxidant activity increased with increasing TPC activity. Similar research findings can be found in the literature. In a study in which lemon slices were dried in both microwave and conventional dryers, it was determined that the DPPH antioxidant activity of fresh lemon slices was lower than that of dry samples [42]. The mechanism underlying the reduction in DPPH activity at higher temperatures is likely the thermal decomposition of flavonoids, anthocyanins, and phenolic acids, which reduces their hydrogen-donating ability [43]. However, another mechanism to consider is the generation of Maillard reaction products (MRPs) during thermal treatment, which themselves possess radical scavenging properties. Indeed, MRPs such as melanoidins formed during heating can enhance antioxidant activity in certain legume sprouts. Therefore, the relatively high DPPH values in some dried samples could be a combined effect of residual phenolics and newly formed antioxidant compounds. The observation that lentil consistently exhibits higher antioxidant capacity than mung bean is consistent with its richer pool of flavonoids and tannins, which are more resistant to degradation compared to the phenolic profile of mung bean microgreens [44]. The difference between the DPPH values of green lentil microgreens dried in microwave and conventional dryers was found to be statistically significant ($P < 0.05$). The difference between the DPPH values of mung bean microgreens dried in microwave and conventional dryers was found to be statistically significant ($P < 0.05$).

Moisture analysis results

Moisture, water activity, and pH results of fresh and dried microgreens are given in Table 6. It was observed that as the microwave power and drying temperature applied to the samples dried in both microwave and conventional dryers increased, the total drying time shortened and the moisture content decreased. In a study conducted on jujube fruit, fruits were dried at 3 different watt powers. As in this study, it was determined that the drying time of the fruits shortened with increasing drying temperature [45]. The ability to achieve low moisture is critical for microbial stability and enzymatic inactivation, as moisture above 15% generally supports microbial growth. The higher residual moisture in mung beans compared with lentil may be due to structural and compositional differences. Mung bean microgreens have larger cotyledonary tissues with higher mucilage and hemicellulose content. This bound water is more difficult to remove by hot-air drying and results in higher residual moisture. From a mechanistic standpoint, microwave drying generally accelerates moisture removal by volumetric heating and pressure buildup inside cells, but its efficiency is limited if the tissues have thick cuticles or high starch–protein matrices, as is the case in mung bean. These differences in drying behavior have been documented across microgreen species, indicating that compositional variability strongly affects final moisture levels [46]. The difference between the moisture values of green lentil microgreens dried in both a microwave oven and a conventional dryer was not found to be statistically significant ($P > 0.05$). The

Table 6 Moisture, water activity, and pH results of dried and fresh microgreens

Sample	Moisture (%)	Water activity (aw)	pH
Green lentil microgreens	89.16 ± 0.60	0.96 ± 00	5.85 ± 0.07
180 W	11.97 ± 1.22^{a}	0.30 ± 00^{c}	6.30 ± 0.11^{a}
300 W	12.15 ± 0.25^{a}	0.28 ± 00^{b}	6.26 ± 0.15^{a}
450 W	12.01 ± 0.56^{a}	0.26 ± 00^{a}	6.20 ± 0.06^{a}
50 °C	13.11 ± 0.46^{a}	0.33 ± 00^{b}	6.08 ± 0.00^{b}
60 °C	12.58 ± 0.75^{a}	0.32 ± 00^{b}	6.03 ± 0.02^{c}
70 °C	12.52 ± 0.13^{a}	0.25 ± 00^{a}	5.97 ± 0.08^{a}
Mung bean microgreens	79.92 ± 1.16	0.97 ± 0.00	5.74 ± 0.01
600 W	18.86 ± 1.21^{a}	0.25 ± 0.00^{a}	6.03 ± 0.14^{b}
700 W	16.94 ± 0.40^{a}	0.22 ± 0.00^{b}	5.89 ± 0.11^{a}
800 W	16.79 ± 2.18^{a}	0.22 ± 0.00^{c}	5.79 ± 0.00^{a}
60 °C	15.83 ± 1.58^{a}	0.31 ± 0.00^{a}	6.23 ± 0.04^{a}
65 °C	14.97 ± 0.48^{a}	0.30 ± 0.00^{b}	6.03 ± 0.06^{b}
70 °C	14.61 ± 0.65^{a}	0.278 ± 0.00^{c}	5.91 ± 0.01^{c}

*Superscript letters indicate differences between groups according to Duncan's multiple comparison test ($P < 0.05$)

difference between the moisture values of mung bean microgreens dried in both a microwave oven and a conventional dryer was not found to be statistically significant ($P > 0.05$).

Water activity results

Water activity is a fixed value that varies between 0 and 1, and when the water activity approaches 1, it means that the sample contains a high amount of water, and when it approaches 0, it means that the sample contains a very low amount of water (Table 6). Water activity results are parallel to moisture content results. In other words, a sample with a high moisture content is expected to have a high-water activity. In the study, water activities of fresh samples were found to be significantly higher than dried microgreens. It was also observed that water activity decreased with increasing drying temperatures and microwave powers. The lower water activity in lentil samples compared to mung beans reflects their lower moisture content and greater efficiency in water removal. Water activity reduction is not solely dependent on moisture percentage but also on the nature of water binding within tissues. Lentil tissues contain higher levels of soluble proteins and salts that can bind water and reduce free water fraction, whereas mung bean tissues may retain freer or loosely bound water [47]. This explains why mung bean microgreens displayed slightly higher water activity despite similar drying conditions. The difference between the water activity values of green lentil microgreens dried in both a microwave oven and a conventional dryer was found to be statistically significant ($P < 0.05$). The difference between the water activity values of mung bean microgreens dried in both a microwave oven and a conventional dryer was found to be statistically significant ($P < 0.05$).

pH analysis results

It was noted that the pH values of dried microgreens were higher than those of fresh microgreens (Table 6). There are drying studies in the literature in which similar results were obtained. The reason for the higher pH value of dried microgreens compared to fresh microgreens is thought to be the loss of acids in the samples due to the effect of temperature and the resulting increase in pH. In a study where jujube fruit was dried in a conventional dryer at different temperatures (50, 60, and 70 °C), it was determined that the pH value of fresh jujube was 2.50, while the pH values of dried jujubes varied between 2.88 and 3.07. In addition, it was observed that pH values increased with increasing drying temperature [48]. The maintenance of pH in this range suggests that organic acid degradation during drying was minimal. pH is influenced by the stability of organic acids such as citric, malic, and succinic acids, which can volatilize or degrade at higher temperatures. The slightly higher pH values in mung bean microgreens compared to lentil microgreens may be explained by higher accumulation of amino acids such as arginine and lysine during sprouting, which neutralize acidic metabolites [41]. Maintaining pH below neutral is advantageous as it supports the oxidative stability of phenolics and suppresses microbial growth. Therefore, the observed pH values reflect both species-specific metabolic traits and the protective effects of drying in preventing acid loss. While the difference between the pH values of green lentil microgreens dried in the microwave oven was not found to be statistically significant ($P > 0.05$), the difference between the pH values of microgreens dried in the conventional oven was found to be statistically significant ($P < 0.05$). The difference between the pH values of green lentil microgreens dried in the microwave oven was found to be statistically significant ($P < 0.05$). The difference between the pH values of microgreens dried in the conventional oven was found to be statistically significant ($P < 0.05$).

Conclusions

1. This study comprehensively evaluated the effects of conventional and microwave drying methods on the physicochemical, nutritional, and color properties of lentil and mung bean microgreens. The study aimed to enable consumers can easily grow and consume microgreens in their daily lives. It is thought that it will make a positive contribution to the health of individuals, especially owing to its high phenolic and antioxidant activities.
2. In the study, the moisture content and water activity values of green lentil microgreens were reduced below 14% and 0.35, respectively, by the drying process. By drying mung bean microgreens, the moisture content and water activity values were reduced below 19% and 0.32, respectively.
3. The best model to predict the drying kinetics for green lentil microgreens dried in both drying ovens was found to be Henderson and Pabis (450 W, $R^2 = 0.997$, $\chi^2 = 0.0032$, RMSE = 0.0490). The best model to predict the drying kinetics for mung bean microgreens dried in both drying ovens was found to be Henderson and Pabis (60 °C, $R^2 = 0.993$, $\chi^2 = 0.0166$, RMSE = 0.0541).
4. The results demonstrated that the drying method significantly influenced the retention of bioactive compounds (phenolics and antioxidants), moisture reduction efficiency, and overall product quality. Also, the study provides valuable insights into selecting appropriate

post-harvest drying techniques to enhance the shelf life, nutritional profile, and market potential of lentil and mung bean microgreens in functional food applications.

5. The drying modeling data, color values, pH, and water activity data obtained in the study are consistent with the drying studies. Furthermore, the higher TPC and antioxidant activity in dried microgreens compared to fresh ones is evidence that the study has produced a food suitable for daily nutrition.
6. Research results show that both fresh and dried microgreens can be easily consumed throughout the day. Especially, newly harvested fresh green lentils and mung beans can be used in snack products such as sandwiches and salads, while their dried forms can be consumed in soups and sauces as a kind of spice. Also, it is thought that individuals with gluten sensitivity or consumers with vegan diets can easily add green lentils and mung bean microgreens to their diet.

In this study, microgreens were grown with soil. Soilless farming practices have become a popular research topic in recent years. One of the planned future studies is the cultivation of soilless vegetable or grain microgreens and their quality parameters.

Acknowledgements The author would like to thank Hakkari University, Scientific Research Projects Coordination Office (Project no: FM23BAP2) for the financial support of this study.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data Availability Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). The data is available upon a reasonable request from the corresponding author.

Declarations

Conflict of interest The author has no relevant financial or non-financial interests to disclose.

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