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Evaluation of Physicochemical, Functional, and Phytochemical Composition of Fluidized Bed Dried Radish (*Raphanus sativus*) Microgreens by High-performance Liquid Chromatography and Inductively Coupled Plasma Mass Spectrometry

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Abstract

Microgreens are young, nutrient-dense greens harvested at an early growth stage, typically when the first true leaves emerge. This study investigated the effects of fluidized bed drying at three different temperatures (40 °C, 45 °C, and 50 °C) on the physicochemical, phytochemical, and functional properties of radish microgreens. The microgreens were harvested 7 - 8 days after germination, reaching a height of 6 - 7 cm. Results indicated that drying temperature had no significant impact on physicochemical or functional properties, but influenced phytochemical retention due to thermal degradation and oxidation of phenolic compounds. Radish microgreens were found to be a rich source of essential minerals, providing substantial percentages of the recommended dietary allowance (RDA) for phosphorus (96%), iron (45%), zinc (36.8%), selenium (17%), and magnesium (13%), along with trace amounts of calcium, potassium, and sodium. They also contained notable levels of ascorbic acid (0.140 mg/100 g), total phenolics (1604 ± 2.26 GAE mg/g), flavonoids (20 ± 0.11 QE mg/g), and exhibited high DPPH antioxidant activity (88.68%). Key bioactive compounds identified included benzoic acid, p-coumaric acid, ellagic acid, caffeic acid, chlorogenic acid, ferulic acid, gallic acid, and β-carotene. The findings suggest that fluidized bed drying at 45 °C is an effective preservation method for radish microgreens, ensuring retention of their high mineral, vitamin, and phytochemical content. This method enhances their potential as a functional food ingredient, supporting their health-promoting dietary applications.

Keywords

Functional food, Fluidized bed drying, Microgreens, Nutrition, Phytochemicals, Recommended dietary allowance

Introduction

With growing interest in functional and nutraceutical foods, microgreens are gaining popularity for their rich nutritional and bioactive content. These nutrient-rich, eco-friendly greens fit into diverse diets and can thrive in various cropping systems. They can be cultivated on a large scale in greenhouses using soilless or hydroponic systems, as well as in smaller home setups for personal use [1, 2]. Additionally, their fast and efficient growth and high nutritional density offer a practical solution to malnutrition caused by today's fast-paced lifestyles [3].

Microgreens are delicate, young greens of vegetables, herbs, or grains, typically 5 - 10 cm tall, harvested once their first true leaves emerge. With a short growth cycle of 7 - 21 days, according to species, they require minimal intervention, such as no fertilization or weed control, making them a natural and organic food option [4]. Microgreens are highly nutritious, boasting significantly higher levels of vitamins, minerals, antioxidants, and phenolic compounds compared to seeds and mature parts [5]. Their abundant bioactive compounds, including vitamins

C, E, and K, beta-carotene, lutein, phenolics, flavonoids, and glucosinolates, elevate their status as functional foods, making them a beautiful dietary choice. Research has highlighted their numerous health benefits, including antioxidant, anti-inflammatory, anti-diabetic, anti-cancer, and anti-obesity properties [6].

There is various vegetable species used in the production of microgreens, such as Asteraceae, Apiaceae, Amarillydaceae, Amaranthaceae, Brassicaceae, Curcubitaceae, and Fabaceae, with different nutritional profiles and health benefits. The microgreens of the Brassicaceae family, such as broccoli, cauliflower, radish, and cabbage, are well-recognized for their significant levels of phytochemicals, vitamins, and minerals [7]. Radish microgreens are an important class of microgreens in the Brassicaceae family. They are highly regarded for their rich content of cancer-fighting glucosinolates, along with carotenoids, phytochemicals, vitamins, and essential minerals [8]. However, similar to green leafy vegetables, microgreens have a very short shelf life due to their highly perishable nature. Therefore, it is essential to preserve microgreens to extend their usability and maximize their potential benefits [9].

Drying is one of the traditional methods of food preservation. It reduces water activity, which inhibits the growth of microorganisms and prolongs shelf life. However, it also significantly impacts the physical, biological, and chemical properties, such as color, enzyme activity, and degradation of sensitive nutrients like vitamins, antioxidants, and bioactive compounds [10, 11]. While drying at higher temperatures shortens drying time, it can lead to lower product quality and increased energy consumption. Conversely, gentle drying at lower temperatures can yield higher-quality products but slows down the drying process and extends the drying period [11, 12].

Fluidized bed drying is a convective hot air-drying technique that provides several key advantages over conventional drying methods. This approach enhances heat and mass transfer efficiently due to the increased surface area exposure of the material being dried. The fluidization process ensures uniform moisture reduction and consistent bed temperature throughout drying, leading to a more controlled and constant drying rate. Additionally, this method significantly reduces overall drying time while maintaining product quality, making it an efficient and effective dehydration technique [13].

However, drying temperature has a significant effect on the nutritional quality of microgreens. This study analyses the effect of three different drying temperatures, 40 °C, 45 °C, and 50 °C, on the physicochemical, functional, and phytochemical composition of radish microgreens dried using a fluidized bed dryer and marks their importance as a valuable addition to the diet.

Materials and Methods

The Radish (*Pusa mridula*) microgreens were procured from the Indian Agriculture Research Institute and were grown using soil and cocopeat in a 4:1 ratio as substrate in 39 × 17 cm trays. For the first 2 - 3 days, the trays were kept in dark conditions for seed germination, and then they were exposed to sunlight and harvested after 7 - 8 days until the true leaves appeared, as shown in figure 1, using sterilized scissors. The height of the microgreens was approximately 10 - 12 cm. The microgreens' initial and final moisture content was determined by drying triplicate samples in an oven at 105 °C for 2 hr until the weight became stable.

Figure 1: Radish microgreens harvested on the 7th day.

Sample preparation

The sample was harvested 7 - 8 days when the first true leaves appeared. The sample is cut just above the soil surface using sterilized scissors. After harvesting, the microgreens were thoroughly washed under running water, and excess water was removed using blotting paper. Further, the sample was dried using a fluidized bed dryer (Retsch TG200) at three different temperatures (40, 45, and 50 °C) with an airflow of 20 m^3/h. The dried microgreens were collected and ground in a laboratory-scale mixer and sieved through a 60 BSS sieve for uniform-sized particles. The sieved and dried powder was packed in an air-sealed pouch and stored in a refrigerator for further analysis.

Fresh yield and dry matter

The cultivation yield of each species was determined by weighing fresh weight (FW) in three replications after harvest using an analytical lab scale (Denver APX200). Further microgreens were dried in a fluidized bed dryer at three different drying temperatures (40, 45, and 50 °C) to a constant dry weight (DW), which was measured using an analytical weighing balance.

Physicochemical characterization

Moisture content

The 5 g of the sample was weighed using a lab scale weighing balance in a Petri plate. The Petri plate was kept in a hot air oven at 105 °C for 2 - 3 h until the constant weight was achieved. Then, the sample was kept in a desiccator. After the sample had cooled off, the final weight of the sample was taken, and the moisture content was determined by the difference between the initial and final moisture content, and calculated using formula [14]

$$Moisture\ content\ (\%) = \frac{W_i - W_f}{W_i} \quad (1)$$

Where, W_i and W_f are the initial and final weights of the sample (g), respectively.

Ash content

The ash content was also determined using the association of official analytical chemists' method [15]. The 5 g of the sample was weighed in a crucible. The sample was charred using a burner until the smoke stopped. Further, the sample was kept in a pre-heated muffle furnace at 550 °C for 6 h until the organic matter was completely burned. Then, the weight of the sample was noted and calculated using the formula

$$Ash\ content\ (\%) = \frac{W_f - W_i}{W_i} \times 100 \quad (2)$$

Where, W_f is the final weight of the sample after burning in the muffle furnace (g) and W_i is the initial weight of the sample (g).

The detailed mineral profiling for macro and micro minerals of radish microgreens was determined using Inductively coupled plasma mass spectrometry (ICPMS) and atomic absorption spectrophotometer methods, using techniques followed by Arbro Labs, Delhi.

Protein content

The protein content was measured by the macro-Kjeldahl method [16]. In its estimation, nitrogen content was determined using a Gel Tech instrument that was operated in three stages: digestion, distillation, and titration. 0.2 ± 0.01 g of sample was taken and mixed with a 5 g catalytic mixture containing copper sulphate and sodium sulphate and 25 ml of concentrated sulphuric acid. The solution was digested at 420 °C until the color of the solution changed to light green. The sample was then removed and allowed to cool. After the sample was cooled, 60 - 65 mL of distilled water was added. Then, the distillation step was continued by pouring 25 ml of 4% boric acid into a conical flask. The conical flask was connected to a condenser by ensuring that the condenser tip was immersed in a boric acid solution. The digestion tube was then connected to the distillation apparatus. 60 ml of 40% NaOH was then dispensed in the digested sample and heated for 4 - 5 min until all the ammonia was converted to boric acid. The distillate was collected in the conical flask and moved to the titration step. 1 ml of indicator was added, and the sample was titrated with 0.1 N sulphuric acid until the color changed from green to pink. The titer value was noted, and protein content can be determined using the equation below

$$Nitrogen\ (\%) = \frac{(Sample\ titre\ value\ (ml) - Blank\ titre\ value\ (ml)) \times HCl\ normality\ (N) \times 14 \times 100}{Weight\ of\ the\ sample(g) \times 1000} \quad (3)$$

$$Protein\ (\%) = Nitrogen\ (\%) \times 6.25 \quad (4)$$

Crude fat content

The crude fat content was determined using the Soxhlet apparatus by the AOAC method [15]. The dried sample after moisture removal was transferred into the thimble, and the top of the thimble was capped with a cotton plug. 100 ml of petroleum ether was poured into a round-bottom flask. Further, the thimble was dropped into the siphon tube connecting the condenser and the round bottom flask, heated using a heating mantle. Further, the power supply to the heating mantle was on, and the temperature was kept up to the boiling point of petroleum ether. The process continued for 6 h until the whole fat was removed. After 6 h, the thimble was removed, and the solvent was recovered. The final weight of the round-bottom flask was noted.

$$Crude\ fat\ (\%) = \frac{W_f - W_i}{W_s} \quad (5)$$

Where, W_s is the weight of the sample (g) and W_i and W_f are the initial and final weights of the round bottom flask (g), respectively.

Crude fiber content

The crude fiber content was determined using the AOAC method [15]. The 2 g of defatted sample and 0.5 g of asbestos were weighed and added to the digestion flask. First, the sample was acid digested using sulphuric acid. The flask was connected with a condenser and heated for 30 min. After 30 min, the flask was removed and filtered through a muslin cloth and washed using boiling water until no acid residue was left. The washed residue was again transferred to the flask and digested using sodium hydroxide for 30 min. The filtrate was filtered in the crucible with boiling water and 20 ml of potassium chloride. The crucible was dried at 110 °C until a constant weight was achieved. The sample was cooled in a desiccator and weighed. The sample was further ignited in a muffle furnace for 20 min. The sample was cooled in a desiccator, and weight loss was determined.

$$Crude\ fiber\ (\%) = \frac{Weight\ loss(g)}{Initial\ weight\ of\ sample\ (g)} \times 100 \quad (6)$$

Carbohydrate content

The carbohydrate content was determined using different methods. It was calculated by the formula given by Onwuka [17]

$$\%\ carbohydrate = 100 - (\%Moisture\ content + \%\ fat + \%ash + \%protein + \%\ crude\ fiber) \quad (7)$$

Functional characterization

Bulk density (BD) and tapped density (TD)

The 2 g of radish microgreens powder was added to a 10 ml measuring cylinder. The volume occupied was noted, and BD was measured using the mass and volume occupied. A known volume cylinder was filled with a known volume, and the cylinder was tapped manually until there was no more change in volume. The ratio of sample mass to volume was used to determine the TD [18]. Three replications were recorded, and the average was recorded.

$$BD = \frac{W_i}{V} \quad (8)$$

$$TD = \frac{W_i}{V_t} \quad (9)$$

Where, W_i is the weight of the sample (g), V is the untapped volume of the sample (mL), and V_t the volume occupied after tapping (mL).

Flowability and cohesiveness

The flowability and cohesiveness of dried powders were determined using Hausner's ratio (HR) and Carr's index (CI). HR was calculated as per the following formula [19].

$$HR = \frac{TD}{BD} \quad (10)$$

CI measures the compressibility of powders. CI was calculated as per the method [20].

$$CI = 100 \times \frac{TD - BD}{BD} \quad (11)$$

Water absorption capacity and water solubility

The 0.1 g (M_i) of powdered sample was mixed with 10 mL of distilled water and centrifuged at 4000 rpm for 10 - 12 min. Further, the supernatant was dried in a hot air oven at 105 °C until it attained a constant weight [21]. The mass of the sample after drying (M_s) was used to determine the solubility of the sample, and the wet sediment (M_w) remaining in the tube was used to determine water absorption.

$$Water\ absorption\ capacity = \frac{M_w}{M_i} \quad (12)$$

$$Water\ solubility(\%) = \frac{M_s}{M_i} \times 100 \quad (13)$$

Where, M_s is the mass of dried supernatant (g), M_i is the initial weight of the sample (g), and M_w is the weight of wet sediment (g).

Porosity and true density

The known quantity of radish microgreen powder (RMP) was immersed in toluene, and the rise in volume was noted as the volume of toluene displaced (V_d) [22].

$$True\ density = \frac{M}{V_d} \quad (14)$$

Where, M is the mass of radish microgreens powder (g) and V_d is the volume of the toluene displaced (ml).

Angle of repose

The radish microgreens powder was poured into the funnel, which was then slowly elevated to let the sample flow out on a flat surface to form a semi-cone structure, and its height and diameter were measured [23].

$$Angle\ of\ repose = \tan^{-1}\frac{2H}{D} \quad (15)$$

Where, H and D is the height and diameter (cm) of the cone formed respectively.

Phytochemical characterization

Total phenolic content (TPC)

The TPC of radish microgreens was estimated using the Folin-ciocalteu method of colorimetry. First, the sample was prepared by steeping 2 g of the sample in 20 ml of 80% methanol and kept undisturbed for 24 h. After 24 h, it was centrifuged at 3000 rpm for 15 min, and the supernatant was collected. The extract prepared was diluted with 80% methanol in a 1:10, 1:100 ratio in triplicate. 1 ml of extract was mixed with 5 ml of Folin-Ciocalteu reagent, with 1 part FC reagent and 9 parts distilled water. After 5 min, 4 ml of saturated sodium carbonate was added. Then, the test tubes were incubated for 90 min under dark conditions with intermittent shaking. The absorbance of the blue-colored solution was measured at 765 nm [24]. The gallic acid standard curve was prepared using different concentrations of gallic acid in solvent. The level obtained was in the range of 1 - 10 µg/ml. Using the standard curve, the TPC was calculated and expressed as gallic acid equivalent mg/g.

$$TPC = \frac{A - B}{m} \times \frac{V \times D}{W \times 1000} \times 100 \quad (16)$$

Where, A is the absorbance of the sample at 765 nm, B is the y-intercept of the calibration curve, m is the slope of the calibration curve, W is the weight of the test material (mg), V is the volume of the sample, and D is dilution factor.

The detailed profiling of phenolics was done using high-performance liquid chromatography (HPLC) using a technique followed by Ichrom Labs, Chandigarh. The extract was prepared similarly, and detection was carried out at 280 nm. The qualitative and quantitative analyses of samples were identified with the help of retention time and peak area by comparing the values with the standard values.

Total flavonoid content

In a 10 ml test tube, 4 ml of distilled water was taken with the addition of 0.3 ml of 5% $NaNO_2$ solution and 1 ml of microgreen extract. After 5 min, 0.3 m of 10% $AlCl_3$ solution was added. Again, wait for 5 min and add 2 ml of 1 N NaOH solution. Further, the solution was mixed properly and incubated at room temperature for 15 min in the dark conditions. The absorbance was measured at 510 nm. Using the standard curve, the total flavonoid content was calculated and expressed as quercetin equivalent mg/g, and concentration was expressed as milligrams of quercetin equivalent (mg QE/g) [25].

DPPH radical scavenging activity

The free radical scavenging activity of radish microgreens was measured in terms of hydrogen donating or radical scavenging ability of the stable free radical diphenyl-1-picrylhydrazyl (DPPH) assay. The stock solution was prepared by dissolving 3.9 mg DPPH in 100 mL of methanol. Further, a 3 mL aliquot of DPPH stock solution was mixed with 1 mL of radish microgreen extract and incubated for 30 min under dark conditions, and absorbance was measured at 517 nm using the spectrophotometer [24]. The control was also prepared without any sample. The inhibition activity was measured based on the equation below.

$$Inhibition\ activity(\%) = \left(\frac{control\ absorbance - sample\ absorbance}{control\ absorbance}\right) \times 100 \quad (17)$$

Ascorbic acid content

The ascorbic acid concentration was determined using the titration method with 2,6-dichloroindophenol dye. The solution was titrated until its color changed to rose pink [26].

$$Dye\ factor = \frac{0.5}{Titre\ value\ (mL)} \quad (18)$$

$$Ascorbic\ acid\ \left(\frac{mg}{100\ g}\right) = \frac{Titre\ value\ (mL) \times 100 \times dye\ factor}{Aliquot\ of\ the\ sample\ taken\ (mL) \times Weight\ of\ the\ sample\ (g)} \quad (19)$$

Statistical analysis

For statistical analysis, one-way analysis of variance was used with p values ≤ 0.05. All data are presented as means ± standard deviation using the Statistical Package for Social Sciences software (SPSS) (IBM SPSS Statistics Version 30).

Results and Discussion

Physicochemical characterization

The proximate composition of radish microgreens powder is presented in table 1. The fresh radish microgreens, harvested at 6 - 8 cm height after 7 - 8 days of growth, exhibited a moisture content of 92.5%. consistent with the findings by Khatoon and Singh [27]. Upon drying, the RMP retained significant nutritional components, including protein (2.691%), fat (0.86%), ash (0.9%), and carbohydrates (2.864%) on a FW basis. The physicochemical composition of RMP showed minimal variation across drying temperatures (40 °C, 45 °C, and 50 °C), indicating that the selected temperature range did not significantly degrade macronutrients. This stability aligns with studies on convective drying of microgreens, where temperatures ≤ 50 °C preserved heat-sensitive compounds. The consistent protein content across temperatures correlates with the findings by Puccinelli et al. [28], who reported that drying temperature below 50 °C prevents significant protein denaturation in Brassica microgreens. The stable fat content supports the observations of Xiao et al. [29] that temperature ≤ 50 °C minimizes lipid oxidation in delicate plant materials. The minor variations in carbohydrate content agree with Weber [30], who demonstrated that low temperature drying preserves reducing sugars in microgreens. The consistent ash content across treatments confirms the findings of Di Gioia et al. [31] that mineral composition remains stable during the gentle drying process. This thermal stability is particularly important for radish microgreens, which contain valuable bioactive compounds. The results of this study corroborate with the work by Treadwell et al. [32], who reported that temperatures between 40 - 50 °C optimally preserve bioactive compounds in microgreens species.

Table 1: Physicochemical and functional characterization of radish microgreens.

Parameters	Value
Height of microgreens	8 - 10 cm
Harvesting time	7 - 8 days
Fresh yield (10 g seeds)	80 - 100 g
Dry matter (g)	6 - 7 g
Moisture (%)	92.68 ± 1.41
Crude protein (%)	2.69 ± 0.11
Crude fat (%)	0.86 ± 0.07
Crude ash (%)	0.9 ± 0.61
Carbohydrates (%)	2.86 ± 0.35
BD (g/ml)	2.01 ± 0.2
TD (g/ml)	3.35 ± 0.57
HR	1.66 ± 0.12
CI (%)	40 ± 4.1
Water absorption capacity (g/g)	6.10 ± 0.12
Water solubility (%)	35.83 ± 0.27
Porosity (%)	54.03 ± 5.62
True density (g/ml)	3.8 ± 0.32
Angle of repose (º)	39.42 ± 3.92

Table 2: Mineral profile of radish microgreens and their contribution to recommended daily intake (Health supplements nutrition guide) [35].

Minerals (DW)	Quantity (mcg/g)	mg/100 g	% RDA
Fe	35.86	3.58	45
Mg	550.86	55.08	13.09
Se	0.095	0.01	17.27
Zn	405.65	4.06	36.8
Ca	0.57	0.57	0.06
K	122	12.20	0.26
Na	103	10.30	0.68
P	6720.60	672.06	96

ICPMS

The mineral profile of radish microgreens (Table 2) reveals their significant contribution to daily nutritional requirements. The microgreens were particularly rich in macro-minerals, including iron (45% of RDA), magnesium (13% of RDA), selenium (17% of RDA), and zinc (36.8% of RDA) and microminerals including phosphorus (96% of RDA), with trace amounts of calcium, potassium and sodium. These findings align with previous studies highlighting microgreens as a concentrated source of essential minerals [28, 29]. The observed high phosphorus content (~96 mg/100 g DW) supports its role in energy metabolism, consistent with reports for *Brassicaceae* microgreens [31]. It also plays a critical role in bone mineralization, ATP synthesis, and cellular repair. Radish microgreens' iron content (~2.1 mg/100 g DW) surpasses mature radish roots (0.3 mg/100 g), emphasizing their nutritional density [33]. The mineral profile of radish microgreens exceeds conventional vegetables (e.g., spinach, lettuce) in phosphorus and iron [30]. This aligns with the broader consensus that microgreens offer 10 - 40% higher mineral concentration than mature plants [34]. Incorporating radish microgreens into the diet could address micronutrient deficiencies, particularly bone health via phosphorus/calcium, energy metabolism (phosphorus/magnesium), and oxidative stress reduction (selenium/zinc). These benefits are especially relevant for populations with limited dietary diversity [35].

Functional properties

The functional properties of RMP remained statistically consistent ($p > 0.05$) across the examined drying temperature range (40 - 50 °C), as evidenced by data presented in table 1. Powder flow characteristics, evaluated through standard pharmaceutical indices, revealed suboptimal flow properties: CI values exceeded 38%, HR were consistently > 1.25, and angle of repose measured > 55°- all indicative of poor flowability, according to the classification system proposed by Carr [36]. Density measurements provided insight into the powder's structural characteristics. The BD and true density values yielded a porosity of 54.03 ± 5.62 %, suggesting that approximately half of the powder volume comprised interstitial air spaces. This elevated porosity, comparable to the findings reported by Teunou et al. [37] for similar plant-derived powders, confers several functional advantages. Elevated porosity enhances hydration capacity, facilitates rapid water absorption, improves miscibility in liquid formulation, and enhances surface area for potential nutrient release. The observed physi-

cal characteristics align with previous studies on microgreen powders by Baba et al. [38], who noted similar flow properties in cruciferous microgreens. While these properties may present challenges in industrial processing contexts requiring free-flowing powders, they offer distinct advantages for end-use applications in food product development, particularly in ready-to-mix nutritional supplements, functional food formulations. The thermal stability of these functional properties across the tested temperature range suggests that drying parameter selection can be optimized for energy efficiency without compromising powder functionality.

Phytochemical characterization of microgreens

The overall phytochemical characterization, including TPC, total flavonoid content, and antioxidant activity of radish microgreens, is presented in table 3. The impact of drying temperature on phytochemical preservation revealed a non-linear relationship. Statistical analysis ($p < 0.05$) demonstrated a significant thermal dependence of bioactive compounds. Drying has a significant effect on the phytochemical content of radish microgreens, TPC, total flavonoid content, and antioxidant activity significantly increase with an increase in temperature from 40 °C - 45 °C. At the same time, it decreases when the temperature increases from 45 °C - 50 °C. It may be because of the thermal breakdown and oxidation of phenolic compounds, flavonoids, and antioxidants above 45 °C. Below 45 °C, the cell disruption leads to better release of phytochemicals [39]. Overall, radish microgreens are found to be a good source of phenolics, with an amount of 2769.05 GAE mg/g DW, flavonoids, with an amount of 37.13 QE mg/g, ascorbic acid content of 0.140 mg/100 g, and antioxidant activity of 88.68% using DPPH at 45 °C. The result complies with the observations by Jauregui et al. [40]. The TPC of radish microgreens exhibited a significantly higher range than other radish plant parts. This content surpasses reported values for radish roots (4 - 5 mg GAE/g DW), seeds (8 - 11 mg GAE/g DW), and sprouts (14 - 20 mg GAE/g DW) [41]. Furthermore, the observed TPC in microgreens was markedly elevated relative to mature radish leaves (78 - 86 mg GAE/g DW) extracted with methanol [42]. Similarly, the total flavonoid content and antioxidant activity were also comparable to the mature plant parts of radish [43]. Overall, radish microgreens are a good source of bioactive compounds, and drying at 45 °C is the optimal temperature for maximum nutrient retention (Figure 2).

HPLC

The detailed phenolic profile of radish microgreens at 45 °C dried microgreens is illustrated in figure 3 and table 4. The major polyphenols present include benzoic acid (176.35 mg/100 g), caffeic acid (13.67 mg/100 g), chlorogenic acid (4.73 mg/100 g), ellagic acid (31.77 mg/100 g), ferulic acid (2.94 mg/100 g), gallic acid (11.68 mg/100 g), p-coumaric acid (82.28 mg/100 g), tannic acid (346.13 mg/100 g), and β-carotene (11.27 mg/100 g) and flavonoids include rutin (6.63 mg/100 g), rutoside (1.62 mg/100 g), catechin HYD (41.23 mg/100 g), quercetin (0.55 mg/100 g). The observed profile demonstrates significant quantitative differences ($p < 0.05$) among compound classes, with tannic acid representing 42.7% of total identified phenolics. This composition aligns with but exceeds values reported for mature radish roots [44], confirming microgreens enhanced phytochemical density. These compounds have various health-boosting properties, such as antioxidants, anti-inflammatory, anti-microbial, anti-cancerous, antidiabetic, skin-related benefits, prevention of cardiovascular diseases, etc. [45]. Notably, the catechin hydrate content (41.23 mg/100 g) surpasses many common teas [46],

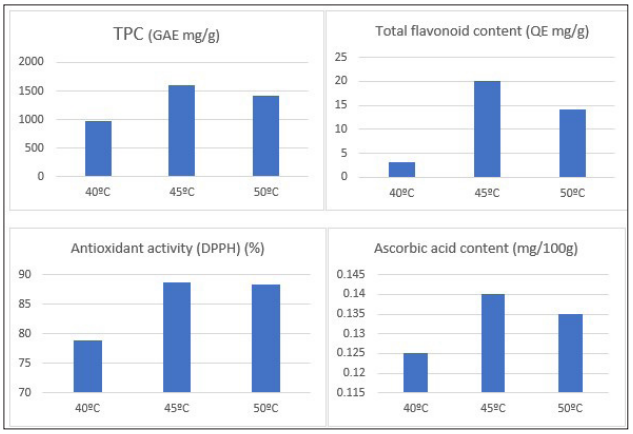

Figure 2: Comparison of TPC (GAE mg/g), total flavonoid content (QE mg/g), antioxidant activity (%), ascorbic acid (mg/100 g) at three different temperatures: 40 °C, 45 °C, and 50 °C.

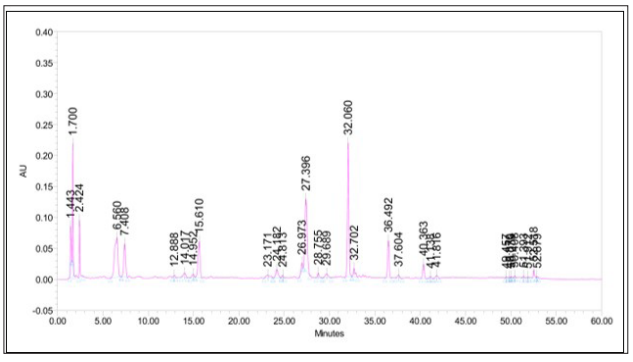

Figure 3: Phenolic profiling of radish microgreens using HPLC.

Table 3: Phytochemical characterization of radish microgreens.

Phytochemicals	Quantity		
Dry basis	**40 °C**	**45 °C**	**50 °C**
TPC (GAE mg/g)	968.57 ± 1.45^{c}	1604.87 ± 2.26^{a}	1421.05 ± 0.47^{b}
Total flavonoid content (QE mg/g)	3.24 ± 0.16^{c}	20 ± 0.11^{a}	14.12 ± 0.12^{b}
Antioxidant activity (DPPH) (%)	78.83 ± 0.53^{b}	88.68 ± 0.15^{a}	88.32 ± 0.32^{a}
Ascorbic acid content (mg/100 g)	0.13 ± 0.01^{a}	0.14 ± 0.01^{a}	0.14± 0.01^{a}

Note: Results are represented as mean ± SD; different letters (a and b) in the same row are varied significantly at 95% ($p < 0.05$) confidence level. Data is represented on a dry basis.

Table 4: Phenolic profile of radish microgreens.

Name of the compound	Retention time	Area	% Area	Quantity (mg/100 g)
Flavonoids				
Rutoside	28.755	84410	0.71	1.62
Rutin	29.689	132735	1.11	6.63
Catechin HYD	23.171	129028	1.08	41.23
Qurecetin	41.816	72402	0.61	0.55
Polyphenols				
Benzoic acid	32.06	2213738	18.52	176.35
Caeffic acid	15.61	923601	7.73	13.67
Chlorogenic acid	14.017	123873	1.04	4.73
Ellagic acid	27.39	1941802	16.25	31.77
Ferulic acid	29.69	132735	1.11	2.94
Gallic acid	2.42	466834	3.91	11.68
P-coumaric acid	27.39	1941802	16.25	82.28
Tannic acid	32.06	2213738	18.52	346.13
Beta-carotene	50.41	21070	0.18	11.27

while tannic acid concentration approaches therapeutic levels demonstrated *in vitro* against *Staphylococcus aureus* [47].

Conclusion

This study investigated the impact of drying temperatures (40 °C, 45 °C, and 50 °C) on radish microgreens, revealing that while temperature did not significantly affect physicochemical and functional properties, it played a crucial role in phytochemical retention. The optimum drying temperature was 45 °C, which maximized the preservation of phenolics, flavonoids, and antioxidants. Nutritional analysis confirmed that radish microgreens are a rich source of essential nutrients, including ascorbic acid, phosphorus, iron, zinc, selenium, and magnesium, along with trace amounts of calcium, potassium, and sodium. Notably, these microgreens contributed to the RDA of minerals, with phosphorus alone providing up to 95% of the RDA. Additionally, their phytochemical content (phenols, flavonoids, and antioxidants) surpassed that of mature radish, underscoring their potential health benefits. Hence, incorporating RMP into food products could enhance nutritional value. However, further research is needed to optimize drying techniques for improved nutrient retention and to evaluate the functional effects of microgreen-enriched foods. Future studies should also explore the bioavailability of these nutrients and their impact on human health when consumed as part of a regular diet. These results highlight the potential of radish microgreens as a functional food ingredient, supporting their use in nutrient-fortified products for improving dietary intake.

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Conflict of Interest

None.

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