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The Performance of Growing-Media-Shaped Microgreens: The Growth, Yield, and Nutrient Profiles of Broccoli, Red Beet, and Black Radish

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Abstract: Sprouts, microgreens, and baby leaves are plant-based functional foods that have recently gained popularity for use in human diets as novel foods due to their high nutraceutical value. Microgreens, harvested shortly after germination with one true leaf, include vitamins and minerals with potential health benefits. Achieving high yields, robust growth, and maximum nutrient accumulation requires optimal cultivation, especially when selecting the appropriate growing medium. This study assessed the effectiveness of six different growing media for the cultivation of microgreens, specifically black radish (*Raphanus sativus* L. var. *niger*), broccoli (*Brassica oleracea* var. *italica*), and red beet (*Beta vulgaris* L.). The growing media tested included vermiculite, perlite, a peat-based medium, filter paper, cotton textile, and agril. The results revealed that vermiculite and the peat-based medium led to the highest yields. The phenolic content ranged from 110.77 mg GA·100 g^{-1} FW in red beet to 169.96 mg GA·100 g^{-1} FW in broccoli. The flavonoid content varied between 17.99 mg RU·100 g^{-1} FW in black radish and 120.36 mg RU·100 g^{-1} FW in red beet. Agril and filter paper media yielded the highest SPAD–chlorophyll values (47.34 and 44.36, respectively). The protein content peaked at 3.03 g·100 g^{-1} FW in black radish grown on filter paper, while the vitamin C content reached a maximum of 29.75 mg·100 g^{-1} FW in black radish grown in agril. The findings suggest that while the optimal conditions vary by species, the choice of growing medium plays a crucial role in determining microgreens' quality and nutrient content.

Keywords: total phenols; total flavonoids; vitamin C; minerals; *Raphanus sativus* L. var. *niger*; *Brassica oleracea* var. *italica*; *Beta vulgaris* L.

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1. Introduction

Microgreens, sprouts, and baby leaf vegetables represent different stages of plant development, each offering distinct characteristics and requiring specific growing techniques. Sprouts are harvested before cotyledon leaves develop and are typically grown in water or moist environments without soil. They are rich in enzymes and amino acids, which provide a rapid nutrient uptake [1]. Microgreens, harvested slightly later, contain concentrated amounts of bioactive compounds such as phenolics, flavonoids, and vitamins [2,3]. They thrive in substrates with balanced water retention and aeration, making soilless systems ideal for their cultivation.

As plants develop, they enter the baby leaf stage. Baby leaf vegetables, typically grown in soil-based or hydroponic systems, require more nutrients to support their advanced growth [4]. Tailoring environmental conditions such as light intensity, light quality, nutrient solutions, and substrate types to each stage is essential to maximize yield and nutritional content [5].

This study is dedicated to microgreens. Microgreens are young and immature plants harvested during the development of cotyledon leaves. They first gained attention in the San Francisco area in the late 1980s, making their debut on chefs' menus. Microgreens quickly became popular with their rich flavors, vibrant colors, and appealing sensory characteristics. Today, they are widely used in sandwiches, salads, and garnishes to enhance the sensory qualities of various dishes [5,6].

Phenotypically, microgreens exhibit cotyledons, stems, and initial true leaves, and they are typically harvested approximately 6–15 days after the seedlings emerge. Microgreens can be cultivated using diverse growing media such as soil, a blend of coco and peat, and vermiculite, encompassing loose and soilless germination media [7]. Microgreens are immature, delicate, and characterized by hypocotyl-colored cotyledonary leaves. They are commonly found in various plant families, particularly in the *Brassicaceae, Lamiaceae, Amaryllidaceae, Apiaceae, Amaranthaceous, Cucurbitaceae, Fabaceae,* and *Asteraceae* families, encompassing a wide range of fruits, vegetables, grains, and herbs [3].

Microgreens possess elevated levels of essential phytonutrients (ascorbic acid, β-carotene, α-tocopherol, and phylloquinone) and minerals (Ca, Mg, Fe, Mn, Zn, Se, and Mo) compared to their fully developed counterparts [8]. Microgreens are considered to be "functional food" or "nutrient-dense foods" due to their ability to contain high concentrations of health-promoting compounds such as antioxidants, vitamins, and minerals [1]. Moreover, scientists have indicated that consuming microgreens might offer health advantages by preventing inflammation-related diseases while encouraging a nutritious diet because of the abundant phytochemicals and vitamins [2,3].

Microgreens can be cultivated in standard, sterile, and loose germination growing media without soil. Various combinations have been successfully employed, including peat-based growing media, vermiculite, perlite, coconut fiber, and other materials. Trays are partially filled with the chosen medium to a depth of 1 to 2.5 or 5 cm, depending on the irrigation plan [5]. Typically, these systems apply overhead mist irrigation only during the germination phase. Following germination, it is recommended to sub-irrigate the trays to prevent excessive moisture in the plant canopy [5].

Broccoli microgreens are recognized for their high sulforaphane content, a bioactive compound with anticancer and antioxidant properties. They also contain ascorbic acid (vitamin C), phenolic compounds, and flavonoids, contributing to their anti-inflammatory effects [2,3]. Red beet microgreens are rich in betalains, a pigment group that provides potent antioxidant and anti-inflammatory properties [8]. Red beet also contains fumaric acid and other organic acids that enhance plant metabolism. Black radish microgreens are valued for their high levels of glucosinolates, compounds known for their role in detoxification and cancer prevention [6]. Additionally, red beet microgreens contain significant amounts of phenolics and flavonoids, further enhancing their antioxidant potential [2,4].

Broccoli microgreens grow optimally in environments with controlled light (16 h per day) and moderate temperatures, typically 18–22 °C. These conditions are essential to ensure proper development and the accumulation of bioactive metabolites, as demonstrated in studies on the optimal growth conditions for *Brassicaceae* microgreens [4]. Red beet microgreens grow best in substrates with a high moisture retention to support rapid development, given their high water demand during the early stages of growth [1]. While substrate characteristics significantly influence microgreen growth, irrigation frequency adjustments can further complement these properties to achieve optimal conditions. Black radish microgreens benefit from well-aerated growing media with stable moisture levels to ensure optimal germination and growth [5]. Well-aerated substrates are essential for optimal black radish microgreen growth, but balancing aeration with moisture retention through proper irrigation programming is crucial to avoid water stress or oxygen limitations.

Selecting the appropriate growing medium is crucial for optimal microgreen growth. With rapid urbanization and global population growth, maximizing plant yield has become essential, highlighting the growing importance of research on plant cultivation. A critical factor in choosing a suitable growing environment is its accessibility and cost-effectiveness.

In microgreen cultivation, the right growing medium directly affects seedling development and significantly impacts the root system [9].

The growing medium plays a crucial role in plant growth by influencing water retention and aeration and, in some cases, nutrient availability, which can also be supplemented through irrigation systems. All of these are essential for robust development [9]. In microgreen cultivation, efficient root establishment can enhance nutrient uptake, contributing to higher yields and improved plant quality [7]. Different media, such as peat-based media and vermiculite, promote better root development by maintaining optimal moisture and aeration [4].

Here, we aimed to evaluate the influence of different growing media on the growth, yield, and nutrient profile of broccoli, red beet, and black radish microgreens. With increasing interest in microgreens as a nutrient-dense food source, selecting the optimal growing medium is crucial for enhancing their productivity and nutritional quality. We hypothesized that varying the growing medium would significantly affect the performance of the microgreens, and our goal was to identify which medium offers the best balance between plant development, yield, and nutrient content, ensuring efficient and sustainable production methods.

2. Materials and Methods

2.1. Plant Material

Plant materials included black radish (*Raphanus sativus* L. var. *niger*) and broccoli (*Brassica oleracea* var. *italica*) from the *Brassicaceae* family, known for their nutrient content and aromatic qualities, and red beet (*Beta vulgaris* L.) from the *Amaranthaceae* family. Red beet is known for its beautiful and eye-catching red color. Open-pollinated local standard varieties from the Arzuman® seed company were used for black radish, broccoli, and red beet seeds. The plant materials used in this experiment are known for their intermediate maturity and high yield potential. These varieties are widely preferred for open-field cultivation.

2.2. Plant Growing Conditions

This study was conducted in a climate chamber, as illustrated in Figure 1. Six different growing media were experimented with for microgreen cultivation. The microgreen growing media included (1) a peat-based substrate (Klasmann Potground P20 ®), (2) perlite with an inorganic structure (Agrekal®), (3) vermiculite (Agrekal®), (4) a cotton–linen textile, (5) agril (which is made from synthetic polymers and is characterized by its lightweight and porous nature), and (6) filter paper (a product with a water-resistant paper texture with a density of 50 g m^{-2}), making the total number of different soilless growing media employed in the experiment six (Figure 2). The main components of the peat-based substrate included 20% TerrAktiv® compost, 10% GreenFibre® wood fibers, frozen black peat for stability and water retention, and white peat for water absorption and retention. Perlite is a volcanic amorphous mineral primarily composed of silicon dioxide, with small amounts of aluminum, sodium, potassium, and iron oxides. Vermiculite is a mineral (magnesium–aluminum–iron silicate) that expands when heated, forming lightweight, absorbent flakes.

The chemical properties of the substrates used in the experiment are described as follows: The peat-based substrate (Klasmann Potground P20®) had a pH range of 5.5 to 6.5 and a high cation exchange capacity (CEC) of 150–200 meq 100 g^{-1}. It contained a starter fertilizer that provided essential nutrients such as nitrogen (0.8%), phosphorus, and potassium, supporting initial plant development. Perlite (Agrekal®) is an inert and inorganic medium with a neutral to slightly alkaline pH of 7.0 to 7.5. It has a low CEC (<10 meq 100 g^{-1}) and minimal nutrient content, containing only trace amounts of potassium and calcium. Vermiculite (Agrekal®) has a pH range of 6.5 to 7.2 and offers a moderate CEC of 100–150 meq 100 g^{-1}. It naturally contains magnesium and small amounts of calcium and iron, contributing to nutrient availability. The cotton textile medium serves primarily as a structural support with a neutral pH of 7.0. It does not have a measurable

cation exchange capacity and lacks significant nutrient content, functioning solely as a physical medium. Agril, a synthetic polymer, exhibits a neutral-to-slightly alkaline pH of 7.0 to 7.5 and an extremely low CEC. It does not provide any nutrients but offers structural support and facilitates aeration. Filter paper, with a pH range of 6.0 to 6.5, does not exhibit a cation exchange capacity. As a non-nutritive medium, it serves only as a support for seed germination and seedling growth.



Figure 1. A visual representation of the controlled climate chamber used for microgreen cultivation.

The physical properties of substrates, such as water retention and aeration, are critical factors that influence the growth and development of plants by ensuring adequate moisture availability and oxygenation for root systems [9]. Peat-based substrates have a high water retention capacity, holding approximately 10–12 times their water weight, providing good aeration. Perlite retains around 20–50% of its volume in water, ensuring moderate water availability, while its porous structure provides excellent aeration, supporting root oxygenation. Vermiculite exhibits a very high water holding capacity, retaining 200–500% of its weight in water, but offers moderate aeration, which is lower than that of perlite. Cotton–linen textiles can absorb and retain 100–150% of their weight in water, and their woven structure allows for sufficient aeration. Agril, a lightweight and porous synthetic polymer, retains 50–100% of its weight in water and provides excellent aeration due to its porous nature. Filter paper, with a water-resistant texture and a density of 50 g/m^2, retains 200–300% of its weight in water, but its dense structure limits aeration compared to more porous substrates.

Experiments were conducted in a climate-controlled growth chamber to determine the most suitable soilless growing medium for microgreen plants. Black radish, broccoli, and red beet plants were cultivated at 20 °C and under 50% relative humidity. The growth conditions included 16 h of light and 8 h of darkness, provided by daylight-simulating LED lamps. These provide a balanced light spectrum similar to natural sunlight. These lamps are designed to deliver a consistent light intensity and quality, supporting optimal photosynthesis with a light intensity of 350 µmol m^{-2} s^{-1}. Transparent containers measuring 16 cm × 9 cm × 7 cm (length × width × height) made of clear plastic were utilized as microgreen growing trays (Figure 2). Peat, vermiculite, and perlite substrates were used at a volume of 250 cm^3 for each container. Seeds were sown at the following densities to ensure contact between seeds without leaving gaps: radish 32 g m^{-2}, red beet 16 g m^{-2},

broccoli 13 g m^{-2} [8]. The treatments were arranged in the growth chamber following a completely randomized experimental design, ensuring an equal probability of treatment distribution across all parcels.



Figure 2. The growing media used in the study, listed from bottom to top: perlite, peat-based substrate, vermiculite, agril, cotton textile, and filter paper.

2.3. Plant Nutrition

The sown seeds were rinsed with pure water until the first green cotyledon leaves appeared. Immediately after the emergence of the green cotyledons, irrigations were performed with the nutrient solution specified below. A modified Hoagland nutrient solution was utilized at half strength to produce microgreens. Plants were supplied with the following nutrient solution at ¼ strength (in mg L^{-1}): N (200), P (50), K (300), Ca (200), Mg (65), Fe (5.0), Mn (0.8), Cu (0.3), Zn (0.3), B (0.3) and Mo (0.05). The following conditions were also used for irrigation: pH: 5.5; electrical conductivity (EC): 1.2–1.6 dS cm^{-1} (initial and later stages) [10].

The nutrient solution was applied manually to ensure a precise water distribution. The containers used for microgreen cultivation were weighed on a sensitive scale, and each was initially brought to field capacity based on its known weight. During subsequent irrigations, the weight difference between the field capacity and the measured weight was calculated, and the required amount of water was applied accordingly. This method accounted for the different physical properties of each substrate, ensuring that water was applied accurately based on their specific needs.

2.4. Plant Harvest

Microgreens were cultivated for 7–15 days, depending on the growth rate of the three different plant species. Harvesting occurred when the seedlings reached the stage where the first true leaf was fully developed, the second leaf began to emerge, and the cotyledon leaves were at the rounded margin stage.

2.5. Measurements of Plant Growth Parameters

When the plants were harvested, measurements of plant height, hypocotyl length, stem diameter, and single plant weight were taken for the microgreens of 3 different plant species in 4 repetitions under various cultivation environments. The yield per unit area was calculated. A leaf area meter (Li-3100, LICOR, Lincoln, NE, USA) was utilized to determine the leaf area per plant in square centimeters. After the harvest, plants were weighed on a digital balance to ascertain the fresh leaf weight per plant in grams. An SPAD–chlorophyll meter (Minolta 502, Osaka, Japan) was utilized to measure the chlorophyll content in the leaves. Fresh leaves were subsequently dried in a forced-air oven at 65 °C for 48 h, and the dry weight per plant was determined.

2.6. Macro and Micro-Nutrient Element Analysis

Macro and microelement analyses included phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn). Microgreens were harvested 7 to 15 days after seed emergence, with four replicates per treatment used for nutrient analysis. Approximately 5 g of fresh microgreens were collected for each replicate. The samples were washed with distilled water and then dried in an oven at 65 °C to prepare them for analysis. The dried samples were ground in a leaf grinding mill (20 mesh), incinerated at 550 °C for 8 h, and the resulting ash was dissolved in 3.3% (*v*/*v*) HCl acid. Readings for K, Ca, and Mg were taken in emission mode. In contrast, Fe, Mn, Zn, and Cu readings were taken in absorbance mode using a Varian FS 220 model atomic absorption spectrometer (Mulgrave Virginia, Australia) [11]. Phosphorus analyses were conducted spectrophotometrically using the extract prepared above, following the Barton method.

2.7. Determination of Total Phenols

Total phenolic content was determined using a spectrophotometric method modified by Spanos and Wrolstad [12]. Each sample, dissolved in 80% methanol, was subjected to ultrasound for 10 min at 40 °C to enhance phenolic compound liberation, followed by centrifugation at 1500 rpm for 5 min. The supernatant was then mixed with Folin–Ciocalteu reagent and 20% sodium carbonate before being incubated in the dark for 2 h, and the absorbance was read at 765 nm using a spectrophotometer (Analytik Jena second 200 plus, Jena, Germany). A calibration curve with known concentrations of gallic acid (GA) was used to determine the total phenolic contents, expressed as milligrams of GA equivalents per gram fresh weight (FW). A total phenol analysis was performed with four replicates, using plants harvested 10 days after sowing.

2.8. Determination of Total Flavonoids

Total flavonoid content was determined according to the method developed by Quettier et al. [13]. In brief, an aliquot of 1 mL of each extract was mixed with 0.05 mL of AlCl 3 (10%), 0.05 mL potassium acetate (1 M), and 1.8 mL of milli Q-water. We mixed all reagents thoroughly using a vortex, and they were kept in the dark for 45 min at room temperature. After incubation, the absorbance was recorded using a spectrophotometer (Analytik Jena specord 200 plus, Germany) at 450 nm. The results are expressed as mg rutin equivalent per 100 g fresh matter. A total flavonoid analysis was conducted with four replicates using plants harvested 10 days after sowing.

2.9. Determination of Crude Protein

Crude protein (CP) content was quantified using the Kjeldahl method [14], which involves measuring nitrogen content and subsequent conversion to protein quantity by applying a conversion factor 6.25. The analysis was performed with four replicates, using plants harvested 10 days after sowing.

2.10. Determination of Vitamin C

Vitamin C content was determined using a modified version of the method described by Elgailani et al. [15]. The microgreens were processed in a juicer to obtain an extract. Five milliliters of this extract were mixed with forty-five milliliters of 0.4% oxalic acid solution and filtered. From the filtered solution, one milliliter was combined with nine milliliters of 2,6-dichlorophenolindophenol and thoroughly mixed. Finally, the absorbance of all samples was measured at 518 nm using a UV spectrophotometer. The vitamin C analysis was carried out with four replicates, using plants harvested 10 days after sowing.

2.11. Statistical Analyses

All data were analyzed using JMP v5.0.1 statistical software, and an analysis of variance (ANOVA) was conducted to assess the main effects of growing media, and their interaction on the measured parameters. This type of ANOVA was selected to evaluate these factors' independent and combined influence. Treatment means were compared using LSD's significant difference test at a significance level of $p \leq 0.05$. The results, including significance levels, are presented in Table 1 to highlight the statistical outcomes of the ANOVA.

Table 1. Significance levels from ANOVA analyzing the effects of growing media and their interactions.

	Growing Medium	**Plant Species × Growing Medium**
Plant length	****	****
Hypocotyl length	****	****
Stem diameter	****	****
Single plant weight	*	*
Leaf Area	****	****
SPAD–Chlorophyll	****	*
Yield	****	****
Dry Matter Ratio	****	***
Total Phenols	****	****
Total Flavonoids	****	****
Crude Protein	****	****
Vitamin C	****	****
Phosphorus	****	****
Potassium	****	****
Magnesium	***	****
Calcium	****	****
Iron	****	****
Manganese	****	****
Copper	****	****
Zinc	****	****

*: $p > 0.05$, ***: $p \leq 0.01$, ****: $p \leq 0.001$.

3. Results

The significance levels from the ANOVA, presented in Table 1, reveal how the growing media, the conditions (nutrient solution supply/irrigation schedule), and their interactions influenced various growth parameters and nutrient content. Plant length, hypocotyl length, stem diameter, single plant weight, and leaf area showed statistically significant variation. Among these, leaf area and plant length exhibited the highest significance levels across all species, suggesting that the growing media substantially influenced vegetative growth. The growing medium significantly influenced yield per plant and SPAD–chlorophyll readings. The total phenolic and flavonoid contents displayed strong statistical significance in response to the growing medium, reflecting the critical role of media composition in secondary metabolite accumulation. Similarly, crude protein and vitamin C content varied significantly, highlighting the influence of the growing medium's environmental conditions on plant nutritional quality. Macronutrients such as phosphorus, potassium, calcium, and magnesium, along with micronutrients including iron, manganese, copper, and zinc,

exhibited significant differences across treatments. The dry matter ratio varied across the species, with significant results being recorded for most treatments. This suggests that the growing medium conditions influenced water retention and biomass accumulation

3.1. Plant Growth Assessment

This study aimed to determine the most effective growing medium for microgreen production by evaluating key growth parameters, including plant length, hypocotyl length, stem diameter, single plant weight, leaf area, and yield (Table 2, Figures 3 and 4). The comparison highlights differences across the six growing media for the three plant species used—broccoli, black radish, and red beet.

Table 2. The effects of growing media on plant growth parameters of the microgreens.

Factor		Plant Length (cm)	Hypocotyl Length (cm)	Stem Diameter (mm)	Single Plant Weight (g)	Leaf Area (cm^2 $Plant^{-1}$)
Growing medium						
Vermiculite		10.29 ^{a}	7.15 ^{a}	0.97 ^{a}	0.12 ^{a}	0.98 ^{a}
Peat-based		8.87 ^{b}	6.67 ^{b}	0.92 ^{b}	0.12 ^{a}	0.99 ^{a}
Perlite		8.62 ^{b}	6.28 ^{bc}	0.83 ^{d}	0.11 ^{a}	0.92 ^{b}
Cotton textile		8.09 ^{c}	6.11 ^{c}	0.85 ^{cd}	0.085 ^{a}	0.77 ^{c}
Filter paper		7.07 ^{d}	5.30 ^{d}	0.89 ^{b}	0.16 ^{a}	0.69 ^{d}
Agril		6.10 ^{e}	4.53 ^{e}	0.88 ^{bc}	0.074 ^{a}	0.70 ^{d}
Plant species × Growing medium						
Broccoli	Vermiculite	9.86 ^{c}	7.75 ^{bc}	0.67 ^{f}	0.047 ^{d}	0.67 ^{h}
	Peat	6.47 $^{g–i}$	5.30 ^{gh}	0.67 ^{f}	0.035 ^{d}	0.73 ^{g}
	Perlite	6.92 $^{f–h}$	5.97 ^{fg}	0.56 ^{g}	0.047 ^{d}	0.58 ^{j}
	Cotton textile	7.36 ^{ef}	6.32 ^{ef}	0.67 ^{f}	0.052 ^{d}	0.64 ^{hı}
	Filter paper	6.53 $^{g–i}$	5.28 $^{g–i}$	0.61 ^{fg}	0.024 ^{d}	0.61 ^{i}
	Agril	5.87 ^{i}	4.27 ^{k}	0.67 ^{f}	0.033 ^{d}	0.62 ^{i}
Black radish	Vermiculite	12.95 ^{a}	9.12 ^{a}	1.25 ^{a}	0.24 ^{b}	1.54 ^{a}
	Peat	13.27 ^{a}	9.54 ^{a}	1.08 ^{b}	0.25 ^{b}	1.32 ^{b}
	Perlite	12.06 ^{b}	8.38 ^{b}	1.07 ^{b}	0.23 ^{bc}	1.52 ^{a}
	Cotton textile	9.79 ^{c}	7.39 ^{cd}	1.08 ^{b}	0.16 $^{b–d}$	1.23 ^{c}
	Filter paper	8.45 ^{d}	6.51 ^{ef}	1.14 ^{b}	0.41 ^{a}	1.03 ^{e}
	Agril	8.70 ^{d}	6.77 ^{de}	1.12 ^{b}	0.15 $^{b–d}$	1.15 ^{d}
Red beet	Vermiculite	8.05 ^{de}	4.59 $^{i–k}$	0.99 ^{c}	0.085 $^{b–d}$	0.73 ^{g}
	Peat	6.87 $^{f–h}$	5.17 $^{h–j}$	0.99 ^{c}	0.087 $^{b–d}$	0.94 ^{f}
	Perlite	6.89 $^{f–h}$	4.48 ^{jk}	0.86 ^{de}	0.071 ^{cd}	0.67 ^{h}
	Cotton textile	7.13 ^{fg}	4.63 $^{h–k}$	0.79 ^{e}	0.047 ^{d}	0.44 ^{k}
	Filter paper	6.25 ^{hi}	4.10 ^{k}	0.91 ^{d}	0.030 ^{d}	0.42 ^{k}
	Agril	3.71 ^{j}	2.55 ^{l}	0.84 ^{de}	0.040 ^{d}	0.33 ^{l}

No significant difference was observed between means sharing the same letter within the same column for each factor ($p < 0.05$).

Effect of Growing Media: Vermiculite stood out as the most effective medium, producing the tallest plants (10.29 cm) and longest hypocotyls (7.15 cm), along with the highest stem diameter (0.97 mm) and yield (0.58 g cm^{-2}). The peat-based substrate followed closely, offering a competitive plant height (8.87 cm) and leaf area (0.99 cm^2 per plant). The perlite and cotton textiles provided moderate results. In contrast, filter paper and agril were the least effective, particularly in supporting plant length and hypocotyl development.

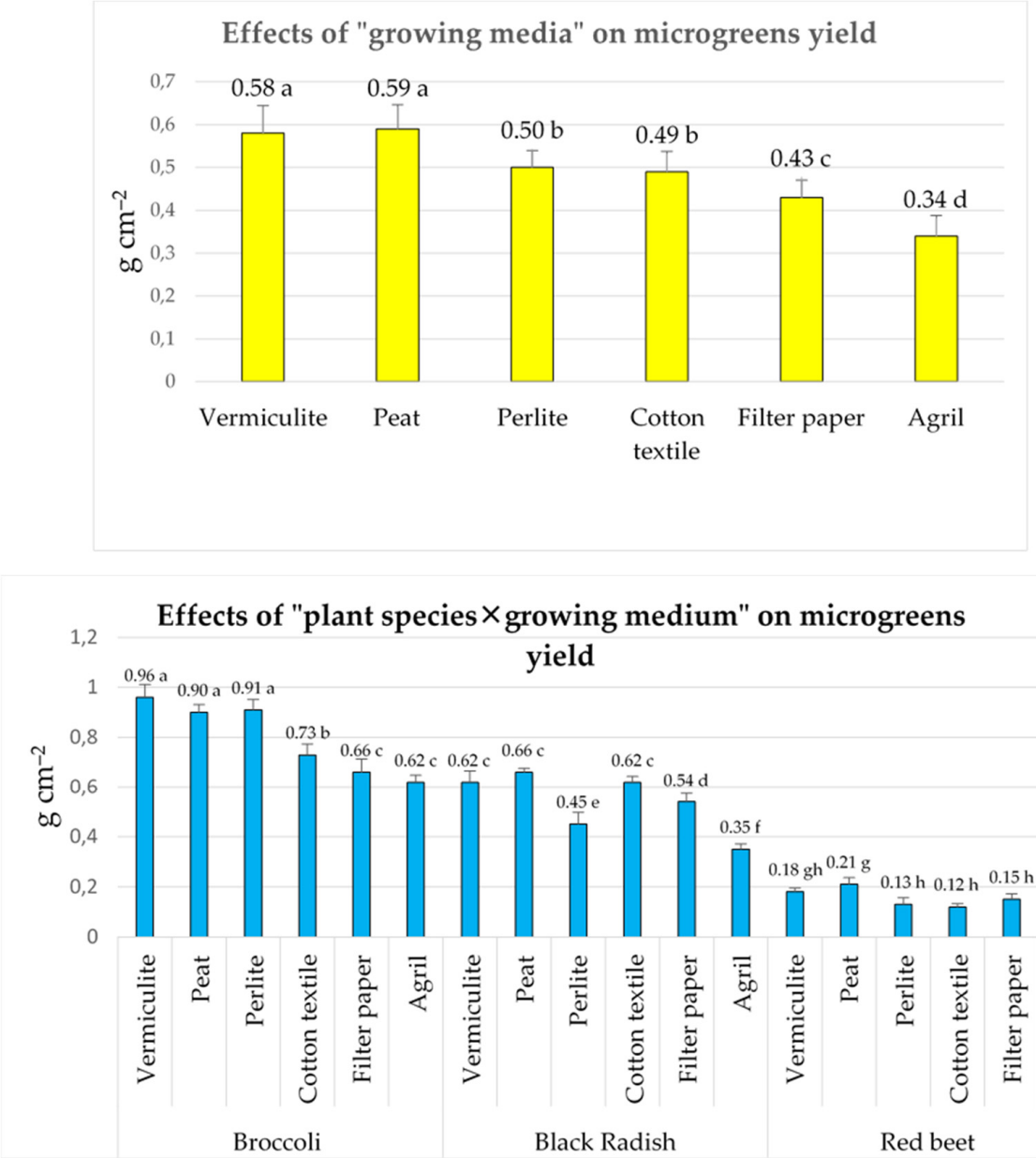

Figure 3. The effects of growing media on the yield of the microgreens. No significant difference was observed between means represented by the same letter on the histogram for each factor ($p < 0.05$).

Interaction of Plant Species and Growing Media: For broccoli, vermiculite proved to be the optimal medium, resulting in significant improvements in plant length (9.86 cm), hypocotyl length (7.75 cm), and yield (0.96 g cm^{-2}). Both vermiculite and the peat-based substrate were highly influential for the black radish, with the peat-based substrate delivering the highest plant length (13.27 cm) and leaf area (1.32 cm^2 per plant). Although vermiculite enhanced the growth of red beet as well, the overall performance of the red beet remained lower than that of the broccoli and black radish across all media.

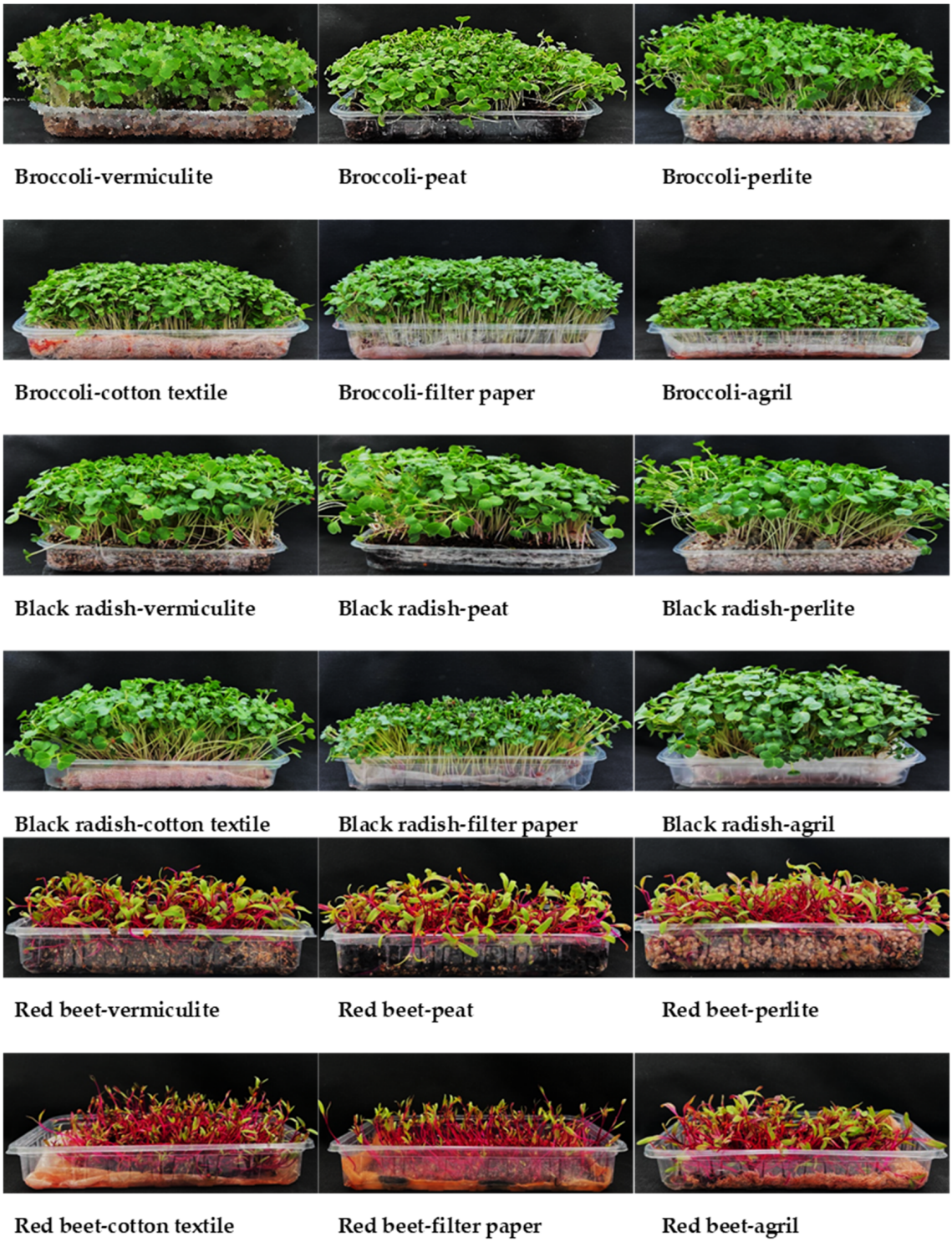

Figure 4. Microgreens of broccoli, black radish, and red beet grown in different growing media.

3.2. Effects of Growing Media on Chlorophyll, Dry Matter, Phenol, Flavonoids, Protein, and Vitamin C in Microgreens

This section examines how different growing media affect the biochemical traits of the three microgreen species. The results demonstrate that plant species and media significantly influence these parameters (Figures 5 and 6, and Table 3).

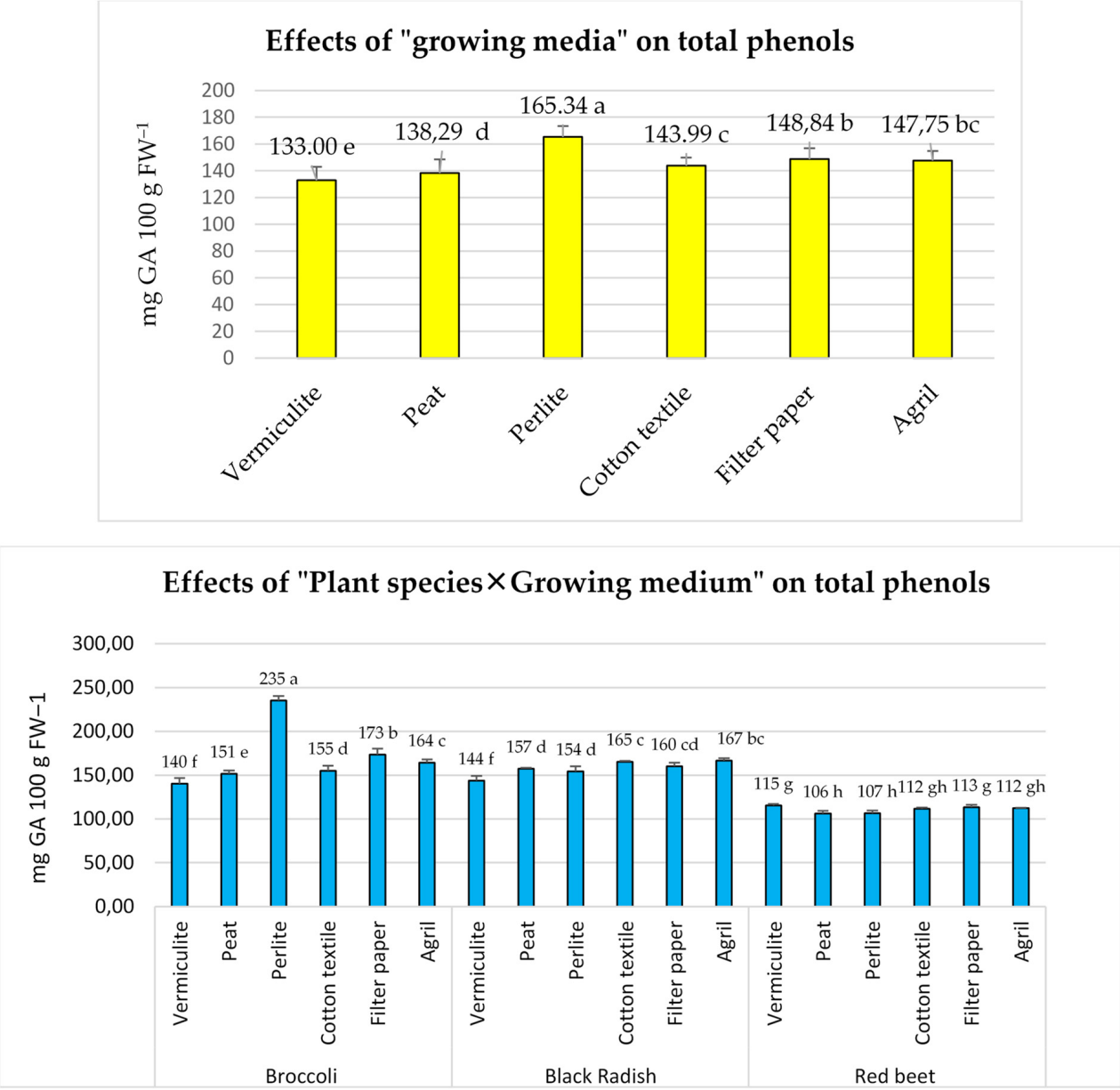

Figure 5. The effects growing media on total phenols. No significant difference was observed between means represented by the same letter on the histogram for each factor ($p < 0.05$).

Impact of growing media: Agril was the most effective medium for SPAD–chlorophyll (47.34) and the dry matter ratio (6.32 percent). It also performed well in terms of total phenols, 147.75 mg GA 100 g^{-1} FW, and total flavonoids, 53.57 mg RU 100 g^{-1} FW. Filter paper achieved a high SPAD–chlorophyll (44.36) level and the highest total flavonoid content, 62.23 mg RU 100 g^{-1} FW. It had moderate dry matter (5.23 percent) and total phenols, 148.84 mg GA 100 g^{-1} FW. The peat-based medium performed well in terms of phenolic content, 138.29 mg GA 100 g^{-1} FW, and flavonoid content, 60.95 mg RU 100 g^{-1} FW, with a dry matter ratio of 4.87 percent and an SPAD–chlorophyll level of 40.36. Vermiculite had high SPAD–chlorophyll (41.78) levels but showed a lower performance for phenolic content, 133.00 mg GA 100 g^{-1} FW, and flavonoids, 46.66 mg RU 100 g^{-1} FW. Among the media, agril provided the highest protein content, 2.52 g 100 g^{-1} FW, while the highest vitamin C levels, 26.10 mg 100 g^{-1} FW, were observed in microgreens grown on filter paper.

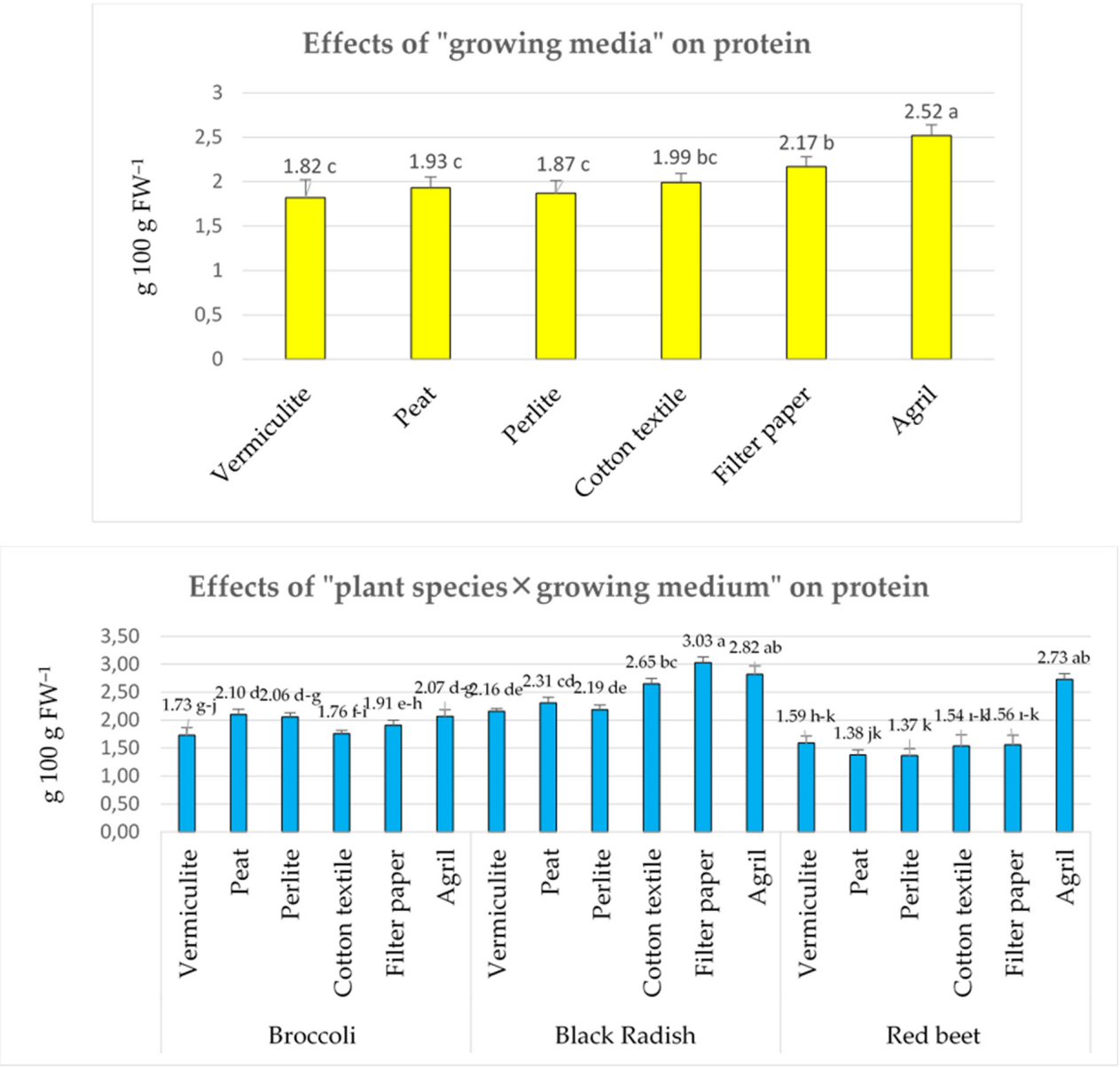

Figure 6. The effects of growing media on protein content. No significant difference was observed between means represented by the same letter on the histogram for each factor ($p < 0.05$).

Interaction between plant species and growing media: Broccoli responded best to the filter paper and agril. The filter paper resulted in the highest total phenols, 173.35 mg GA 100 g^{-1} FW, while agril enhanced SPAD–chlorophyll (41.94) and the total flavonoid content, 21.67 mg RU 100 g^{-1} FW. The black radish performed best on the agril and filter paper, achieving high SPAD–chlorophyll values (56.01 and 52.52) and dry matter ratios (6.49 percent and 6.52 percent). These media also enhanced the total phenolic content, 166.74 and 159.92 mg GA 100 g^{-1} FW. Although agril promoted a high flavonoid content, 122.23 mg RU 100 g^{-1} FW, for red beet, the total phenols remained relatively low at 112.17 mg GA 100 g^{-1} FW.

Protein and vitamin C content: Black radish exhibited the highest protein levels, reaching 3.03 g 100 g^{-1} FW in filter paper and 2.53 g 100 g^{-1} FW in the peat-based medium. This species also showed the highest vitamin C content at 29.75 mg 100 g^{-1} FW when grown in agril. Broccoli showed moderate protein levels, peaking at 2.17 g 100 g^{-1} FW in filter paper and vitamin C levels of 28.70 mg 100 g^{-1} FW. Red beet had the lowest protein levels,

reaching 2.73 g 100 g^{-1} FW in agril, and the lowest vitamin C content, with a maximum of 18.35 mg 100 g^{-1} FW in vermiculite.

Table 3. The effects growing media on the microgreens' chlorophyll, dry matter, total flavonoids, and vitamin C contents.

Factor		SPAD–Chlorophyll	Dry Matter (%)	Total Flavonoids (mg RU 100 g^{-1})	Vitamin C (g 100 g^{-1} FW)
Growing medium					
Vermiculite		41.78 ^{cd}	4.56 ^{c}	46.66 ^{d}	23.15 ^{cd}
Peat		40.36 ^{d}	4.87 ^{bc}	60.95 ^{a}	21.90 ^{d}
Perlite		43.14 ^{bc}	4.84 ^{bc}	51.75 ^{bc}	25.30 ^{ab}
Cotton textile		43.31 ^{bc}	4.90 ^{bc}	48.29 ^{cd}	26.10 ^{a}
Filter paper		44.36 ^{b}	5.23 ^{b}	62.23 ^{a}	23.50 ^{c}
Agril		47.34 ^{a}	6.32 ^{a}	53.57 ^{b}	24.15 ^{bc}
Plant species × Growing medium					
Broccoli	Vermiculite	38.27 ^{e}	4.50 ^{ef}	8.35 ^{gh}	24.70 ^{fg}
	Peat	37.27 ^{f}	5.09 $^{c–e}$	37.62 ^{d}	23.20 ^{g}
	Perlite	39.92 ^{de}	5.03 $^{c–f}$	21.94 ^{ef}	30.75 ^{ab}
	Cotton textile	39.73 ^{de}	4.53 $^{d–f}$	17.76 ^{ef}	28.15 $^{c–e}$
	Filter paper	41.95 ^{cd}	4.57 $^{d–f}$	32.92 ^{d}	28.10 $^{c–e}$
	Agril	41.94 ^{cd}	5.46 ^{cd}	21.67 ^{ef}	29.30 $^{a–c}$
Black radish	Vermiculite	49.68 ^{b}	5.06 $^{c–f}$	3.87 ^{h}	26.40 ^{ef}
	Peat	50.50 ^{b}	4.99 $^{c–f}$	23.00 ^{e}	26.75 $^{d–f}$
	Perlite	51.64 ^{b}	4.95 $^{d–f}$	18.09 ^{ef}	28.65 $^{b–d}$
	Cotton textile	50.51 ^{b}	5.93 ^{bc}	15.36 ^{fg}	31.15 ^{a}
	Filter paper	52.52 ^{b}	6.52 ^{ab}	30.77 ^{d}	29.65 $^{a–c}$
	Agril	56.01 ^{a}	6.49 ^{ab}	16.83 ^{ef}	29.75 $^{a–c}$
Red beet	Vermiculite	37.38 ^{e}	4.12 ^{f}	127.76 ^{a}	18.35 ^{hı}
	Peat	33.29 ^{f}	4.53 $^{d–f}$	122.22 ^{ab}	15.75 ^{j}
	Perlite	37.87 ^{e}	4.53 $^{d–f}$	115.23 ^{bc}	16.55 ^{ij}
	Cotton textile	39.69 ^{de}	4.25 ^{ef}	111.74 ^{c}	19.10 ^{h}
	Filter paper	38.63 ^{e}	4.59 $^{d–f}$	122.99 ^{a}	12.70 ^{k}
	Agril	44.07 ^{c}	7.01 ^{a}	122.23 ^{ab}	13.35 ^{k}

No significant difference was observed between means sharing the same letter within the same column for each factor ($p < 0.05$).

3.3. Effects of Growing Media on Phosphorus, Potassium, Magnesium, and Calcium in Microgreens

The treatments strongly influence macronutrient uptake in microgreens. The peat-based and vermiculite media emerged as optimal substrates for phosphorus and calcium accumulation, while perlite was more effective for magnesium. Filter paper and cotton textiles excelled in supporting potassium uptake, particularly for red beet. These findings provide valuable insights into how different combinations of species and growing media can optimize the nutrient content in microgreens (Table 4).

Effect of Growing Media: The peat-based and vermiculite substrates were the most effective media for phosphorus, with the peat-based medium reaching the highest value, 43 mg 100 g^{-1} FW. Both substrates also promoted high potassium levels, with the peat-based and vermiculite media recording identical values, 192.17 mg 100 g^{-1} FW.

Perlite-grown microgreens showed a superior magnesium content, 37.73 mg 100 g^{-1} FW, compared to those grown in other media, while filter paper and cotton textile also performed well, exceeding 38 mg 100 g^{-1} FW. Peat was the best medium for calcium accumulation, 99.10 mg 100 g^{-1} FW, followed by perlite, 86.12 mg 100 g^{-1} FW. In contrast, agril and filter paper resulted in the lowest calcium concentrations.

Table 4. The effects of growing media on phosphorus, potassium, magnesium, and calcium content of the microgreens (mg 100 g^{-1} FW).

Factor		Phosphorus	Potassium	Magnesium	Calcium
Growing medium					
Vermiculite		40 ^{b}	192.13 ^{a}	32.98 ^{b}	66.22 ^{c}
Peat		43 ^{a}	192.17 ^{a}	33.88 ^{b}	99.10 ^{a}
Perlite		39 ^{b}	147.83 ^{bc}	37.73 ^{a}	86.12 ^{b}
Cotton textile		43 ^{a}	153.98 ^{b}	38.42 ^{a}	48.95 ^{d}
Filter paper		39 ^{b}	162.38 ^{b}	38.71 ^{a}	50.54 ^{d}
Agril		34 ^{c}	130.13 ^{c}	32.15 ^{b}	61.91 ^{c}
Plant species × Growing medium					
Broccoli	Vermiculite	44 $^{a–c}$	167.71 ^{d}	33.24 $^{d–g}$	116.48 ^{b}
	Peat	43 ^{c}	191.40 ^{d}	31.92 $^{e–h}$	152.62 ^{a}
	Perlite	38 ^{e}	110.23 ^{e}	31.16 $^{e–h}$	151.71 ^{a}
	Cotton textile	39 ^{de}	92.88 ^{ef}	29.64 $^{f–h}$	67.30 ^{ef}
	Filter paper	36 $^{e–g}$	63.54 ^{f}	28.61 ^{gh}	89.92 ^{cd}
	Agril	35 ^{fg}	103.11 ^{e}	26.08 ^{h}	59.67 ^{f}
Black radish	Vermiculite	38 ^{ef}	166.34 ^{d}	31.37 $^{e–h}$	59.28 ^{f}
	Peat	48 ^{a}	185.95 ^{d}	38.19 ^{cd}	77.61 ^{de}
	Perlite	45 $^{a–b}$	97.27 ^{ef}	37.02 $^{c–e}$	39.87 ^{gh}
	Cotton textile	42 ^{cd}	92.20 ^{ef}	31.03 $^{e–h}$	26.99 ^{hi}
	Filter paper	38 ^{e}	116.25 ^{e}	35.63 $^{c–f}$	39.55 ^{gh}
	Agril	37 $^{e–g}$	107.16 ^{e}	30.66 $^{f–h}$	24.94 ^{hi}
Red beet	Vermiculite	39 ^{de}	242.35 ^{bc}	34.35 $^{c–g}$	22.92 ^{i}
	Peat	38 ^{e}	199.15 ^{d}	31.55 $^{e–h}$	67.09 ^{ef}
	Perlite	33 ^{g}	235.99 ^{c}	45.02 ^{b}	66.78 ^{ef}
	Cotton textile	47 ^{ab}	276.85 ^{ab}	54.60 ^{a}	52.55 ^{fg}
	Filter paper	43 ^{bc}	307.34 ^{a}	51.89 ^{a}	22.16 ^{i}
	Agril	29 ^{h}	180.14 ^{d}	39.71 ^{bc}	101.11 ^{bc}

No significant difference was observed between means sharing the same letter within the same column for each factor ($p < 0.05$).

Interaction between Plant Species and Growing Media: Broccoli performed best in the peat-based medium in terms of its calcium uptake, 152.62 mg 100 g^{-1} FW, and in vermiculite for potassium, 167.71 mg 100 g^{-1} FW. Filter paper and agril were less effective in supporting the magnesium and potassium content of the broccoli. Black radish showed the highest phosphorus content, 48 mg 100 g^{-1} FW, in the peat-based medium, with a moderate potassium accumulation of 185.95 mg 100 g^{-1} FW. However, the calcium content was low across all of the media for black radish, with the highest value bring recorded in the peat-based medium, 77.61 mg 100 g^{-1} FW.

Red beet exhibited outstanding potassium levels when grown in filter paper, 307.34 mg 100 g^{-1} FW, and cotton textile, 276.85 mg 100 g^{-1} FW. It also accumulated the highest magnesium content, 54.60 mg 100 g^{-1} FW, in cotton textiles. However, its calcium uptake was limited, with the highest value, 66.78 mg 100 g^{-1} FW, being observed in perlite.

3.4. Effects of Media on Copper, Manganese, Iron, and Zinc in Microgreens

The results demonstrate that both the plant species and growing media significantly affect the uptake of these micronutrients (Table 5).

Effect of Growing Media: The peat-based medium was the most effective medium for copper uptake, 59.55 mg 100 g^{-1} FW, and also promoted a high iron content, 538.68 mg 100 g^{-1} FW. Filter paper resulted in the highest concentrations of manganese, 269.42 mg 100 g^{-1} FW, and zinc, 332.12 mg 100 g^{-1} FW. It also performed well in terms of iron uptake, 520.22 mg 100 g^{-1} FW. Vermiculite and agril supported a moderate micronutrient accumulation, with vermiculite yielding high iron levels, 507.98 mg 100 g^{-1} FW, and agril promoting balanced copper, 44.84 mg 100 g^{-1} FW, and manganese, 225.97 mg 100 g^{-1} FW.

Perlite showed the lowest copper levels, 14.44 mg 100 g^{-1} FW, but provided moderate zinc concentrations, 288.14 mg 100 g^{-1} FW.

Table 5. The effects of growing media on the copper, manganese, iron, and zinc contents of the microgreens (µg 100 g^{-1} FW).

Factor		Copper	Manganese	Iron	Zinc
Growing medium					
Vermiculite		26.73 ^{d}	232.18 ^{b}	507.98 ^{ab}	238.26 ^{d}
Peat		59.55 ^{a}	183.92 ^{c}	538.68 ^{a}	292.98 ^{b}
Perlite		14.44 ^{e}	194.81 ^{c}	369.58 ^{c}	288.14 ^{bc}
Cotton textile		43.67 ^{b}	220.02 ^{b}	378.71 ^{c}	270.13 ^{bc}
Filter paper		37.62 ^{c}	269.42 ^{a}	520.22 ^{a}	332.12 ^{a}
Agril		44.84 ^{b}	225.97 ^{b}	445.74 ^{b}	257.00 ^{cd}
Plant species × Growing medium					
Broccoli	Vermiculite	23.94 ^{f}	196.08 ^{e}	704.52 ^{ab}	254.22 $^{d–h}$
	Peat	11.40 $^{h–j}$	150.48 ^{fg}	589.38 ^{cd}	255.36 $^{d–h}$
	Perlite	10.26 ^{ij}	125.40 $^{g–j}$	489.06 $^{d–f}$	279.30 $^{c–f}$
	Cotton textile	18.23 $^{f–h}$	127.68 $^{g–j}$	420.66 $^{e–i}$	272.46 $^{c–h}$
	Filter paper	9.08 ^{j}	121.98 $^{g–j}$	454.86 $^{e–h}$	297.54 $^{b–e}$
	Agril	45.60 ^{d}	98.80 ^{j}	478.80 $^{e–g}$	243.20 $^{f–h}$
Black radish	Vermiculite	18.24 $^{f–h}$	140.22 ^{gh}	441.18 $^{e–h}$	218.88 ^{h}
	Peat	16.78 $^{f–i}$	173.28 ^{ef}	395.26 $^{f–k}$	318.06 ^{bc}
	Perlite	19.38 ^{fg}	108.3	324.90 $^{i–k}$	337.44 ^{b}
	Cotton textile	20.51 ^{fg}	115.14 $^{h–j}$	309.84 ^{jk}	264.48 $^{c–h}$
	Filter paper	17.15 $^{f–i}$	148.20 ^{fg}	353.40 $^{h–k}$	247.38 $^{e–h}$
	Agril	9.12 ^{j}	133.38 $^{g–i}$	348.84 $^{h–k}$	224.58 ^{gh}
Red beet	Vermiculite	38.00 ^{e}	360.24 ^{c}	378.24 $^{g–k}$	241.68 $^{f–h}$
	Peat	150.48 ^{a}	228.00 ^{d}	631.42 ^{bc}	305.52 $^{b–d}$
	Perlite	13.69 $^{g–j}$	350.74 ^{c}	294.80 ^{k}	247.68 $^{e–h}$
	Cotton textile	92.26 ^{b}	417.24 ^{b}	405.62 $^{e–j}$	273.45 $^{c–g}$
	Filter paper	86.64 ^{bc}	538.08 ^{a}	752.40 ^{a}	451.44 ^{a}
	Agril	79.80 ^{c}	445.74 ^{b}	509.58 ^{de}	303.24 $^{b–d}$

No significant difference was observed between means sharing the same letter within the same column for each factor ($p < 0.05$).

Interaction between Plant Species and Growing Media: Broccoli accumulated the highest iron levels in vermiculite, 704.52 mg 100 g^{-1} FW, and the peat-based medium, 589.38 mg 100 g^{-1} FW. However, agril was less effective for micronutrient uptake, particularly for manganese, 98.80 mg 100 g^{-1} FW. Black radish showed moderate copper levels across all media, with the peat-based medium yielding the highest zinc concentration, 318.06 mg 100 g^{-1} FW. However, agril produced relatively low iron and zinc levels for black radish. Red beet exhibited an outstanding micronutrient accumulation. Filter paper promoted the highest manganese, 538.08 mg 100 g^{-1} FW, and zinc, 451.44 mg 100 g^{-1} FW, levels, while the peat-based medium provided the highest copper content, 150.48 mg 100 g^{-1} FW. However, perlite was the least effective medium for iron uptake, with only 294.80 mg 100 g^{-1} FW.

4. Discussion

Plant quality parameters and yield are crucial in microgreen cultivation. Since the choice of growing medium significantly affects these quality parameters, gaining new insights in this area is essential. Identifying the most suitable growing media will benefit those involved in microgreen cultivation.

Our results demonstrated that vermiculite produced the highest yield across the microgreens examined, particularly for broccoli (0.96 g m^{-2}), followed by black radish and red beet. In comparison, Xiao et al. [16] reported yields in *Brassicaceae* microgreens ranging

between 0.7 and 1.2 g m^{-2}, depending on the species and environmental conditions. This indicates that our results align with the upper yield range for broccoli but show an enhanced productivity compared to black radish and red beet grown in vermiculite. Moreover, Mohanty et al. [17] highlighted that yield varies significantly with substrate choice, with vermiculite demonstrating a 15–20% higher yield than peat-based substrates in leafy vegetables. In our study, vermiculite increased the yield by 10–18% compared to the peat-based medium, further supporting its effectiveness as a growing medium. Di Gioia et al. [7] found that the peat-based medium yielded the highest production of *Brassica rapa* microgreens; however, our findings suggest that vermiculite offers a superior performance for black radish and red beet, likely due to its higher water retention and nutrient adsorption capacity.

These comparisons underscore the importance of selecting an appropriate growing medium and the right nutrient solution application schedule to optimize the yield of specific microgreen species. The nuanced differences in performance between the vermiculite and peat-based medium emphasize the novelty of our study by providing species-specific recommendations, which previous studies have not addressed in depth.

The data reveal significant variations in SPAD–chlorophyll, dry matter ratio, total phenols, and total flavonoids among plant species and growing media. Black radish generally showed a strong performance regarding chlorophyll content and total phenols, while agril provided the highest values for most parameters. Black radish microgreens typically exhibited higher protein and vitamin C levels than broccoli and red beet microgreens, especially in specific media such as filter paper and agril. Additionally, the protein content of the microgreens varied significantly depending on the plant species and growing medium used [16,18,19].

According to the nutrient content of the microgreens, Klasmann Potground P20 includes a starter fertilizer that provides essential nutrients to support the initial growth phase of plants. Its composition typically contains a balanced mix of nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), along with essential trace elements. This nutrient content may improve nutrient availability and support optimal microgreen development [20,21]. Vermiculite also supplies magnesium (Mg), calcium (Ca), and iron (Fe), which are beneficial for nutrient-demanding plants. Perlite contains potassium (K) and calcium (Ca). In contrast, agril, cotton textile, and filter paper generally do not provide significant mineral nutrients to plants. Overall, the choice of growing medium significantly impacts the nutrient profile of microgreens, with each medium optimizing different nutrient contents based on the type of microgreens. These results suggest that plant species, growing medium, and the nutrient solution supplied by the growing media play crucial roles in determining microgreens' nutritional and biochemical characteristics.

Our results reveal that growing microgreens in vermiculite significantly affects plant height, hypocotyl length, stem diameter, single plant weight, and overall yield. Vermiculite, a phyllosilicate mineral resulting from the hydrothermal alteration of mica minerals such as biotite and phlogopite, is lightweight and resistant to thermal decomposition [22]. It has a low bulk density, conductivity, and specific surface area but exhibits a high total porosity and cation exchange capacity. It is richer in calcium and sulfur and demonstrates superior adsorption capacities for NH_4^+, NO_3^-, PO_4^{3-}, and K^+ ions [23]. Vermiculite's high water retention capacity, sterility, and nutrient holding properties contribute to its effectiveness in promoting plant growth. These characteristics support healthy root development, improved physiological parameters, and ultimately higher yields, as observed in this study [24].

These results suggest that plant species and growing medium play crucial roles in determining microgreens' quality and biochemical profile. Similar findings were reported by Xiao et al. [16], who demonstrated that the growing medium significantly affects microgreens' phenolic and flavonoid content, especially in Brassicaceae species. Our results align with these observations, as the highest phenolic content was obtained in broccoli microgreens grown in perlite; however, it is essential to note that the total phenolic yield

also depends on the biomass production of the substrate, highlighting the trade-off between concentration and total yield.

Microgreens grown in vermiculite had a significantly improved plant height, hypocotyl length, stem diameter, single plant weight, and yield, which aligns with the findings of Tang et al. [23], who reported superior plant growth parameters in vermiculite due to its high cation exchange capacity and water retention properties. Furthermore, our results indicate that vermiculite promoted better root development and nutrient absorption, consistent with Mohanty et al. [17], who found similar benefits of vermiculite for early-stage vegetable crops.

While previous studies, such as those by Di Gioia et al. [25], highlighted peat-based medium as a favorable growing medium for enhancing phenolic content in microgreens, our findings suggest that vermiculite outperformed peat-based in plant growth parameters. This underscores the importance of optimizing growth conditions based on the specific plant species, the interaction between the growing medium, and other factors, such as irrigation schedules tailored to the substrate's properties. Furthermore, we should exercise caution because most studies utilize a peat-based substrate rather than direct peat, making direct comparisons very challenging. And even for peat-based substrates, there are different variations depending on the age of the peat used.

In this study, broccoli microgreens exhibited a phenolic content of 169.96 mg GA 100 g FW^{-1}, higher than the black radish and red beet microgreens. This finding aligns with the results of Xiao et al. [16], who reported a total phenolic content in *Brassicaceae* microgreens ranging from 88.6 mg GA 100 g FW^{-1} to 811.2 mg GA 100 g FW^{-1}. Phenolic compounds, the most abundant group of secondary metabolites, are present in nearly all fruits and vegetables and are derived from the phenylpropanoid biosynthesis pathway. These compounds play a crucial role in plant defense mechanisms and contribute significantly to edible plants' nutritional and antioxidant properties [26,27]. Furthermore, the red beet microgreens demonstrated a flavonoid content of 120.36 mg RU 100 g^{-1}, surpassing the broccoli and black radish microgreens (Table 3). These results highlight the variability in phenolic and flavonoid contents among microgreen species, further emphasizing their potential role in enhancing dietary antioxidant intake.

Microgreens grown in the agril growing medium exhibited the highest levels of chlorophyll (47.34 SPAD–chlorophyll) and dry matter content (6.32%) (Table 3). The agril medium may have provided an optimal balance of water retention, drainage, and nutrient availability, creating favorable conditions for plant growth. Additionally, the physical properties of the agril medium might have facilitated more efficient photosynthetic activity, leading to higher chlorophyll levels and dry matter accumulation. Microgreens grown in peat-based, filter paper, and agril media had higher total flavonoids than others. Toscano et al. [28] noted that defensive flavonoids (e.g., anthocyanins) are costly for plants, and their accumulation often reduces plant growth. To survive, plants develop a range of reversible or irreversible responses to various abiotic environmental factors they perceive as stressors. These responses vary depending on the severity of the stress factor and the plant's genetic and developmental characteristics. Through these stress responses, plants adapt to environmental factors to ensure their survival [29]. In a plant's natural habitat, any change in growth conditions that disrupts metabolic homeostasis can be considered a stressor [30]. In this study, we did not detect any specific stress factors in the plants. However, their cultivation under LED lights, in different growing media, and within a growth chamber, compared to sunlight and soil conditions, might have contributed to the increase in flavonoid content.

According to the study conducted by Nakhel et al. [31], it has been demonstrated that microgreens can be cultivated on a commercial peat-based substrate without nutrient supplementation, and this approach may be suitable for certain species. Additionally, this condition has been shown to increase biologically active secondary metabolites, depending on the species. Similarly, we observed some metabolic increases in the peat-based substrate. It should be noted that, in our study, a peat-based substrate was used. Its main components include 20% TerrAktiv®, a high-quality compost that enhances the substrate's biological

activity; 10% GreenFibre®, wood fibers that improve the substrate's structure and air capacity; frozen black peat that provides a stable structure and good water retention; and white peat that helps with water absorption and retention [32,33]. However, a peat-based medium is not recommended from an environmental and climate change perspective, so alternative substrates should be considered [9,34]. Kyriacou et al. [4] identified cellulose sponge as the substrate providing the highest ascorbate content in pak choi microgreens. We observed a similar pattern with fiber-based growing media, showing a higher vitamin C content than other growth environments.

We observed that the microgreens grown in a peat-based medium had a higher calcium content (99.10 mg kg^{-1}) than those grown in other media. A similar result was obtained in a study by Di Gioia et al. [25], where a peat-based substrate had the highest $NO3^{-}$, PO_4^{2-}, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^{-} contents. We suppose that this is an effect of the initial fertilizer used in the peat-based substrates. Jute-kenaf fiber mats promoted the highest K^{+}, Cl^{-}, and Na^{+} concentrations, similar to peat-based substrates [35]. As noted by Mohanty et al. [17], the elemental composition of microgreens varies across different stages in various growing media. Similarly, our study also observed that different growth environments significantly impact the elemental composition of microgreens.

5. Conclusions

This study evaluated the impact of six different growing media on microgreen production. Our results identified vermiculite as the most effective medium for maximizing yield in broccoli microgreens, while a peat-based medium proved to be optimal for black radish and red beet. The findings highlight that the effectiveness of growing media varies by plant species, underscoring the importance of selecting the appropriate medium and fertigation to optimize growth and nutritional quality. The results demonstrate that the ideal growing medium should align with the specific plant species and desired product characteristics, emphasizing the need for a tailored approach to microgreen cultivation. Producers should carefully consider the plant type and target product attributes when selecting a growing medium to achieve high-quality production. Given the limited research in this field, further studies are needed to deepen our understanding and develop more comprehensive guidelines for optimizing microgreen production.

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