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Nutritional quality and health benefits of microgreens, a crop of modern agriculture

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ABSTRACT

Microgreens are young, tender greens that are used to enhance the color, texture, or flavor of salads and main dishes. They can be grown in small scales and indoors, making them widely adopted by controlled environment agriculture, an indoor farming practice is particularly important for feeding increasing urban populations. Besides, microgreens are attracting more consumers' attention due to their high nutritional value and unique sensory characteristics. This review focuses on the nutrition quality, sensory evaluation, pre- and post-harvest interventions, and health benefits of microgreens. Microgreens are rich in vitamins (e.g., VC), minerals (e.g., copper and zinc), and phytochemicals, including carotenoids and phenolic compounds, which act as antioxidants in human body. Pre-harvest interventions, such as illumination, salinity stress, nutrient fortification, and natural substrates, influence the photosynthetic and metabolic activities of microgreens and were shown to improve their nutritional quality, while the effects varied among species. After harvesting, packaging method and storage temperature can influence the nutrient retention in microgreens. Both *in vitro* and *in vivo* studies have shown that microgreens have anti-inflammatory, anti-cancer, anti-bacterial, and anti-hyperglycemia properties, making it a new functional food beneficial to human health. The sensory attributes and overall acceptability and liking of microgreens are primarily influenced by their phytochemical content. Microgreens are only getting popular during the last decades and research on microgreens is still at its early stage. More studies are warranted to optimize the pre- and post-harvest practices for nutrient enhancement and retention and to explore the potential health benefits of different microgreens for the prevention and treatment of chronic diseases.

1. Introduction

With the global urban population boom, there is a huge and growing demand for a more sustainable, accessible, and nutritious food supply. Urban farming, especially controlled environment agriculture (e.g., vertical farms, greenhouses, hydroponics, aquaponics, etc.), has grabbed the attention of both government and private sectors [1]. In controlled environmental agriculture practice, the crops are grown in an enclosed space where climate, lighting, and irrigation can be controlled, optimized, and even automated by the help of data analytics and machine learning. Besides, this indoor farming can be more accessible for urban dwellers and more environmentally friendly (e.g., less water usage and soil depletion). Despite the promises of controlled environment agriculture, nowadays, it is still at its early stage and applicable to limited agricultural commodities. Microgreens are among the most adopted crops of controlled environment agriculture, as they can easily be grown hydroponically (the most prevalent indoor farming method) or in soil.

Microgreens are immature vegetable greens harvested after cotyledonary leaves are developed (Fig. 1). Microgreens were produced in Southern California since 1990s and they have gained

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increased popularity due to their fresh taste and nutritional benefits over the past decade [2]. Microgreens can be considered as better substitutes for sprouts due to their rich nutritional content and more intense flavor and taste [3]. In addition, microgreens may contain a higher amount of phytochemicals, minerals, and vitamins in comparison to their mature counterparts [4,5]. Therefore, incorporating microgreens into diets may improve the nutritional quality and contribute to better health outcomes for consumers. However, microgreens also have presented many challenges to the growers and the supply chain because microgreens are extremely delicate and usually have a short shelf life [3]. In order to extend the shelf life of microgreens and improve their nutritional quality, several pre- and post-interventions have been investigated [6]. Overall, since microgreens are relatively new specialty commodities, the research in their nutritional quality and health benefits is also at dawn.

This review article is dedicated to gathering recent research findings on the determination of nutrient compositions and health benefits of various microgreens. Additionally, the effect of pre- and post-harvest interventions on the nutritional quality and the effect of sensory attributes on consumer acceptability of the microgreens are also discussed.

Fig. 1 Photos of various microgreens taken in the Nutrition and Metabolism Research Lab at the University of Alabama, USA.

2. Nutrient contents

The abundance of bioactive compounds in microgreens, including vitamins, minerals, and phytochemicals, has been examined in many research studies. Researchers have been particularly interested in analyzing antioxidants that neutralize free radicals and help prevent damage caused by oxidative stress, such as vitamin C (VC), phytochemicals (e.g., carotenoids and phenolics), and certain minerals, including copper (Cu), zinc (Zn), and selenium (Se). There have been comparisons of antioxidant contents and capacity between microgreens and their mature counterparts [7,8]. Several microgreens showed higher concentrations of antioxidants, but the results were not generalizable [4,9].

VC, also known as ascorbic acid, is a potent antioxidant and is essential for a variety of biological functions, such as wound healing, collagen synthesis, and immune system regulation [10]. Vegetables are rich sources of VC and thus many researchers determined VC content in various microgreens [5,11]. For instance, Yadav et al. [4] measured VC contents in 9 microgreens and found that jute (*Corchoris olitorisu* L.) and cucumber (*Cucumis sativus* L.) microgreens had higher VC (25 mg/100 g fresh weight (FW) and 34.90 mg/100 g FW, respectively) as compared to their mature stages (17.45 mg/100 g FW and 10.00 mg/100 g FW, respectively). The VC content was similar in the microgreen and mature stages of water spinach. For other species, including Amaranthus (*Amarnthus tricolor* L.), bottle gourd (*Lagenaria siceraria* Standl), palak (*Beta vulgaris* L. var. *bengalensis* Roxb), pumpik (*Cucurbita moschata* Duchesne), and radish (*Raphanus raphanistrum*), their mature plants showed higher VC as compared to the microgreen stage. Di Bella et al. [9] noted a significantly higher VC content in the microgreen stage of traditional Sicilian broccoli (7.5 mg/g) as compared to its baby green stage (6.1 mg/g) ($P < 0.05$). A similar result was found by Ghoora et al. [12], in which a 120%, 127%, and 119% higher VC content was found in microgreen stages of fenugreek (*Trigonella foenum-graecum* L.), spinach (*Spinacia oleraceae* L. var.), and roselle (*Hibiscus sabdariffa* L.) as compared to their mature stage ($P \leq 0.05$). The VC contents in 10 commercially available microgreens ranged from 29.9–123.2 mg/100 g FW [12], which is comparable to citrus fruits [13], a well-known food source of VC. Xiao et al. [5] reported a range of total VC contents (20.4–147.0 mg/100g FW) in 25 commercially available microgreens and claimed many had higher total VC concentration than their mature plants. As microgreens are usually consumed fresh, VC can be largely retained without cooking [4,14].

Several trace minerals, i.e., Cu, Zn and Se, as cofactors or components of antioxidant enzyme (such as superoxidase dismutase), play an essential role in the endogenous antioxidant defense system of human body, and are therefore referred to as antioxidant minerals [15]. Inadequate intake of antioxidant minerals in the diet can reduce the activity of antioxidant enzyme [16]. These antioxidant minerals, among other minerals, have been routinely analyzed in microgreen samples and compared with their mature plants [2,7,17]. For example, Yadav et al. [4] found a significantly higher Zn concentration ($P < 0.01$) in the microgreen stage of 9 summer season leafy greens (range from 4.76 mg/kg FW to 29.12 mg/kg FW) than that of their mature stage (range from 1.23 mg/kg FW to 5.50 mg/kg FW). Bottle gourd and water spinach contained higher Cu concentration at their microgreen stage as compared to the mature stage [4]. Waterland et al. [18] assessed the mineral contents of cultivars of kale (*Brassica oleracea*) at the stage of microgreen, baby leaf, and adult, showing significantly higher contents of Zn and Cu in microgreens compared to their relative adult stage ($P < 0.05$). Butkute et al. [19] studied the mineral contents of *Trifolium pratense*, *T. medium*, *Medicago sativa*, *M. lupulina*, *Onobrychis viciifolia*, *Astragalus glycyphyllos*, and *A. cicer* legumes at seeds, sprouted seeds, and microgreen stages. Compared with raw seeds and sprout seeds of these small legumes, microgreens showed 0.6- to 3.2-fold higher Zn content, leading to significantly improved nutritional profiles in mineral composition [19].

Phytochemicals, such as carotenoids and phenolics, are also found in abundance in microgreens. Carotenoids are a group of lipophilic plant pigments showing yellow, orange, and red color, including carotenes (e.g., β-carotene and lycopene) and xanthophylls (e.g., lutein and zeaxanthin) [20]. Carotenoids possess antioxidant activity and play important physiological roles in human body [21]. Vegetables, especially bright colored ones, can be major dietary sources of carotenoids [22]. Niroula et al. [23] studied the carotenoid profile of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) microgreen and found that the carotenoid content in the microgreen phase was higher than that in the seed phase. After 16 days of sowing, the carotenoid content of wheat increased from 0.42 mg/100 g dry weight (DW) to 53.36 mg/100 g DW, while that of barley increased from 0.78 mg/100 g DW to 56.08 mg/100 g DW [23]. Phenolic compounds are the most abundant secondary metabolites of plants ranging from small molecules, e.g., phenolic acids, to flavonoids with multiple rings, and to highly polymerized compounds, e.g., tannins [24]. Phenolics are antioxidants for plants to repair damage caused by free radicals and have shown many health benefits for human [24]. Sun et al. [25] identified 164 polyphenols, including 30 anthocyanins, 105 flavanol glycosides, and 29 hydroxycinnamic acids, in the 5 *Brassica* species microgreens. Microgreens have more complex polyphenol profiles and higher contents than mature *Brassica* plants [26], making them good sources of antioxidants.

The antioxidant contents of microgreens vary among species. Lenzi et al. [2] investigated the mineral contents in small burnet (*Sanguisorba minor*), wild mustard (*Sinapis arvensis* L.), and common dandelion (*Taraxacum officinale* Weber ex F.H. Wigg) and significant higher Zn contents were found in small burnet, and higher Se concentrations were present in small burnet and common dandelion, respectively. Xiao et al. [17] compared the mineral contents in 30 varieties of Brassicaceae and found that the highest contents of Zn were present in rapini microgreens while lower contents were found in red kale, red mustard, Chinses cabbage, and ruby radish microgreens. Kyriacou et al. [27] investigated the phytochemicals in coriander (*Coriandrum sativum* L.), Brassicaceae microgreens including cress, kohlrabi, komatsuna, mibuna, mustard, pak choi, radish, and tatsoi, green and purple basil (Lamiaceae), jute (Malvaceae), and Swiss chard (Chenopodiaceae), noting a higher content of total chlorophyll in pak choi and tatsoi compared to other species. Lutein in mustard was as low as 193.5 mg/kg FW, while the concentration was 827.9 mg/kg FW in jute. Kohlrabi contains 426.1 mg/kg FW of β-carotene, while the number was 8 592.2 mg/kg FW in green basil. Lenzi et al. [2] noted that total anthocyanins concentration was the highest in wild mustard (0.19 mg/g FW) compared to small burnet and common dandelion (0.13 and 0.13 mg/g FW, respectively). In 5 microgreens of the Brassicaceae family, mustard contained significantly higher anthocyanins (405.53 μg/g FW) than broccoli, daikon, watercress, and rocket salad at 172.51, 57.56, 52.29, and 42.26 μg/g FW, respectively [28]. However, it was found that broccoli had the highest total polyphenol content (3.63 μg/g FW) among those 5 microgreens, while mustard had the lowest total polyphenol content (1.02 μg/g FW) [28]. Xiao et al. [5] measured the carotenoid contents of 25 commercially grown microgreens. It was noted that red sorrel (*Rumex acetosa* L.), cilantro (*Coriandrum sativum* L.), red cabbage (*Brassica oleracea* L. var. *capitata f. rubra*), and peppercress (*Lepidium bonariense* L.) microgreens were good sources of β-carotene (12.1, 11.7, 11.5, and 11.1 mg/100 g FW, respectively), while cilantro, red sorrel, red cabbage, and garnet amaranth microgreens had a higher concentration of lutein/zeaxanthin compared to other microgreens (10.1, 8.8, 8.6, and 8.4 mg/100 g FW, respectively). Genotypes of microgreens, including the variation of photosynthetic and metabolic activities of microgreens, may be the main factors leading to difference in bioactive compounds in microgreens [23].

While individual nutrients and phytochemicals are evaluated, some efforts were attempted to assess the overall nutritional quality of microgreens. For example, Renna et al. [29] evaluated the Nutrient Quality Score (NQS), the overall nutritional quality of foods calculated by the sum contents of protein, dietary fiber, micronutrients (VA and VE), and minerals (Ca, Mg, K, Mn, Fe, Cu, and Zn) of *Brassica* microgreens cauliflower, broccoli, and broccoli raab microgreens are grown with nutrient solutions. It was found that microgreen cauliflower showed six-fold higher NQS than its mature stage, mainly due to the higher level of VA, VE, and carotenoids content in the microgreen stage [29].

3. Pre-harvest interventions

Pre- and post-harvest interventions of microgreens have been shown to influence the nutritional quality of microgreens. Generally, preharvest interventions aim to increase yield, eliminate the pathogen, and minimize safety hazards. Several preharvest intervention strategies have been applied to enhancing the nutritional value of microgreens. The illumination treatment to microgreen could effectively stimulate seed germination and affect the biosynthesis of microgreen [30,31]. Mlinarić et al. [32] compared the nutrients contents of chia microgreens under a dark room or constant light (100 μmol photons/m^2·s) and noted a significantly higher carotenoid, chlorophyll, and ascorbic acid level in the light treatment group. Red light (663 nm and 642 nm) stimulates the formation of the red absorption and far-red absorption forms of photosensitive pigment in plant photosensitive pigment receptors, which are responsible for plant growth, including germination, stem elongation, leaf expansion, and flowering [33]. Cryptochrome and plant hormones regulate phototropism, endogenous, and redox balance in microgreen plants by sensing red light [34]. Therefore, light exposure before harvest is one of the most important interventions for nutrients accumulation and growth of plants.

Compared with high-pressure sodium (HPS) light, traditional light treatment for improving the biomass of microgreens, LED treatment has a narrower spectrum, lower electrical consumption and light exothermal, and adjustable photosynthetic photon flux density [35]. In addition, the spectral composition of HPS lamps is mainly in the yellow-orange-red region, which may not have a beneficial effect on the photophysiological process of plants [35]. The supplementation of red LED light +HPS light increased the phenolic content, α-tocopherol, and lutein, and β-carotene by 36.7%, 18.6%, 48.8%, and 47.9% in basil (*Ocimum basilicum* L.) ($P < 0.05$), respectively, as compared to those solely under HPS light [36]. Kopsell et al. [37] revealed a significantly higher concentration of β-carotene, lutein, and neoxanthin in the LED treatment groups as compared to the fluorescent/incandescent light group.

Red and blue lights are the primary LEDs involved in stimulating the growth and accumulation of vitamins, antioxidants, and minerals in microgreens. These LEDs are mainly absorbed by chlorophyll pigments [38], thus play a vital role in regulating endogenous rhythms of plants and promoting the opening of light-induced stomata through photosensitive pigment receptors and phytotropins [39]. Secondary metabolites, such as carotenoids and other phytochemicals, are accumulated in microgreens under excessive photooxidation and stress environments [40]. Samuolienė et al. [41] noted a dose-dependent higher concentrations of carotenoids in beet (*Beta vulgaris* L.), mustard (*Brassica juncea* L.), and parsley (*Petroselinum crispum* Mill.), respectively, after 10 to 14 days of continuous LEDs exposure with 16% to 33% blue light. Blue lights may also increase the contents of macrominerals (i.e., phosphorus, potassium, magnesium, calcium, and sulfur), trace minerals (i.e., boron, copper, iron, manganese, molybdenum, sodium, and zinc), and glucosinolates in microgreens [42]. Total phenolic contents and total flavonoid contents were enhanced under blue and ultraviolet-A (UV-A) lights [43]. The combination of red and blue LEDs may increase the concentration of chlorophyll a, chlorophyll b, total phenolic contents, and anthocyanin content in various microgreens as compared to sole red and sole blue treatments [44]. The ratio of blue to red at 20% to 80% may be effective in increasing the overall nutritional profiles (e.g., total carotenoid and antioxidant minerals) in microgreens as compared to other ratios of LEDs [45-47]. It is worth noting that although red light is the primary wavelength involved in photosynthesis, too much red light can lead to "red light syndrome", which manifests microgreens in poor morphology and faulty gene expression. The combination of red light and other light sources, especially blue light, can effectively regulate stomatal opening and improve the carbon dioxide acquisition of plants, thereby preventing the generation of "red light syndrome" [48,49].

Higher levels of photosynthetically photon flux density may induce the accumulation of phenolic compounds and other antioxidants [50]. For example, Loedolff et al. [51] found that the radish and kale microgreens under high light intensity (270 μmol/m^2·s) had a significantly 1.7- and 2.5-fold higher antioxidant capacity than that of samples grown under normal light (70 μmol/m^2·s), mainly due to the diversified phytochemicals, including coumarin, proanthocyanins, and flavonoids that were induced by high light intensity. However, the effect of high light intensity was not consistent on improving the nutritional profiles [52] and may vary by species [50]. Furthermore, higher light intensity stimulates the xanthophyll cycle, which helps microgreens fight oxidative stress induced by light stress. In xanthophyll cycle, the occurrence of de-epoxidation reaction happens, leading to the conversion of violaxanthin (i.e., epoxidized xanthophylls) to zeaxanthin (i.e., de-epoxidized xanthophyll) through antheraxanthin to promote the dissipation of light energy [53]. Kopsell et al. [54] found that violaxanthin concentration of mustard microgreens was 1.2 fold lower after the exposure of 36 h pre-harvest high-intensity light (463 μmol/m^2·s) as compared to the control group (275 μmol/m^2·s), while the lutein and antheraxanthin concentration was significantly increased by 2.3 and 1.5 fold, respectively. Brazaitytė et al. [55] also found an increased lutein and zeaxanthin concentration under 330–440 μmol/m^2·s as compared to 220 μmol/m^2·s (Control group) in mustard. Given that zeaxanthin and lutein are macular pigments and act as potent antioxidants [56], increasing zeaxanthin and lutein are beneficial for the protection against eye diseases caused by free radicals.

As antioxidants, carotenoids, phenolic compounds, and some minerals in microgreens can scavenge free-radicals and protect against diseases that are induced by high oxidative stress [57]. The antioxidant capacity of microgreens has been reported to be influenced by light spectrum and light density. Lobiuc et al. [46] showed a significantly higher antioxidant capacity in the green basil after exposure under 2:1 of red:blue LED treatment for 17 days than that of the white light group. Microgreens exposed under UV-A light showed a significantly higher free radial scavenging capacity and ferric reducing antioxidant power as compared to white light and other LED treatments (i.e., red, far-red, green and blue), mainly due to the improvement of total phenolic and flavonoid content induced by UV-A light [43]. Loedolff et al. [51] found that radish and kale microgreens under the exposure of high light intensity showed a significantly 1.7- and 2.5-fold higher total antioxidant capacity as compared to those under low light density (70 μmol/m^2·s). Samuolienė et al. [50] found that under light exposure of combined LEDs treatments (B+R+FR), microgreens under 330–440 μmol/m^2·s irradiation showed higher antioxidant capacity, and a positive correlation between antioxidant capacity and ascorbic acid and β-carotene was noted in basil and parsley microgreens. Vaštakaitė et al. [58] found that red pak choi (*Brassica rapa* var. *chinensis*) and tatsoi (*Brassica rapa* var. *rosularis*) microgreens showed 12%–42% and 40%–60% higher antiradical activity under the blue LEDs at 2 and 32 Hz as compared to the 0 Hz treatment.

The effects of monochromatic LED and the combination of LEDs on the nutrient accumulation in microgreens vary and are dependent on microgreen species. Ying et al. [59] studied the effects of different blue to red light ratios on phytochemical profile ratio in arugula (*Eruca sativa* L.), "Red Russian" kale (*Brassica napus* L. subsp. *napus* var. *pabularia*), mustard, and red cabbage microgreens and found that 30% blue/70% red increased total anthocyanin level in all microgreens except mustard as compared to 5% blue/95% red light group, and this treatment increased the total phenolic contents in kale and mustard but not in other microgreens [59]. The VC content was increased in arugula, "Red Russian" kale, and mustard microgreens under 20% blue/80% red treatment [59]. Samuolienė et al. [41] investigated the effect of 8%, 16%, 25%, and 33% of supplemental blue light on the accumulation of carotenoids and tocopherol in beet, mustard, and parsley for 10 to 14 days, and noted that mustard and parsley microgreens had the highest total tocopherol content at 16% blue light, while beet microgreens had the highest total tocopherol content at 33% blue light [45]. Therefore, more studies are needed to determine the regulatory mechanism of secondary metabolites during environmental stress and the appropriate treatment to enhance the nutrient quality of various genotypes of microgreens. Red amaranth microgreens accumulated more VC content under the exposure of blue LEDs and more carotenoids and anthocyanin content under red plus blue LEDs, whereas the same effects were not observed in green leafy anthocyanin microgreens [60].

In addition to applying various illumination treatments, other pre-harvest interventions have been investigated. Approaches, including salinity stress, nutrient fortification, and natural substrates, were found to be effective in increasing the nutrient and antioxidant contents in microgreens. For example, Islam et al. [61] treated wheat microgreens with different concentrations of NaCl (0, 12.5, 25, 50, and 100 mmol/L), and noted that the treatment of 12.5 mmol/L improved total chlorophyll, β-carotene, phenolic acid, flavonoids, VC, and sodium contents by 1.48, 4.65, 1.06, 1.22, 1.17, and 2.5 times, respectively, as compared to those in the control group (0 mmol/L NaCl). A significant increase of anthocyanin was noted in wheat microgreens under 25 mmol/L NaCl group compared to the control group and other treatment groups (P < 0.01). Besides sodium stress, Islam et al. [62] treated white winter wheat with Se biofortification for 10 days, which was shown to significantly increase the level of Se, phenolic compounds, flavonoids, VC, and anthocyanin in wheat microgreens. Similarly, Pannico et al. [63] treated coriander, green and purple basil, and tatsoi with 0, 8, and 16 μmol/L of Se for 12 days, and found that Se contents were improved by 480, 158, 37, and 1 237.5 fold in coriander, green basil, purple basil, and tatsoi microgreens, respectively, under the treatment of 16 μmol/L of Se. Lutein content in green basil and purple basil microgreens, and beta carotene content in coriander microgreens were both improved with 8 μmol/L of Se fortification as compared to the control group [63]. Li et al. [64] treated 10 species of microgreen seeds using a water-soluble fertilizer containing macronutrients (i.e., phosphorus, potassium, and nitrogen), and micronutrients (i.e., iron, magnesium, boron, copper, and molybdenum) for 4 days after planting, and noted a significantly 1.1- and 1.8-fold higher antioxidant minerals Zn and Cu as compared to the unfertilized group. Moreover, Kyriacou et al. [65] noted that microgreens grown in natural peat moss medium had a significantly higher level of phosphorus, potassium, calcium, and sulfur content as compared to synthetic substrates (i.e., capillary mat and cellulose sponge). El-Nakhel et al. [66] fertigated three *Brassica* L. microgreens, including Brussels sprouts, cabbage, and rocket microgreens, with the combination of peat-based medium and nutrient solution, found that total chlorophyll, lutein and β-carotene contents were increased in Brussels sprouts and cabbage microgreens with both peat-based medium and nutritional solution. No strengthening effect of nutritional fortification on rocket microgreens was noted, suggesting that the response to nutritional fortification may depend on the genotype of microgreens [66]. Also, kohlrabi and coriander microgreens grown on peat moss showed the highest phenolic content and ascorbate content, respectively, as compared to those on synthetic fiber substrates [65]. Luang-In et al. [67] treated the seed of Thai-rat-tailed radish microgreens under cold plasma (air plasma, voltage: 21 kV, supplied current: 0.53 mA) for 5 min and then germinated on vermiculite with sprayed water, $CaCl_2$ or NaCl solutions. It was found that compared to the control group, a 1.3- and 1.24-fold higher total isothiocyanates were noted in microgreens treated with cold plasma + NaCl and plasma, respectively, and a 1.1- and 1.1-fold higher total phenolic contents in plasma and plasma + $CaCl_2$ group.

Therefore, several pre-harvest treatments showed the effect on improving the micronutrients, minerals, and phytochemicals of microgreens, which increase their potential as functional foods. The effect of light illumination depends on microgreens species, which shed light for further studies to investigate the impact of microgreens varieties on the effectiveness of treatment.

4. Post-harvest interventions

Post-harvest interventions, e.g., chlorine wash, ozone wash, coating, and modified atmosphere packaging, are usually employed to ensure the safety and extend the shelf life of microgreens since they are fragile and highly perishable products [68,69]. Some of these post-harvest treatments also influenced the nutritional quality of the microgreens. For example, packaging method, storage temperature, and lighting have an impact on the nutrients' composition and concentration in plants. Preservation at low temperatures, i.e., 4 °C, has been shown to be an effective way to maintain and/or improve nutrient contents of microgreens [70]. Rocchetti et al. [71] found that red beet and Amaranth stored at 4 °C for 10 days showed increased total phenolic and β-carotene contents, as well as the antioxidant capacity as compared to the fresh group. As the microgreens were not watered during the 10 days storage, abiotic stress may stimulate the phenylpropanoid/shikimate biosynthetic pathway and upregulate enzymes involved in the process, thus increasing polyphenols concentration in microgreens [72,73]. Xiao et al. [74] found that after 16 days of exposure to light, radish microgreen showed increased ascorbic acid level and antioxidant capacity compared with samples stored in the dark. Supapvanich et al. [75] soaked sunflower sprouts, daikon sprouts, and red amaranth microgreens with low dose (0.1 μmol/L) of cyanocobalamin (vitamin B_{12}), and noted a significantly higher total phenols, flavonoid, and ascorbic acid content compared to the control group (soaking in water) after 9 days of storage. Dalal et al. [76] investigated the effects of ethanol, citric acid, ascorbic acid, citric acid + ethanol, and citric acid + ascorbic acid on preserving the shelf life and nutritional qualities of sunflower microgreens for 16 days. The results showed that spraying ascorbic acid and citric acid + ascorbic acid significantly increased the contents of total ascorbic acid and phenols in sunflower microgreens after 16 days of storage [76].

However, long-term storage and light exposure may impact the weight, appearance, and taste of microgreens [74]. Therefore, more research is needed to study the reasonable storage time and treatment to maximize the retention of nutrients in microgreens without affecting their flavor, texture, and appearance.

5. Health-beneficial effects

Microgreens are being recognized as a functional food and have become increasingly popular in western countries [77,78]. Although only a few studies have focused on the *in vivo* health benefits of microgreens, their effectiveness in blood glucose and weight control, as well as regulation of adipose tissue as shown in *in vitro* and *in vivo* studies lay the foundation for studying the potential value of microgreens on preventing and treating chronic diseases, such as obesity, type 2 diabetes, and cardiovascular diseases [79,80]. Tomas et al. [81] investigated the *in vitro* bioaccessibility of polyphenols and glucosinolates in Brassicaceae microgreens kale, red cabbage, kohlrabi, and purple radish microgreens. In this study, the highest percentage of total phenolics and glucosinolate levels were released from kohlrabi and kale microgreens, respectively, after *in vitro* digestion. The high bioaccessibility of these bioactive compounds after digestion can provide anti-inflammatory, anticancer, antimicrobial, and anti-diabetic activities [82]. An *in vitro* study has shown that tumoral colon cells treated with kale, radish, mustard, and broccoli microgreens, exhibited significantly lower cell viability than the blank group (P < 0.05), indicating the antiproliferative effects of microgreen on colon cancer cell development [83]. Mustard and radish microgreens showed stronger antiproliferative effects than kale and broccoli, in line with their higher VC, total carotenoids, and total isothiocyanates contents [83]. Marotti et al. [84] studied the anti-inflammatory properties of licorice (*Glycyrrhiza glabra* L.) microgreen on lipopolysaccharide-induced Caco-2 cell and found that the treatment of 2.50 μg/mL of root extracts from the licorice microgreen preserved cell viability and proliferation compared with the untreated group, suggesting that the licorice microgreen has a protective effect on cells by inhibiting the proinflammatory cascade. Wadhawan et al. [79] assessed the regulation of microgreens on the enzymatic release of glucose and found that compared to fennel seeds, curry leaves, and asafetida (control groups), 2–3.3 mg/mL of fenugreek microgreen extract (FME) decreased the porcine *α*-amylase activity, the enzyme that is responsible for hydrolyzing the *α*-1,4-glycosidic linkages in starch to produce glucose. In addition, FME at 2 mg/mL significantly decreased the nonenzymatic glycation by 70% than that of control groups, indicating a beneficial effect on regulating blood glucose levels [79].

Huang et al. [80] investigated the effects of red cabbage microgreens on modulating hypercholesterolemia in obese mice induced by high fat diet. Rats fed with a high fat diet and red cabbage microgreens powder showed a significantly lower plasma low-density lipoprotein (LDL) level and lower hepatic triglycerides level compared with those receiving a high fat diet supplemented with mature red cabbage powder. Additionally, microgreens-fed mice showed a significantly lower sterol *O*-acyltransferase 1 and diacylglycerol *O*-acyltransferase 1 gene expression than that of control groups. The downregulation of sterol *O*-acyltransferase 1 and diacylglycerol *O*-acyltransferase 1 gene expression inhibited the cholesterol ester and triglycerides synthesis [80], indicating the beneficial effect of red cabbage microgreens on regulating plasma and liver lipid metabolism. The consumption of red cabbage microgreen also decreased the mRNA expression of C-reactive protein and tumor necrosis factor α in the liver, suggesting an inhibitory effect of red cabbage microgreens on inflammation induced by high fat diet [80].

More pre-clinical and clinical trials are needed to determine the effects of different microgreens consumption on chronic diseases as well as the underlying mechanisms. Existing studies only measured the effects of microgreens on several biochemical markers of diseases, such as plasma lipid level and liver inflammatory cytokines. The effects of microgreens consumption on the intervention of physiological status of diseases by using disease-induced animal models remain to be elucidated in further studies.

6. Sensory evaluation

Microgreens are on the rise in the culinary world due to their naturally higher nutritional value as well as their sensory attributes, such as intense flavor, tender texture, and vibrant color. Nutrient and phytochemical contents have a great contribution to the color, smell, and taste of microgreens, although these vary greatly among different types of microgreens. Therefore, sensory evaluations of individual attributes are not usually comparable among species without the rating of the "overall liking" or the overall "acceptability" of the products. Caracciolo et al. [85] conducted a sensory evaluation test of 12 microgreens species in young adult participants, noted that the total acceptability largely depended on the sensory characteristics (e.g., aroma, bitterness, astringency, grassy, heat, and sourness). Microgreens such as Swiss chard and coriander with a lower level of sourness, bitterness and grassy, were significantly more acceptable than mibuna, cress, and amaranth, which were characterized by bitterness and grass taste. A strong correlation was noted between the taste of microgreens and the evaluator's overall preference of the sample [86]. Tan et al. [86] conducted a sensory evaluation to evaluate the broccoli microgreens from a commercial and local farm, and noted that local farms had a higher score on tasting, probably due to the higher contents of chlorophyll, which results in a higher sugar production [86]. The flavor of microgreens may also be influenced by their phenolic content, as they usually taste astringent in vegetables and fruits. Besides, Xiao et al. [87] pointed out that the "sweet taste" of microgreens may be related to the modification of acid and aroma compounds instead of sucrose content in microgreens. For example, red amaranth and Bull's blood beet microgreens with a lower titratable acidity levels and lower intensity of aroma had higher consumer acceptance [87]. Brassicaceae families such as Dijon mustard and China rose radish are rich in a group of bitter compounds called glucosinolates [88], limited their consumers' acceptance [87]. Additionally, microgreens with higher total phenolic content are positively related to overall eating quality, sweetness, and acceptance of flavor, which may be making it as a potential indicator of sensory evaluation [87].

Individual sensory preference determines the degree of liking for microgreens. Microgreens rich in allyl isothiocyanate have pungent and spicy flavors, such as mustard and wasabi. For those who like the spicy taste, microgreens with a pungent taste were favorable, while for those who do not like the spicy flavors, their acceptability was low [89]. Participants who preferred sweet and mild flavor may have low acceptability with microgreens with pungent flavor, especially those rich in glucosinolates and isothiocyanates, despite the importance of these nutrients for health [90]. Participants who had higher familiarity with microgreens and higher educational level tent to be more likely to purchase microgreens [91]. In addition, sensory evaluation and perceived benefits are indicators of consumers' willingness to buy, while this relationship was not found between perceived pricing and consumers' willingness-to-buy [92]. Therefore, increasing public awareness and acceptance of microgreens may be an important consideration in the promotion of this new functional food to the general population.

7. Conclusions

This review focused on evaluating the nutritional quality of microgreens, the influence of pre- and post-harvest treatments on nutrient and phytochemical content, and the health benefits of microgreens as reported from *in vitro* and *in vivo* studies. Microgreens are good sources of nutrients and antioxidants, including VC, minerals (e.g., Cu and Zn), carotenoids, and phenolic compounds. Many studies showed higher nutritional quality in microgreens than in their mature plants. Several pre- and post-harvest treatments are effective in enhancing the nutritional quality of microgreens, for instance, light exposure, salinity stress, nutrient fortification, and the use of natural medium substrates. Due to the richness of vitamins and phytochemicals, microgreens have a strong antioxidant capacity and are effective in the regulation of plasma lipoprotein and cholesterol metabolism, showing a potential value in the prevention and/or treatment of chronic diseases.

Microgreens, as a novel food, have shown an increase in their acceptability and popularity on the market due to their high nutrient density and potential health benefits. Microgreens are easy to grow, especially using controlled environment agriculture approaches, such as hydroponics and aquaponics. In term of their nutritional quality, further research is warranted to develop pre- and post-harvest interventions to maximize nutrient retention and investigate potential health beneficial effects of different species of microgreens.

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Conflicts of interests

The authors declare no conflicts of interests.

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