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REVIEW ARTICLE

# Microgreens as functional foods: Advances in cultivation, nutrient enrichment and postharvest management

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## Abstract

The increasing global demand for nutrient-dense, functional foods has fuelled interest in microgreens, which are young, edible seedlings harvested at the cotyledon or first true leaf stage. These miniature greens are valued for their vibrant appearance, concentrated flavors and superior nutritional content, including high levels of vitamins, minerals, antioxidants and secondary metabolites. This review discusses recent developments in microgreen cultivation, including advances in soilless substrates, controlled environment agriculture, seed density optimization, seed treatments and fertilization strategies. Substrates such as cocopeat, peat moss and jute fiber, along with hydroponic and aeroponic systems, have been shown to enhance yield and nutrient concentration. Manipulating light quality, particularly with red and blue LED combinations, significantly improves plant growth and phytochemical content. Seed treatments, including nutrient biofortification and disinfection, further promoted germination, nutrient uptake and safety. Although microgreens generally contain lower levels of anti-nutritional factors like phytic acid compared to their mature counterparts, these compounds can still impact mineral bioavailability. However, research demonstrates that targeted biofortification can effectively reduce such limitations. This review provides a comprehensive overview of the production techniques, nutritional potential and safety considerations of microgreens, highlighting their relevance as a sustainable and health-promoting food source.

**Keywords:** harvest; microgreens; postharvest; production; storage

**Abbreviation:** POD- Guaiacol peroxidase, CAT- Catalase activity, GR- Glutathione reductase, SOD- Superoxide dismutase, DPPH- 2,2-diphenyl-1- picrylhydrazyl, ABTS- 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid), $ZnSO_4$- Zinc sulphate, ZIP- ZRT IRT- like protein, NRAMP- Natural Resistance-Associated Macrophage Protein, YSL- Yellow stripe-like, CEA- Controlled environment agriculture, LED- Light emitting diode

## Introduction

The combination of growing population and declining nutrient levels in diets has driven the rising popularity of microgreens, valued for their quick growth and rich nutrient profile (1). Microgreens, also known as "vegetable confetti" can thus be described as young seedlings that have germinated, featuring fully developed and healthy cotyledons along with the initial formation of one or two true leaves (2). Typically, microgreens can be grown from the seeds of nearly any vegetable, herb or grain species, with the most commonly used being from the Amaranthaceae, Apiaceae, Asteraceae and Brassicaceae families (3) except those that are toxic at seedling stage, as in the case of Solanaceae (4). These functional microgreens range from 2 to 8 cm in height and are characterized by intense sensory qualities such as texture, flavor, appearance, aroma, exotic colors and high levels of various phytonutrients (5). Microgreens are typically cultivated in greenhouses using growing flats filled with potting mixes, peat-based mixes, hydroponic media or even recycled textile fibers (6). Microgreens are phenologically between sprouts and baby greens and should be harvested without roots 10 to 14 days after seeding (7, 8). Since microgreens are packed with vitamins, minerals, antioxidants and have anti-inflammatory properties, they are termed "functional foods" or "superfoods" (9-11).

Microgreens can be grown at home using potting mix or capillary mats, as well as produced on a large scale utilizing advanced controlled environment agriculture (CEA) technologies using IoT (Internet of Things) (12-15). Microgreens can also be cultivated in soilless media such as hydroponics (16, 17), aeroponics (18) and space farming (19). Microgreens which are abundant in bioactive compounds can be grown in space to maintain the balanced diet of astronauts (20, 21). However, the limitations of microgreens in space farming include their inability to produce progeny, which leads to high seed consumption and their comparatively low biomass accumulation and oxygen generation when compared with larger plants (22, 23). Several techniques are involved in improving the yield and quality of microgreens such as presowing seed treatments, varying seed densities, fertilizer application, altering the combination and intensity of light, biofortification of several nutrients, preharvest treatments and post-harvest practices to improve shelf life (24-32). Furthermore, microgreens have been shown to be an excellent educational tool for enhancing nutrition awareness and for promoting indoor farming practices within local communities (33, 34).

Despite their numerous benefits, microgreens present several challenges for growers and distributors due to their extreme fragility and short shelf life (35). The short shelf life is attributed to enhanced respiration, which likely triggered higher ROS production, resulting in the decline of bioactive compounds (36). Microgreens are challenging to store due to factors such as rapid postharvest transpiration decay, tissue damage, leakage of nutrient-rich exudates, a high respiration rate, a high surface area to volume ratio and their delicate leaves that wilt easily (37). Further, the production of indoor microgreens using soilless substrates, may also associated with pathogens known as produce-associated pathogens (38). To date, there are no commodity specific guidelines for microgreens (39). Since low shelf life was directly associated with pathogen attack, proper training regarding production of microgreens in soilless media, disinfection of seeds, testing of irrigation water, proper storage and packing of microgreens should reach the microgreen growers (40). Thus, this review focuses on recent studies and trends in microgreen production, different substrates, seed treatments, storage, health benefits and food safety measures.

## Growing media and growing conditions for microgreen production

Microgreens are preferably grown in a soilless substrate. This soilless cultivation can alter the nutrient uptake of plants and improve the nutritional quality to some extent (41). Microgreens can be grown in natural substrates such as cocopeat (41), jute fiber (42), agave fiber (12), peat moss (43, 44) and the synthetic alternatives such as capillary mat (12) and cellulose sponge (45). Since cocopeat retains water efficiently and has a low bulk density, it is best suited for use as a substrate (46). Various microgreens such as flaxseed, radish sango, broccoli, cabbage, pak choi, beetroot and red amaranthus have been grown in two different substrates, soil and cocopeat and it was found that cocopeat outperformed soil (47). Similarly, cocopeat supplemented with coconut water provided the best growth and yield for hydroponically cultured microgreen broccoli, followed by planting media such as rockwool, husk charcoal and sand (48). Six different microgreens grown in cocopeat showed increased growth compared to soil and water (49). Apart from growth, the amount of sulforaphane in red cabbage microgreens increased twofold with the use of cocopeat and young coconut water (50). The combination of soil and cocopeat substrate, when paired with different types of LED lighting, led to an increase in both the yield and the flavonoid content of Ethiopian kale microgreens (51). The limitation of cocopeat is that it has high potassium levels, which can cause toxicity and negatively impact crop production (52).

Peat moss provided ideal physicochemical conditions, that promote growth rate and both the fresh and dry yield of microgreens (12). Peat moss often promotes nitrate accumulation in microgreens, particularly in brassicaceous varieties known as nitrate hyperaccumulators. To minimize consumer exposure to nitrates, nitrate deprivation practices should be implemented for microgreens grown on such substrates (12). The major disadvantage of growing microgreens in peat moss is that it is susceptible to microbial contamination (6).

Jute fiber, an inexpensive and renewable material, can also be used as the substrate for microgreen cultivation. When grown on jute fiber, rocket microgreens achieved the highest yield of 3201 g/m$^2$, surpassing those grown on coconut fiber and vermiculite substrates (53). Similarly, green mustard (*Brassica nigra*) grown on jute fiber exhibited slightly higher carotenoid levels, while the phenol and chlorophyll levels remained unchanged (42).

Recently, commercial microgreen production has transitioned to hydroponics, since it enhances plant growth, biomass production, yield and chemical composition, making it ideal for earlier harvesting (17). The cultivation of five different microgreens including four *Brassica* and one *Raphanus* in a hydroponic pad positively affected the fresh and dry weight of the shoots as well as their mineral nutrient content (54). Growing microgreens in vertical hydroponic system has been reported to enhance both the germination rate and harvest compared to other substrates (55). Besides all these advantages, it is crucial to consider the absence of a soil microbiome in hydroponic systems as the plants become susceptible to harmful spoilage by microorganisms (56, 57).

Aeroponic techniques have demonstrated commercial success in the production of microgreens (58). The modular automated aeroponic growing system was developed by Richter and although aeroponics is more expensive to set up when compared to traditional growing methods, its low operational costs can allow it to pay for itself within a year (59).

Controlled Environment Agriculture (CEA) is an increasingly popular production system that enhances food security, environmental stewardship and resource efficiency, with a recent report projecting the global CEA market to grow at an annual rate of 18.7 % and reach $172 billion by 2025 (60). Microgreens are particularly well-suited for CEA production due to their high yield, rapid growth, efficient use of space and their role in feeding growing urban populations (9, 61).

One of the most crucial interventions in CEA is illumination treatment (62), as light duration and intensity significantly influence nutrient accumulation in microgreens (63). The mechanism by which LEDs influence plant growth and quality involve the emission of photons that activate specific photoreceptors, such as phytochrome and cryptochrome, resulting in changes in leaf area, thickness, stem length and metabolite production (64). A mixed red-blue light, particularly with a 5:1 red-to-blue ratio, proved advantageous for broccoli microgreens, enhancing their hypocotyl length, fresh weight and edible rate (65). Brassicaceae microgreens grown under blue LED lighting exhibited the highest ascorbic acid content (112.70 mg·100 g fw$^{-1}$), total phenolics (412.39 mg GAE·100 g fw$^{-1}$) and antioxidant capacity (2443.62 μmol TE·L$^{-1}$) compared to those grown under red and 50:50 blue-red LED spectra (66). This is attributed to the effective absorption of red and blue light by photosynthetic pigments, which generally outperforms other regions of the spectrum in promoting plant growth (64). However, the effect of red and blue LED light on microgreens is species-dependent, as mustard microgreens showed decreased nutritional value with varying blue-red light ratios, while kale microgreens were unaffected (62). A similar result was observed when a 30 % blue light supply led to maximal anthocyanin accumulation in arugula, kale and red cabbage, but not in mustard (67). Furthermore, the addition of green light at an irradiance of 340 µmol $m^{-2}$ $s^{-1}$ within the red and blue light environment enhanced growth (measured by dry weight biomass) and boosted the accumulation of bioactive phytochemicals in some of the microgreen species (68).

## Optimum seed density for microgreen growth

Seed density is a key factor for achieving optimal growth outcomes from both an economic and commercial perspective (69). In addition to the substrate, seed density also significantly affects the morphological, nutritional and phytochemical properties of microgreens (70). Although seeding density is essential, considering the landrace and harvest date is equally important in microgreen production planning due to their significant influence on both yield and quality (25). In kale, rapini and cress microgreens, varying seed densities (3.5, 4 and 4.5 seeds·$cm^{-2}$) showed that the highest density (4.5 seeds·$cm^{-2}$) produced a 19 % higher yield compared to the lowest density (3.5 seeds·$cm^{-2}$), with kale achieving the highest yield, surpassing rapini by 0.44 kg·$m^{-2}$ and cress by 0.97 kg·$m^{-2}$ (25). Similarly, microgreens such as basil, carrot and blends of mild and radish exhibited increased fresh weight with higher seed density (71). Seed density is directly influenced by the seed size of different microgreen species, with the optimal seed density being three seeds/$cm^2$ for *C. intybus* and *L. sativa*, while *B. oleracea* genotypes requires four seeds/$cm^2$ for optimal growth (72). The optimum seed density for microgreen production also depends on the spectrum of artificial light provided. The optimal seed density for red beet microgreens, tested at 50, 150, 300 and 450 g/$m^2$ under white and purple spectrum, was 300 g/$m^2$ in the white spectrum, while fresh weight continued to increase at 450 g/$m^2$ under the purple spectrum (73). However, microgreen yield increases with higher seeding densities, exceeding the optimum density can reduce marketable quality and increase the risk of fungal infections, negatively affecting both quality and productivity (72, 74). Higher seeding density leads to an excessive number of plants, causing undesirable elongated shoots due to increased congestion and competition (72). This also hinders air circulation, creating conditions favorable for fungal growth (75). Brassicaceae microgreens sown at high seed densities are susceptible to pythium root rot, a disease caused by fungal species such as *Pythium aphanidermatum* and *Pythium dissotocum* (76). In addition, the economics of seed density raise concerns due to the high cost of seeds, making it a significant consideration for those involved in cultivation (71).

## Seed treatments for enhanced growth of microgreens

Fast and uniform germination is essential for the successful growth and production of microgreens (77). This uniform and optimal germination can be attained through seed pre-sowing treatments, which enhance germination rate, speed and seed vigour (78). Additionally, the nutritional composition of microgreens is influenced by seed treatment (77). Dill, carrot, parsley and celery microgreen seeds treated with four fertilizers Bioforce, Humustim, Biotor and Algreen, showed the best performance with Bioforce, which enhanced germination, increased dry matter content, elevated total sugar levels and influenced plastid pigment concentration (79). Apart from plant biometric traits, the chlorophyll and carotenoid content indices were significantly higher in pea microgreens whose seeds were soaked in a 10 % solution of *Chlorella vulgaris* algae before sowing and sprayed with the same solution during growth (80). Presoaking and growing barley and wheat microgreens in organic soil resulted in the highest levels of bioactive compounds, including carotenoids, phenolics, flavonoids, vitamin C and anthocyanin, while also enhancing antioxidant enzymes (POD, CAT, GR) and antioxidant activities (DPPH, ABTS, NSA and SOD-like activity) in microgreen (81). Radish microgreens seeds treated with a 100 ppm salicylic acid solution showed an increase in protein content, total antioxidants, phenols and flavonoids, while also displaying a notable reduction in oxalic acid content, even under salt stress (82). Seed treatments can also be intentionally used for micronutrient enhancement through seed biofortification, as this approach is simple, practical, low-cost and economically viable, improving seed and crop quality in resource-limited areas (83). Soaking seeds in a 200 ppm $ZnSO_4$ solution led to significantly higher Zn biofortification in both pea (126.1 %) and sunflower microgreens (229.8 %), but it caused an antagonistic effect on the accumulation of other micronutrients (Fe, Mn and Cu) only in pea microgreens (84). This antagonistic effect for peas was due to the competition for common transporters (ZIP, NRAMP, YSL), though the extent of such antagonism depends on crop tolerance to excess Zn (85-87). The five microgreen (mizuna, arugula, cress, green basil and radish) seeds when soaked with 2 mg Se/L sodium selenate resulted in the highest selenium content (17.507 µg/g fresh weight) in mizuna microgreens, along with increased chlorophyll a content and nutrient levels (88). Certain seed treatment techniques such as seed sanitization, can play a crucial role in minimizing the microbial load on seeds used for growing microgreens (89). For example, 60 °C heat treatment for 20 hr, combined with a 10 min soak of amaranth, carrot seeds in 3 % $H_2O_2$, significantly reduced Enterobacteriaceae, coliforms, molds and yeasts, without adversely affecting germination rates (90). Moreover, Brassicaceae seeds contaminated with *E. coli* O157:H7 were sanitized through a seed treatment process using 55 °C warm water combined with ultrasound for 5 min (91). Some of the recent seed treatment techniques, including high-pressure processing, ultrasound, UV light, non-thermal plasma and microwave radiation, are also being used to enhance the quality of microgreens paving the way for future research (92).

## Fertilization impact on yield and growth of microgreens

Fertilization management plays a pivotal role as a pre-harvest factor, significantly influencing the overall quality of the produce by ensuring the optimal nutrient supply (45) for fast growth and high yield of microgreens (77). Although chemical fertilizers are unnecessary for microgreens, as the seeds supply sufficient nutrients for the developing embryo, a small amount of fertilizers can be applied to support the growth of microgreens with longer growing periods such as carrot, dill and celery (93). Fertilization with a general-purpose soluble fertilizer (20-20-20 with micronutrients) at 100 mg $L^{-1}$ nitrogen increased fresh shoot weight and enhanced nutrient concentrations in ten microgreens. However, calcium, magnesium and manganese levels decreased, likely due to the dilution of elements absent in the fertilizer (77).

Nanofertilizer based on superparamagnetic iron oxide nanoparticles (SPIONs) at the rate of 667 µg $L^{-1}$ has been shown to boost biomass, promote root growth and enhance iron absorption in onion microgreens compared to traditional ionic iron treatments (94). Calcium fertilization at 5 mM and 10 mM in radish microgreens led to the highest percentage of shoots (48.7 %), with increased average hypocotyl length (3.331 cm) and cotyledon surface area (1.294 $cm^2$) per plant, but exceeding 20 mM Ca resulted in toxic effects such as yellowing of cotyledons, accumulation of calcium in shoots and reduced microgreen growth (95). In contrast, the absence of nutrient supplementation imposed abiotic stress, which led to a significant increase in lutein, β-carotene, total ascorbic acid and total anthocyanins in rocket (*Diplotaxis tenuifolia*) microgreens, while it had no effect on secondary metabolites in Brussels sprout (*Brassica oleracea* var. *gemmifera*) microgreens (43). The application of NPK controlled-release fertilizer to basil microgreens positively influenced plant growth by significantly enhancing various parameters, including height, total fresh mass, total dry mass, leaf area index and specific leaf area index, compared to the control (96). A single application of 120 mL of water-soluble 20 N-8.7 P-16.6 K fertilizer increased fresh shoot height and macronutrient concentrations in four *Brassica* microgreens and one *Raphanus* microgreen (77). However, crop-specific fertilizer requirements for microgreen production remain unclear (77).

## Suitable harvest and postharvest practices for maintaining the microgreen quality

Harvesting and postharvest handling conditions play a significant role in determining the overall quality of microgreens (97). The time required to harvest microgreens after planting varies based on the type of seed and species chosen, typically ranging from 2 to 3 weeks (98). Microgreens are ready to harvest when their cotyledonary leaf is fully extended, with the ideal harvest time determined by a combination of their height and leaf area (99). It should be harvested without roots and seed coats, by cutting the base of the seedling, just above the lower hypocotyl, close to the substrate surface (2, 74). The timing of harvest also influenced the dry matter content, which can positively affect post-harvest outcomes, as higher dry weight has been shown to prolong the shelf life of microgreens (25). Harvested microgreens are extremely perishable and need to be washed and cooled promptly to maintain their freshness (100). During post-harvest storage, microgreens exhibit signs of browning, physiological breakdown, weight loss, microbial growth, biochemical changes and overall quality decline (101). The limited marketing potential of microgreens is due to their short lifespan and rapid senescence makes it crucial to improve production and storage conditions to enhance their post-harvest quality, shelf life and safety (32). The post-harvest practice of dipping broccoli microgreens in a 50 mmol·$L^{-1}$ calcium lactate solution proved effective in extending their shelf life and minimizing tissue electrolyte leakage (102). Sunflower microgreens sprayed with citric acid and ascorbic acid (2.5 g/L each) exhibited an extended shelf life of up to 16 days. They retained the highest levels of total chlorophyll and ascorbic acid while maintaining the lowest microbial load by the end of storage (103). Some preharvest treatments can also influence the post-harvest quality of microgreens (104). The reduction in glucosinolates in broccoli microgreens during postharvest storage, primarily caused by myrosinase-catalyzed glucosinolate breakdown, may be delayed by pre-harvest treatments with UVB (0.27 Wh/$m^2$) and 10 mM $CaCl_2$ spray, which reduce myrosinase gene expression (105). Red:blue LED illumination during microgreen growth coupled with post-harvest UV-C irradiation for 10 min reduces weight loss in radish microgreens after 12 days of storage by potentially forming a thin dried layer on the surface, which slows water loss (106). Similarly, 8 hr of red light (35 µM $m^{-2}$ $s^{-1}$) improves the postharvest quality of pak-choi microgreens by suppressing the expression of genes linked to chlorophyll degradation and senescence, while enhancing the expression of genes involved in vitamin C biosynthesis (107). A study reported that when chlorinated water was sprayed during the growth of radish microgreens, it reduced *Salmonella* populations by 1.1 log CFU/g and *E. coli* O 157: H 7 populations by 0.9 log CFU/g (108). In a comparison of pre-harvest spray treatment and post-harvest dip coating using *Aloe vera* gel for storing radish microgreens at 5 °C, the *Aloe vera* spray coating created an initial edible layer that helped reduce physiological weight loss, lower microbial counts and preserve higher ascorbic acid levels (109).

## Packing and Storage conditions for prolonged shelf life of microgreens

The shelf life of microgreens after harvest is influenced by several factors, including storage temperature, humidity levels, the type of packaging film used and the initial amount of microbial load (110). In several developing and underdeveloped regions, packaging microgreens remains a major challenge, as maintaining sufficiently low temperatures from harvest until consumption is difficult (111). Washing microgreens before packaging lowers the initial bacterial count, but it also creates a humid environment that fosters microbial growth, making it essential to remove excess moisture to prevent this (37). One of the most effective ways to extend the shelf life of microgreens is by modifying the atmosphere inside the packaging (109). In this method, oxygen is substituted with nitrogen or carbon dioxide, thereby reducing oxidative reactions and slowing down metabolic processes (112). Additionally, storing microgreens in a low temperature environment slows down the majority of metabolic reactions, effectively maintaining higher levels of antioxidant activity and extending freshness (36). Tartary buckwheat microgreens, when stored at 5 °C with low-density polyethylene (LDPE) packaging and treated with a chlorine dioxide $ClO_2$ + citric acid wash, inhibit quality deterioration and extend the shelf life of microgreens (113). Similarly, broccoli microgreens treated with 0.25 % w/v ascorbic and citric acid and stored at 5 °C with modified atmospheric packaging (15 % $CO_2$, 5 % $O_2$, balanced $N_2$) can be preserved for up to 12 days. They retain higher levels of bioactive compounds such as total phenols (1247.68 mg GAE/100 g FW), flavonoids (56.9 mg QE/100 g FW) and chlorophyll (42.12 mg/100 g FW), along with improved antioxidant activity (44.78 % inhibition) (32). Microgreens packaging should vary based on transportation needs. While macro-perforated PET clamshell (PET-CS) packaging has proven superior to LDPE self-seal bag (LDPE-SSB) for storing radish and roselle microgreens, PET-CS is more suitable as rigid packaging for long-distance transport. However, LDPE-SSB serves as a cost-effective option for shorter-distance markets and sturdier microgreens (109).

## Economic viability of microgreens

Microgreens are economically viable because they can be produced year-round, unlike traditional crops (114). Their cultivation is often carried out by small-scale enterprises, as production does not require sophisticated or high-tech equipment

(115). In addition, microgreens are frequently marketed close to the site of production, supporting sustainable short supply chains. Such localized distribution reduces transportation distances, minimizes quality losses during handling and ensures proximity to the target market (116). Furthermore, due to their relatively short growth cycle, microgreens typically do not require pesticide application. The economic feasibility of microgreen production has been further demonstrated in diverse systems, including vertical farming, aquaponics and urban rooftop farming (117-119).

## Nutrient profile of microgreens

Microgreens are primarily associated with rich sources of both micronutrients and macronutrients (4, 5) (Table 1). Their rich concentrations of essential nutrients make them ideal for health-supporting diets, as consuming even small amounts can help prevent nutrient deficiencies and chronic diseases that are prevalent in today's world (129). The nutrient composition and yield of microgreens can be impacted by cultural practices, including pre-sowing seed treatments, seeding rates and fertilization, as well as by microenvironmental factors like temperature, light and growth media (77) (Fig. 1). Purple mint microgreens, when exposed to short-term red LED light of 638 nm, showed enhanced anthocyanin and ascorbic acid levels while reducing nitrate content (130). The mineral concentration in spinach microgreens increased when a nutrient solution was supplied for 10 days (129). Under high-temperature conditions, broccoli microgreens exhibited greater accumulation of Hg, As, Co, Cr, Na, K, Ni, Se, Pb and Sn, while showing decreases in P, Mg, Ca, Mn, Cu and Cd (131).

## Secondary metabolites of microgreens

Secondary metabolites are not essential for immediate survival but play a crucial role in long-term health, disease prevention and overall well-being (132). In general, microgreens are rich in secondary metabolites (1) (Table 2). Enhancing the production of secondary metabolites can lead to improved nutritional value and better sensory qualities. This can be achieved by modifying agronomic practices such as seed selection, growing media, light quality and nutrient biofortification, ultimately resulting in nutrient-enriched produce (97).

## Anti-nutritional factors of microgreens

Anti-nutritional factors are compounds commonly present in various food sources that hinder the body's ability to absorb and utilize nutrients effectively, thereby reducing the overall nutritional value of the food (140). The major anti-nutritional factors are oxalates, tannins and phytic acid.

Oxalates interfere with calcium and magnesium metabolism and bind with proteins to form complexes that hinder peptic digestion (141). Microgreens generally contain lower oxalate levels, as shown in the previous studies which reported 14.3 mg/100 g FW in radish microgreens and 68.2 mg/100 g FW in fennel microgreens, both lower compared to their mature counterparts (109). Similarly, roselle and spinach microgreens contained approximately six-fold and

**Table 1.** Nutrient composition of microgreens

| Category | Component | Range / Content | Microgreen Examples | References |
|---|---|---|---|---|
| Macronutrients | Potassium (K) | 176-416 mg/100 g FW | Brassicaceae, Sunflower, Pea, Bean, Red beet | (120, 121) |
| | Magnesium (Mg) | 45.96-86.83 mg/100 g FW | Black radish, Broccoli, Pea, Bean, Red beet, Sunflower | (121) |
| | Calcium (Ca) | 8.76 mg/g DW | Romaine lettuce | (122) |
| | Phosphorus (P) | 16.7-39.8 µg/g DW | Red amaranth, Pea, Broccoli, Red beet | (123) |
| Micronutrients | Iron (Fe) | 14 mg/kg FW | Lettuce | (124) |
| | Zinc (Zn) | 31.92-129.78 µg/100 g FW | Black radish, Broccoli, Pea, Bean, Red beet, Sunflower | (121) |
| | Copper (Cu) | 2.69-2.72 mg/kg FW | Water spinach, Bottle gourd | (125) |
| | Manganese (Mn) | 4.84-14.22 mg/100 g DW | Nigella, Safflower, Camelina | (126) |
| Vitamins | Ascorbic Acid (Vitamin C) | 51.10 mg/100 g FW | Beet | (127) |
| | Vitamin E (α/γ-tocopherol) | α: 34.5-47.7, γ: 8.3-19.7 mg/100 g FW | Red beet, Pea, peppercress, radish | (128) |
| | Phylloquinone (Vitamin $K_1$) | 2.8-3.3 µg/g FW | Red cabbage, Pea, Red sorrel | (128) |

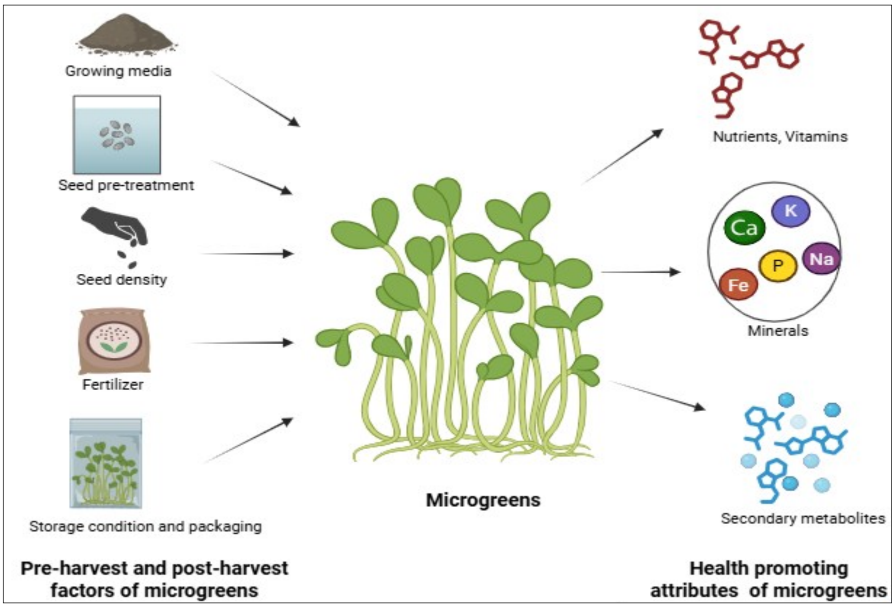


**Fig. 1.** Production and quality traits of microgreens.

**Table 2.** Secondary metabolites of microgreens

| Secondary metabolites | Microgreens | References |
|---|---|---|
| Glucosinolates, Flavonols, Phenolic acids | Arugula, Radish, Red cabbage, Red amaranth | (123, 133) |
| Organosulfur compounds | Arugula | (123) |
| Betanin, Amaranthin | Red beet, Red amaranth | (123) |
| Total dietary fiber | Radish | (134) |
| Organic acids, Carotenoids | Kale, Radish, Beetroot, Green peas, Amaranth | (135) |
| Polyphenols, flavonoids | Kale, Kohlrabi, Red cabbage, Radish | (136) |
| Phytoestrogens, Triterpene Saponins, Condensed tannins | Alfalfa, Black medick, Sainfoin | (137) |
| Aliphatic glucosinolates | Choy sum | (138) |
| Flavonoid | Sunflower | (139) |
| Flavonol glycosides, Hydroxycinnamic acids and their derivatives, Flavone glycosides, Caffeoyl quinic acid, Quercetin-3-sinapoyl triglucoside, Synapoyl-hexose. | Lettuce, Mustard and Rocket | (12) |

sixteen-fold less oxalate respectively, than their mature leaves (142).

Tannin is a bitter, astringent plant-derived polyphenol that can bind to or precipitate proteins, as well as other organic compounds such as amino acids and alkaloids (141). However, tannin content is lower in microgreens since it is higher in raw seeds and decreases once the seeds start germinating (143, 144).

Phytic acid carries negative charge, allowing it to bind with positively charged metal ions such as zinc, iron, magnesium and calcium. This interaction forms complexes that reduce the bioavailability of these minerals by limiting their absorption in the body (145). Phytic acid levels in microgreens are generally low and within permissible limits, though they vary among species. The phytic acid content of six microgreens such as mung bean, lentil, red radish, pearl millet, mustard and red cabbage was studied, with pearl millet microgreens showing the highest content (0.304 g/100 g fresh weight) and red radish microgreens the lowest (0.156 g/100 g FW) (99). Similarly, the phytic acid content in beetroot, red amaranthus, radish sango, cabbage, broccoli, flaxseed and pak choi microgreens was found to range from 145.32 to 507.46 mg/100 g FW, with the highest concentration in red amaranthus and the lowest in radish sango microgreens (146).

However, the phytic acid content of microgreens was lower compared to their mature counterpart as reported in earlier studies, showing that fenugreek and broccoli microgreens had lower phytic acid content compared to their mature forms, which contributed to enhanced iron absorption (147). Biofortification strategies have been shown to mitigate the negative effects of phytic acid. Soaking pea and sunflower seeds in high concentrations of $ZnSO_4$ and ZnO solutions significantly reduced the phytic acid-to-zinc molar ratio, suggesting improved zinc bioaccessibility in the resulting microgreens (84).

## Conclusion

Microgreens offered an effective and sustainable approach to improving human nutrition, particularly in the context of rising population pressures and limited agricultural space. Their fast growth cycle, high nutrient density and compatibility with urban and controlled-environment farming systems made them a valuable addition to modern food production. Advances in growing substrates, lighting conditions, seed treatments and fertilization contributed significantly to improving both the yield and nutritional quality of microgreens. In addition, biofortification and sanitation practices enhanced their safety and nutrient bioavailability. Despite these advantages, challenges remained in standardizing cultivation protocols, developing cost-effective biodegradable substrates, reducing anti-nutritional factors while enhancing biofortification of key micronutrients and improving postharvest technologies including edible coatings and modified atmosphere packaging, to extend shelf life without nutrient loss. Ongoing research and technological advancements were essential to fully harness the potential of microgreens for improving public health and supporting global food security.

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## Authors' contributions

APB and CV conceptualised the work, carried out the literature review and drafted the manuscript. RU, RP, MK, SPT and AMAR edited the manuscript. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors do not have any conflicts of interest to declare.

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