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Review Article

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Future Prospects of Microgreens in Global Food and Nutritional Security

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Abstract

Microgreens young seedlings harvested 7 - 21 days after germination have emerged as a nutrient-dense, resource-efficient crop with significant potential to address global food and nutritional security challenges. Their exceptional concentrations of vitamins (A, C, K, and E), minerals (Iron (Fe), zinc (Zn), and selenium (Se)), carotenoids, phenolics, and bioactive phytochemicals position them as next-generation functional foods capable of combating micronutrient deficiencies in both urban and rural populations. Their rapid growth cycle, minimal land requirement, and compatibility with soil, hydroponic, and vertical farming systems make microgreens well suited for household production, controlled-environment agriculture (CEA), and climate-resilient food systems. Advances in light emitting diodes (LED) lighting, optimized substrates, precision nutrient management, and artificial intelligence (AI)-integrated cultivation platforms further enhance yield, phytonutrient density, and production consistency. Microgreens also demonstrate promising therapeutic properties, including anti-inflammatory, anti-diabetic, and cardioprotective effects, supporting their use in nutrition-sensitive interventions. As a low-cost enterprise, microgreens generate livelihood opportunities for women, youth, and small-scale urban growers, while contributing to sustainable development goals (SDGs) related to hunger, health, gender equity, sustainable cities, and responsible production. Emerging applications in biofortification, value-added products, humanitarian food supply, and closed-loop life-support systems including space missions underscore their global relevance. This review synthesizes current knowledge on microgreen biology, cultivation strategies, nutritional composition, food safety, and market outlook, while highlighting future research and policy priorities for integrating microgreens into resilient, nutrition-sensitive food systems.

Keywords

Microgreens, Nutrient density, Biofortification, Controlled-environment agriculture, Urban farming, Functional foods, Food safety, Sustainable development goals

Introduction

Access to sufficient, nutritious, and safe food is universally recognized as a basic human right, yet vast populations continue to struggle with inadequate dietary quality due to persistent poverty, rapid urbanization, and evolving global food systems [1, 2]. Urban households and low-income communities face a dual burden of undernutrition and rising diet-related non-communicable

diseases (NCDs), highlighting the urgent need for innovative, resource-efficient food sources. Microgreens young, tender seedlings harvested between 7 and 21 days after germination have gained considerable attention as a practical and nutrient-dense solution to these challenges. Their cultivation is highly compatible with small, confined spaces and requires minimal time, water, and land, making them ideal for household, rooftop, peri-urban, and controlled-environment food production systems [3]. Unlike traditional vegetables that take months to mature, microgreens offer a continuous year-round supply of fresh edible biomass, aligning closely with the principles of climate-smart agriculture and sustainable food production [4, 5]. Their exceptional nutrient density particularly vitamins A, C, and K, along with minerals such as Fe, Zn, and Se combined with their vibrant colors and diverse flavors, enhances dietary diversity and consumer acceptability [6, 7]. Growing scientific evidence and commercial interest now position microgreens as a "next generation" functional food category capable of addressing micronutrient deficiencies, improving dietary quality, and strengthening urban food systems [8, 9].

Defining microgreens: morphology and developmental characteristics

Microgreens are defined primarily by their unique developmental stage, being harvested when the cotyledons are fully expanded and the first pair of true leaves begins to emerge. This typically occurs within one to three weeks after snowing, depending on the species and environmental conditions [4]. At harvest, microgreens measure only a few centimeters in height and consist of hypocotyl, cotyledons, and early true leaves, while the root system is generally removed. This growth stage differentiates them from sprouts, which are consumed immediately after germination without leaf formation and before photosynthesis initiates. The onset of photosynthesis in microgreens contributes to their diverse pigmentation patterns, enhanced phytonutrient accumulation, and distinct flavor attributes. A wide spectrum of botanical families offers species suitable for microgreen production, including Brassicaceae (mustard, broccoli, and kale), Apiaceae (carrot and celery), Amaranthaceae (amaranth and beet), Chenopodiaceae (quinoa), Fabaceae (peas and lentils), Poaceae (wheat and millets), and Lamiaceae (basil and chia), among others [10, 11]. Increasing interest is being directed toward underutilized grains and legumes, including millets, chickpea, and sunflower, which demonstrate high nutrient yields at the microgreen stage (Table 1). Species such as *Brassica oleracea* var. *italica* (broccoli) and *B. oleracea* var. *capitata* f. *rubra* (red cabbage) are noted for their substantial levels of bioactive compounds like sulforaphane, while pea and sunflower microgreens appeal to consumers due to their sweet flavor profiles and relatively high protein content [12, 13].

Microgreens can be cultivated effectively across a wide range of production systems, each offering distinct advantages in terms of resource use, environmental control, and scalability. Traditional soil-based or organic substrate systems, typically implemented in shallow trays, remain the most accessible approach for household, rooftop, and community-level cultivation. These substrates provide a natural matrix for root anchorage while supporting adequate moisture retention and aeration. In more controlled setups, soilless media such as cocopeat, vermiculite, and peat are preferred due to their uniformity, low pathogen load, and ability to maintain consistent moisture levels, thereby improving hygiene and reducing the risk of contamination during early plant development.

Advanced indoor production relies increasingly on hydroponic systems, including nutrient film techniques (NFT) and deep-water culture, which eliminate the need for solid substrates altogether and enable precise management of nutrient concentrations and water quality [4, 14]. Aeroponic systems further enhance nutrient delivery by suspending roots in a fine mist, increasing oxygen availability and potentially accelerating growth rates. These technologies are integral to modern CEA and have become foundational to commercial-scale microgreen operations.

Vertical farming systems maximize productivity by stacking multiple tiers of trays under carefully regulated LED lighting, greatly increasing yield per unit area. Figure 1 illustrates red-stemmed microgreens cultivated under LED illumination in a multi-tier indoor farm, highlighting how artificial lighting and vertical space can be optimized to sustain dense, uniform growth. Such controlled-environment systems allow uninterrupted year-round production, independent of external climatic fluctuations, and enable precise manipulation of environmental variables. Adjustments in light spectra, temperature regimes, and carbon dioxide (CO_2) enrichment can be systematically applied to enhance biomass accumulation, pigment development, and nutrient composition, contributing to the production of premium-quality microgreens with targeted nutritional profiles [15].

Table 1: Plant families and representative microgreens.

Crop families	Representative microgreen species
Brassicaceae	*Raphanus sativus* (radish), *B. oleracea* (broccoli, cabbage, cauliflower, kale, and kohlrabi), *Brassica rapa*, and *Eruca sativa*
Amaranthaceae	*Amaranthus tricolor*, *A. cruentus*, *Beta vulgaris* (beet and Swiss chard), and *Spinacia oleracea*
Chenopodiaceae	*Chenopodium quinoa* and *B. vulgaris var. bengalensis*
Apiaceae	*Daucus carota*, *Coriandrum sativum*, *Apium graveolens*, and *Petroselinum crispum*
Fabaceae	Pea (*Pisum sativum*), mung bean, chickpea, lentil, horse gram, and alfalfa
Poaceae	Wheat, maize, pearl millet, finger millet, little millet, and barnyard millet
Lamiaceae	Basil (*Ocimum basilicum*) and chia (*Salvia hispanica*)
Cucurbitaceae	Bottle gourd, cucumber, and pumpkin
Asteraceae	Sunflower (*Helianthus annuus*)
Others	Onion (*Allium cepa*), flax, and buckwheat

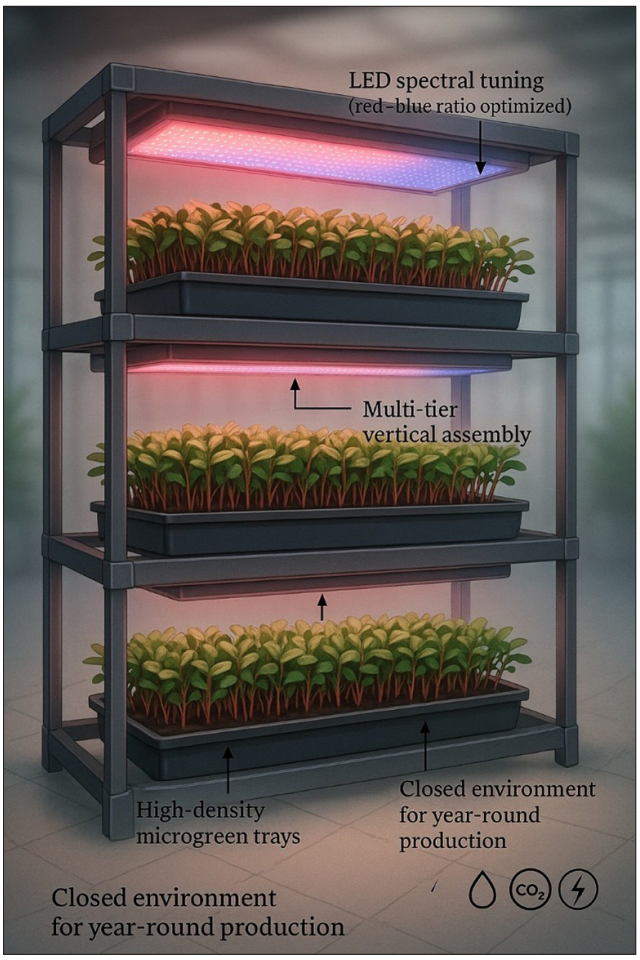


Figure 1: Microgreens grown under LED lighting in a vertical indoor farm. Controlled environmental systems enable year-round, space-efficient production with optimized light spectra and resource use.

Growing techniques must balance density and space [14, 16]. Typical sowing rates vary widely: small seeds (mustard and arugula) may be sown densely (several grams per square decimeter), while larger seeds (pea and sunflower) require fewer (Table 2).

Overcrowding within microgreen trays can significantly impede air circulation, elevate humidity levels, and increase susceptibility to fungal and bacterial diseases. For this reason, experimental trials are often conducted to determine optimal seeding densities that balance maximum yield with desirable morphological and sensory quality. Proper density ensures uniform growth, reduces etiolation, and minimizes post-harvest losses associated with poor aeration or pathogen incidence. Once seedlings reach the desired developmental stage, microgreens are typically harvested by cutting the shoots just above the substrate surface using clean, sanitized scissors to prevent contamination and tissue damage.

The timing of harvest is highly crop dependent. Leafy members of the Brassicaceae, such as *Brassica juncea*, *B. rapa*, and *B. oleracea* microgreens, generally reach marketable maturity within 6 - 12 days. Cereal crops, including species of *Triticum*, *Oryza*, and *Panicum*, require approximately 10 - 14 days, while many aromatic herbs particularly those within the Lamiaceae take 14 - 21 days to achieve optimal size and flavor [4, 16]. The short production cycle across diverse crop groups underscores one of the most significant advantages of microgreen cultivation: the ability to generate complete, nutrient-rich harvests from very small growing areas in a matter of days. This rapid turnover makes microgreens particularly valuable for urban growers, households, and resource-limited communities seeking reliable, fast-growing sources of fresh vegetables (Table 3).

Table 2: Optimum seed densities for common microgreens.

Crop	Optimal seed density	Ref.
Arugula	50 - 189 g/m^2	[17]
Beetroot	200 - 250 g/m^2	[11, 18]
Kale	30,000 - 40,000 seeds/m^2	[5]
Basil	50 - 190 g/m^2	[19]
Swiss chard	~240 g/m^2	[20]
Cabbage and lettuce	80 - 100 g/m^2 or 30,000 - 40,000 seeds/m^2	[13]
Broccoli/ cauliflower	100 - 120 g/m^2	[21]
Mustard/radish	50 - 60 g/m^2	[16]
Amaranth	50 - 100 g/m^2 or ~80,000 seeds/m^2	[7]
Chia	~200 g/m^2	[22]
Pea	~1,300 g/m^2	[14]
Wheat/fenugreek	~200 g/m^2	[11]
Mung bean/lentil	~220 g/m^2 or 30,000 seeds/m^2	[7]
Pearl millet	~140 g/m^2	[11]

Nutritional composition and health benefits

Microgreens are widely recognized for their exceptional nutrient density, a characteristic that has been consistently demonstrated across multiple scientific studies. These young seedlings often accumulate markedly higher concentrations of vitamins, minerals, and bioactive phytochemicals than their fully mature counterparts, with reported increases ranging from four-fold to as high as forty-fold depending on species and growing conditions [5, 6, 13]. Their biochemical composition is notable for elevated levels of vitamin C (ascorbic acid), which functions as a major antioxidant, alongside substantial amounts of carotenoids such as β-carotene, lutein, and zeaxanthin that serve as precursors to vitamin A and contribute to pigmentation and photoprotection. Vitamins K and E are also present in considerable quantities, with species-specific variations; for instance, red cabbage microgreens are distinguished by exceptionally high vitamin C concentrations, whereas green daikon radish microgreens exhibit remarkably elevated levels of vitamin E [6].

Beyond vitamins, microgreens frequently contain enriched mineral profiles, including potassium, Fe, magnesium (Mg),

Table 3: Recommended harvest time for major microgreen groups.

Crop types	Optimal harvest time (Days after sowing)	Ref.
Leafy brassicas (arugula, mustard, kale, radish, cabbage, beet, and Swiss chard)	6 - 12 days	[6, 7]
Cereals and millets (wheat, ragi, barnyard millet, and pearl millet)	10 - 14 days	[23]
Legumes (mung bean, lentil, and pea)	7 - 10 days	[16]
Aromatic herbs (basil, dill, fennel, and chervil)	14 - 23 days	[19]

Zn, and Se, contributing to their value as micronutrient-dense components of the diet. Pigmented species, particularly red-leafed lettuce, purple basil, and red amaranth (*Amaranthus* spp.), accumulate substantial amounts of phenolic compounds and flavonoids, which are recognized for their antioxidant activity and potential roles in mitigating oxidative stress [24, 25]. Members of the Brassicaceae family are of special interest due to their ability to synthesize glucosinolates and, following enzymatic hydrolysis, produce isothiocyanates bioactive compounds associated with chemoprotective properties and modulation of detoxification pathways [21]. This unique phytochemical richness underscores the importance of microgreens as compact, nutrient-intense foods capable of enhancing dietary quality and supporting human health across diverse populations (Table 4).

Because even a small serving of microgreens, typically in the range of 30 - 50 g, can deliver a significant proportion of daily micronutrient requirements, these young plants are particularly effective in addressing the widespread problem of "hidden hunger," which arises from inadequate intake of essential vitamins and minerals despite sufficient caloric consumption. In many species, a 100 g serving provides a remarkably high percentage of the recommended daily allowance for nutrients such as vitamin C and vitamin E, underscoring their value as concentrated nutritional sources. Comparative assessments, such as those summarized in table 1, consistently demonstrate that microgreens possess enriched concentrations of vitamins, minerals, and health-promoting phytochemicals relative to their mature plant forms.

Their early developmental stage also contributes to favorable nutritional attributes, including reduced levels of anti-nutritional factors such as phytate and nitrates, which can otherwise hinder mineral absorption in mature leaves. Lower anti-nutrient content enhances the bioavailability of minerals like Fe, Zn, and Mg, making microgreens particularly suitable for populations at risk of micronutrient deficiencies [29]. Additionally, the intensely pigmented appearances of many microgreens for example, purple mustard, ruby chard, and red *Amaranthus* spp. serve as visual indicators of elevated antioxidant compounds and can further encourage consumer acceptance by appealing to sensory preferences (Figure 2).

Beyond their exceptional micronutrient composition, microgreens have demonstrated a range of promising functional and therapeutic effects in preliminary animal and cell-based studies. Extracts derived from species such as red cabbage, fenugreek, and broccoli have been reported to exhibit anti-inflammatory, anti-diabetic, and cholesterol-lowering activities, suggesting their potential role in modulating metabolic and inflammatory pathways [30]. The consistently high antioxidant capacity observed in many microgreen varieties further supports possible benefits for cardiovascular protection and cognitive health by mitigating oxidative stress and associated cellular damage. Compounds such as lutein and zeaxanthin, abundant in vividly colored microgreens, contribute specifically to eye health by enhancing macular pigment density and protecting retinal tissues. Meanwhile, glucosinolates and their isothiocyanate derivatives in Brassica

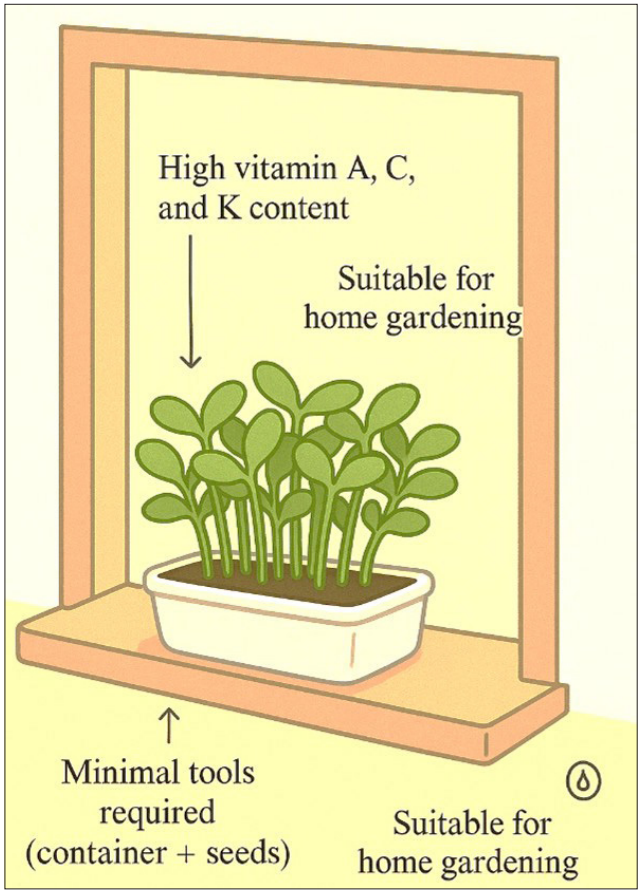


Figure 2: A container of sunflower microgreens growing on a windowsill. Microgreens often contain significantly more vitamins (e.g., A, C, and K) and minerals (e.g., Fe and Zn) per gram than mature plants [6].

Table 4: Major nutritional components across microgreens.

Nutritional component	Representative microgreens	Ref.
Minerals (Calcium, Mg, K, Fe, Zn, manganese, copper, Se, and molybdenum)	Lettuce, brassicas (arugula, broccoli, kale, cabbage, kohlrabi, mustard, and radish), *Amaranthus* spp., cucurbits, legumes (mung bean, chickpea, and pea), basil, Swiss chard, and sunflower	[5, 7, 13]
Vitamins (C, K, and E)	Arugula, radish, mustard, red cabbage, beet, spinach, amaranth, basil, pea, pearl millet, and sunflower	[6, 11]
Carotenoids (lutein, neoxanthin, and violaxanthin)	Basil, parsley, mustard, mizuna, kohlrabi, *Amaranthus* spp., and radish	[26, 27]
Phenolic acids (caffeic and rosmarinic)	Red basil, mustard, and amaranth	[20, 28]
Pigments (chlorophyll, carotenoids, anthocyanins, and betalains)	Red cabbage, mustard, kohlrabi, mizuna, buckwheat, amaranth, beet, spinach, basil, cereals, and legumes	[6, 20]
Phytochemicals (polyphenols, flavonoids, and antioxidant capacity)	Mustard, kale, radish; amaranth, coriander, legumes, flaxseed, buckwheat, and soybean	[7, 21]

microgreens may exert chemopreventive effects through the induction of detoxification enzymes and modulation of carcinogenic processes [31].

A defining advantage of microgreens is that they are generally consumed raw, allowing the preservation of heat-sensitive vitamins, volatile phytonutrients, and enzymatic activities that may otherwise degrade during cooking. This characteristic enhances their functional value and makes them particularly suitable as nutrient-dense additions to meals and dietary interventions. Incorporating microgreens into community nutrition programs, school lunches, or prenatal diets has the potential to simultaneously address micronutrient deficiencies and reduce the risk of NCDs, thereby offering a dual nutritional and health benefit [12, 32]. Even a simple addition, such as a mixed microgreen salad, can substantially elevate vitamin and mineral intake while contributing minimal caloric load [7]. Their concentrated flavors, crisp textures, and vibrant colors also make microgreens attractive for culinary innovation, enabling chefs and food service providers to integrate them creatively into dishes and potentially stimulate greater overall vegetable consumption (Figure 3).

Agronomic and technological innovations

Maximizing microgreen yield and ensuring consistent quality depend heavily on advances in cultivation practices, particularly those related to substrate choice and management.

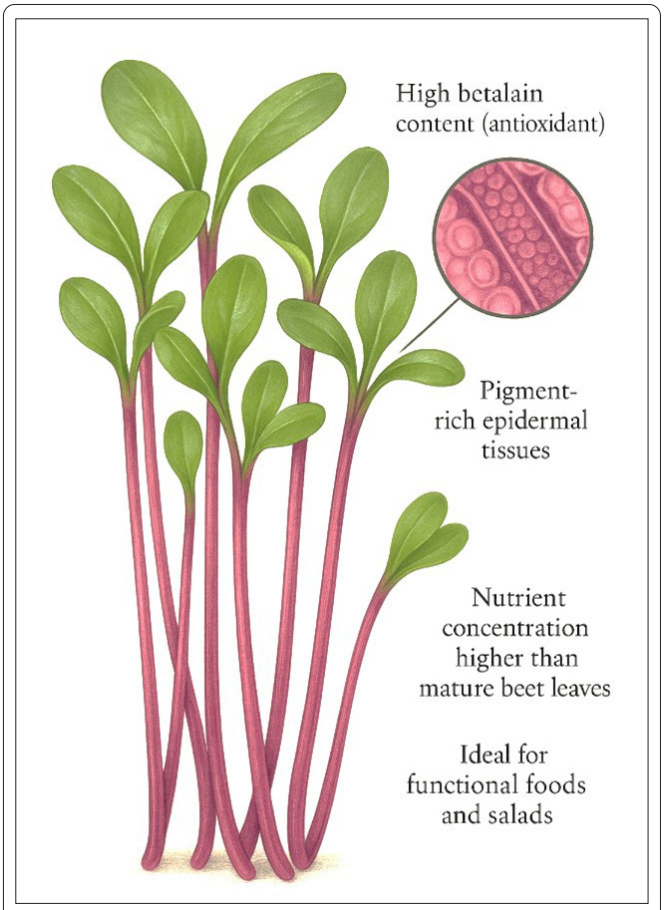


Figure 3: Red beet microgreens (above) compared to mature beet leaves (not shown) - microgreens often offer more concentrated nutrients and pigments. Red-stemmed varieties also provide betalains and antioxidants. Incorporating diverse microgreens into diets can improve phytonutrient variety and intake.

The selection of an appropriate growing medium is fundamental, as substrates must provide sufficient porosity for aeration, adequate moisture retention, and food-safe conditions suitable for young, delicate seedlings. Although peat-based mixes have traditionally offered reliable germination and uniform growth, their long-term sustainability has been questioned due to environmental concerns surrounding peat extraction. Consequently, renewable and eco-friendly substrate alternatives such as cocopeat, jute fiber mats, and well-prepared compost blends are increasingly being adopted in both small-scale and commercial systems [33].

In hydroponic production systems, growers may rely on inert materials like rockwool, perlite, or in some cases completely substrate-free configurations in which seeds germinate over mesh supports or air gaps, allowing roots to access nutrient solutions directly. The search for sustainable and low-cost substrate options has also extended to unconventional materials; studies have demonstrated that recycled paper, cellulose-based textile fibers, and other biodegradable matrices can effectively support microgreen growth without compromising yield or nutritional quality [14, 17].

Substrate enhancement represents another frontier in optimizing microgreen production. Incorporating biological amendments or beneficial microorganisms into the growing medium can enhance seedling vigor and suppress disease. A notable example is the application of *Trichoderma* spp. for bio-priming, which has been shown to significantly reduce damping-off caused by *Pythium* spp. in microgreens, thereby improving overall stand establishment and post-emergence health [34]. These innovations collectively highlight the importance of substrate science and biological interventions as integral components of modern microgreen cultivation systems (Table 5).

Light management is one of the most influential factors governing microgreen productivity and biochemical composition, as these young plants respond quickly and predictably to variations in light spectrum, intensity, and photoperiod. Higher photosynthetic photon flux densities (PPFD) generally stimulate increases in biomass accumulation, leaf expansion, and overall canopy development, although the magnitude and direction of these responses remain dependent on the species. The advent of advanced LED technology has enabled precise spectral manipulation,

Table 5: Common substrates for microgreens cultivation.

Substrate/Medium	Crops using this medium	Ref.
Soil	Brassicas, amaranth, beet, lettuce, buckwheat, barley, and millets	[18, 35]
Cocopeat	Beet, amaranth, flax, mustard, cabbage, and legumes	[36-38]
Sand/coir/paper	Wheat, ragi, mung bean, horse gram, and mustard	[16]
Hydroponics (NFT/ deep flow technique)	Beet, radish, broccoli, lettuce, basil, and Swiss chard	[14, 18]
Aquaponics	Arugula	[4]
Rockwool/vermiculite/ fiber mats	Brassicas, beet, amaranth, pea, and sunflower	[11]
Compost mixes	Kale, Swiss chard, amaranth, coriander, and sesame	[14]

allowing growers to tailor light environments that optimize both growth and nutritional quality. Blue light, for example, is frequently associated with enhanced synthesis of carotenoids, glucosinolates, and other secondary metabolites, while red light tends to promote elongation, biomass accumulation, and efficient photosynthetic performance [26, 27].

Many studies have demonstrated that strategic combinations of red and blue wavelengths often in ratios such as 80:20 can simultaneously maximize yield and enrich phytochemical profiles, offering a balanced approach that supports both agronomic and nutritional objectives [15]. Extending photoperiod duration from 12 h to 16 h or more can further stimulate biomass production and increase antioxidant accumulation, though these gains must be weighed against the added energy demands associated with longer operating times. In greenhouse or urban farming systems, supplemental LED lighting used in conjunction with natural sunlight has been shown to accelerate production cycles and stabilize quality across seasons [36].

Emerging technological innovations are poised to transform light management even further. Integrating sensor-based feedback systems and machine learning algorithms offers the potential for dynamic, real-time control of light quality and intensity. Such AI-driven lighting platforms could adjust spectral outputs based on plant developmental stage or physiological status, enabling targeted modulation of growth patterns and nutritional attributes. This convergence of photobiology and digital agriculture represents a promising direction for achieving precision control in microgreen production environments (Table 6).

Nutrient management in hydroponic systems provides an additional means of shaping both the growth performance and nutritional attributes of microgreens. Although these crops have comparatively low nutrient requirements due to their short life cycle, the formulation of nutrient solutions can exert meaningful effects on tissue composition and overall quality. Nitrogen availability is particularly influential; moderate nitrogen supply supports vigorous growth and robust leaf development, but excessive levels may lead to undesirable nitrate accumulation in the harvested product, necessitating careful balance in solution design [4, 37]. Water-soluble fertilizers enriched with micronutrients can be used strategically to achieve biofortification, enabling intentional enhancement of elements such as Zn, Se, or iodine (I) within microgreen tissues [38]. Such biofortified microgreens hold potential for addressing region-specific micronutrient deficiencies, and successful enrichment with Se and I have already been demonstrated in controlled studies.

Pre-harvest nutrient deprivation represents another targeted technique; withholding nitrogen for several days prior to harvest can reduce nitrate residues and induce mild physiological stress, which in turn stimulates the synthesis of antioxidants and other protective metabolites [39]. Seed priming enhances early plant vigor and nutrient uptake capacity, as seeds soaked in micronutrient solutions such as Zn or Se phytohormones, or beneficial microbial inoculants often exhibit improved germination rates and superior nutritional profiles at harvest [40]. Vertical farming platforms increasingly integrate optimized combinations of media, light regimes, and nutrient formulations to produce uniform, high-quality microgreens at commercial scale, demonstrating the value of coordinated agronomic interventions [41].

Food safety and post-harvest handling

Food safety and postharvest management represent critical considerations for microgreens, as these products are predominantly consumed raw and therefore bypass pathogen-reducing heat treatments. The warm, humid microenvironments typical of tray-based production can favor microbial proliferation if hygiene practices are inadequate. Although documented foodborne illness outbreaks linked specifically to microgreens remain infrequent compared to sprouts, research indicates that pathogens such as *Escherichia coli* and *Salmonella* can persist on microgreen tissues, with hydroponic systems occasionally presenting heightened risks due to shared nutrient reservoirs [12, 42]. To mitigate these hazards, rigorous sanitation protocols are essential. Seed lots may be disinfected using hot-water or dilute bleach treatments, tools and trays must be cleaned thoroughly between production cycles, and water quality requires continuous monitoring to prevent contamination.

Biological control agents offer promising supplementary safeguards. The application of *Trichoderma* spp. or other beneficial microbes as seed treatments has been shown to suppress pathogenic organisms and improve plant health [34, 43]. Additional interventions, including ultraviolet or blue-light treatment of irrigation water, can further reduce microbial loads and improve system hygiene [44]. Many commercial producers, particularly in developed markets, employ hazard analysis and critical control point-aligned food safety frameworks, incorporating traceability, routine microbial testing, and standardized handling practices throughout the production chain (Table 7).

Post-harvest handling is a critical determinant of microgreen quality because these seedlings exhibit high metabolic activity and consequently rapid respiration rates.

Table 6: Optimal growing conditions (Temperature, relative humidity (RH), and light).

Crop	Temperature/RH	Light conditions	Ref.
Radish	20 - 25 °C; 60 - 75% RH	12 - 16 h; 50 - 300 µmol/m²/s	[11]
Lettuce, chicory, and broccoli	20 - 24 °C; 70 - 85% RH	12 h; LED/HPS	[6]
Brassica mixes	18 - 24 °C; 65 - 90% RH	150 - 420 µmol/m²/s	[20]
Mung bean, pea, and chickpea	20 - 35 °C; 65 - 75% RH	12 - 16 h; LED	[7]
Amaranth, mizuna, and cress	22 - 24 °C; 60 - 75% RH	R:G:B LEDs; 300 µmol/m²/s	[26]
Wheat and barley	19 - 25 °C; 60 - 70% RH	12 h; LED/fluorescent	[18]
Swiss chard and basil	20 - 22 °C; 60 - 70% RH	12 - 16 h; LED	[19]

Table 7: Documented food safety risks in microgreens.

Micro-green	Pathogen(s)	Condition/System	Ref.
Radish	*E. coli* O157:H7, O104:H4; *Listeria monocytogenes*	Soilless and hydroponic systems	[12]
Swiss chard	*Salmonella enterica*	Contaminated irrigation water	[45, 46]
Kale, mustard	Murine norovirus	Hydroponics	[12]
Mixed microgreens	Shiga-toxin–producing *E. coli*	Recirculating hydroponic systems	[11]
Rapini	Lower microbial load	Fiber mat systems	[47]

Without proper cooling, microgreens deteriorate quickly through wilting, yellowing, and nutrient degradation. Refrigerated storage at approximately 4 °C can extend shelf life to roughly 7 - 10 days for most varieties by slowing respiration and delaying senescence. Modified-atmosphere packaging, typically involving reduced oxygen concentrations combined with elevated CO_2 levels, has been shown to further inhibit enzymatic browning and microbial proliferation while preserving texture and pigment stability [12, 23]. Humidity regulation within packaging ideally maintaining high RH to reduce moisture loss while preventing condensation is equally important. Handling practices must remain gentle, as the thin hypocotyls and soft cotyledons of microgreens bruise easily, compromising both quality and shelf life. Current research is exploring additional preservation strategies such as edible bio-coatings, natural antimicrobial washes, and controlled ultraviolet (UV) treatments to maintain color, reduce microbial loads, and retain sensitive nutrients during storage. Maintaining a continuous cold chain is essential, especially when microgreens produced in urban farms are distributed to distant retail markets, institutional food programs, or health-focused supply chains.

Market potential and socioeconomic impact

The commercial potential and socioeconomic impact of microgreens have expanded significantly in recent years due to increased consumer interest in nutrient-rich "superfoods" and growing culinary demand for visually appealing, flavorful greens. In high-income regions including North America and Europe microgreens occupy a premium niche in restaurants, specialty grocery outlets, and farmers' markets, where they command substantially higher prices than conventional leafy vegetables. Typical retail values range from USD 20 - 50/kg, and premium blends marketed as "super-mix salads" may achieve even higher price points [48]. Market analyses indicate that the global microgreens industry is growing at an estimated annual rate of 7 - 10%, with North America maintaining the largest market share and the Asia–Pacific region emerging as the fastest-growing segment. High-tech vertical farms frequently identify microgreens as among their most profitable crops due to their rapid turnover, compact production footprint, and high market value [49].

Beyond commercial-scale production, microgreens offer considerable opportunities for smallholders and urban entrepreneurs because of their low start-up costs and minimal land requirements. Simple tray-based systems on balconies, rooftops, or small indoor spaces can be established with basic inputs such as seeds, trays, and low-energy LED lighting. The short production cycle allows weekly harvests, enabling fast financial returns and flexible scheduling. These characteristics make microgreens particularly attractive for women farmers, youth, and self-help groups with limited land access or limited time availability. Initiatives involving women-led cooperatives and community groups in South Asia have demonstrated improvements in household income and dietary quality through microgreen production, illustrating their dual nutritional and economic benefits [48].

Opportunities for value addition further broaden the economic potential of microgreens. Products such as dried or powdered microgreens can be incorporated into nutraceutical supplements, baked goods, beverages, and convenience foods, creating diversified revenue streams. Their natural pigments and antioxidant compounds also offer promising applications in functional foods, cosmetics, and health supplements, expanding market possibilities well beyond fresh produce.

Future Prospects and Strategic Contributions

Microgreens align closely with several SDGs, particularly those related to zero hunger, good health and well-being, gender equality, sustainable cities, responsible production, and climate action. Their production model exemplifies a convergence of nutritional, economic, and environmental advantages, making them highly relevant within contemporary frameworks for resilient and sustainable food systems. As summarized in table 1, microgreens offer substantial potential to contribute to future agricultural and nutritional priorities while simultaneously creating new avenues for research and policy innovation.

Looking ahead, one strategic pathway involves the development of nutrition-sensitive microgreen varieties, including biofortified genotypes or lines selectively bred for elevated concentrations of Fe, Zn, Se, provitamin A carotenoids, or specific antioxidants. Such targeted enhancements could significantly strengthen their role in public health interventions, particularly in regions where micronutrient deficiencies remain widespread. Another priority involves integrating microgreen production within broader urban-agriculture and city-planning policies. Rooftop gardens, peri-urban greenhouses, community vertical farms, and indoor growing hubs could all incorporate microgreens as high-yield, low-resource crops capable of augmenting urban food supply chains.

Entrepreneurship models tailored to local socioeconomic contexts also hold considerable promise. Microcredit-supported microgreen enterprises, particularly those targeting women and youth, could promote economic empowerment while improving household nutrition. The establishment of small-scale microgreen greenhouses or balcony systems supported by training programs has already proven successful in several regions, illustrating the potential for scalable, community-centered adoption.

Rapid advances in precision agriculture present further

transformative opportunities. AI-assisted growth chambers equipped with sensors, automated nutrient dosing, and customizable lighting algorithms could enable the production of microgreens with predetermined nutrient characteristics, such as Fe rich microgreens designed for populations vulnerable to anemia. Similar systems may eventually support the generation of microgreens tailored for specific therapeutic or functional-food applications.

Microgreens have also attracted interest from humanitarian agencies and space research programs. Their compact growth habit, minimal resource requirements, and rapid production cycle make them suitable for deployment in refugee camps, disaster-relief shelters, and other resource-constrained environments where fresh vegetables are scarce. In aerospace research, microgreens are being evaluated as components of regenerative life-support systems for long-duration space missions, where their efficient biomass yield and nutritional profile offer clear advantages. Their adaptability across terrestrial and extraterrestrial settings underscores the broader relevance of microgreens as a future-oriented crop with unique potential to address global challenges (Figure 4 and table 8).

Each of these dimensions illustrates how microgreens can be leveraged to advance SDG 2 (Zero hunger) by improving nutrient intake, SDG 3 (Good health) through disease-preventive diets, SDG 5 (Gender equality) by empowering women entrepreneurs, SDG 11 (Sustainable cities) via urban agriculture, and SDG 12 (Responsible production) through low-impact farming.

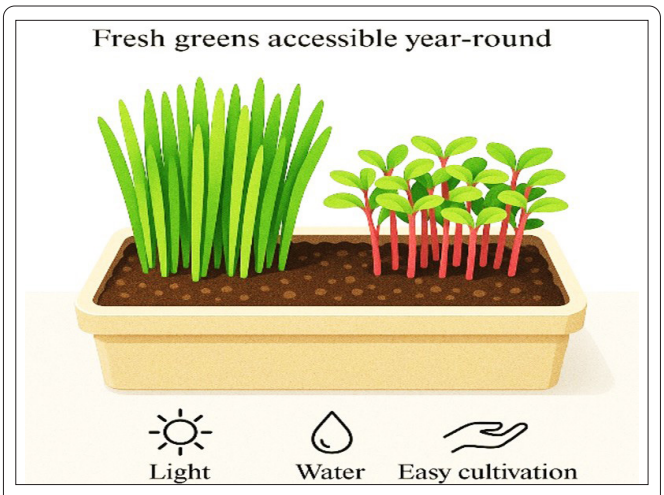


Figure 4: Diverse microgreens (green wheatgrass and amaranth) sprouting in a planter. This illustrates on-site production in urban or home settings, making fresh, nutrient-dense greens accessible in resource-limited environments. Such decentralized cultivation strengthens local food security.

Case Studies

A controlled-environment factorial study by Vrkić et al. [50] provides a technically robust demonstration of how LED spectral quality can be exploited as a precision agronomic lever to enhance the nutritional and functional attributes of microgreens relevant to global food and nutritional security. Broccoli (*B. oleracea* var. *italica*), mustard (*B. juncea*), and garden cress (*Lepidium sativum*) microgreens were cultivated under monochromatic red (R), blue (B), and combined RB LED spectra, and species, light wavelength, and interaction effects were quantified using factorial analysis of variance with statistically validated p-values. Blue light emerged as the dominant driver of dry matter accumulation, indicating increased biomass density and potential post-harvest stability, although species-specific optima were evident, with garden cress responding maximally to red light and mustard to blue light. Spectral effects on color attributes were largely restricted to increased lightness (L*) under blue light without perturbing green chromaticity (a* and b*), preserving visual quality. From a biochemical perspective, microgreens exhibited exceptionally high ascorbic acid concentrations relative to mature Brassicaceae vegetables, with blue light significantly enhancing vitamin C accumulation in broccoli and garden cress, while mustard showed a synergistic response under RB spectra. Secondary metabolism was strongly light- and genotype-dependent, with blue light markedly stimulating total phenolics, non-flavonoids, and flavonoids, particularly in mustard, confirming its role as a potent elicitor of phenylpropanoid pathways. Photosynthetic and photoprotective pigment synthesis showed differential regulation, with mustard accumulating maximal chlorophylls and carotenoids under red light and broccoli under RB spectra, reflecting species-specific spectral integration of pigment biosynthesis. Targeted phenolic profiling further revealed that blue light maximized caffeic and ellagic acids in mustard, RB light enhanced ferulic acid in broccoli, and garden cress accumulated exceptionally high naringin levels under red and RB treatments, highlighting the capacity of LED spectra to selectively modulate individual bioactive compounds. Antioxidant capacity, assessed via ferric

Table 8: Strategic contributions of microgreens to global food and nutritional security.

Dimensions	Microgreens' contribution	Future prospects/needs
Nutrient density	4 - 40 × higher vitamins, minerals, antioxidants; small serving meets large share of recommended dietary allowance (RDA)	Develop biofortified varieties (Fe, Zn, Se, and I) and integrate into school and maternal diets
Production efficiency	7 - 21-day cycle, 5% water of field crops, minimal fertilizers, and pesticide-free potential	Expand renewable-energy CEA and create climate-smart protocols
Urban farming	Suitable for rooftops, balconies, vertical farms and year-round	Include in urban-agriculture policies, subsidize kits, and IoT-enabled home units
Women's livelihood	Low-cost and rapid-return micro-enterprises	Gender-sensitive business models, micro-loans, and training for value-added products
Tech innovation	High compatibility with LED, hydroponics, and AI	Develop AI-driven chambers and affordable sensor systems
Food safety	Few outbreaks and manageable risks	Create global safety standards and rapid pathogen test kits
Value addition	Powders, beverages, supplements, and baked goods	R&D for shelf-stable products and industry partnerships
Consumer acceptance	Attractive colors and flavors boost vegetable intake	Chef collaborations and public health campaigns

ion reducing antioxidant potential (FRAP) and 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid (ABTS) assays, closely tracked phenolic accumulation, with blue-light-grown broccoli and mustard exhibiting the highest reducing power, albeit with assay-specific sensitivity to spectral effects. Collectively, this case study establishes LED spectral optimization as an energy-efficient, genotype-responsive strategy to enhance micronutrient density, antioxidant capacity, and functional phytochemical profiles of microgreens, reinforcing their potential as climate-resilient, high-value crops for urban agriculture and future food-based nutritional security interventions.

Ai et al. [51] demonstrated, through a rigorously controlled preharvest elicitation experiment, that UV a LED (UVA LED) irradiation functions as a precise, non-chemical regulator of growth, antioxidant metabolism, and nitrate safety in Chinese cabbage microgreens, thereby strengthening their relevance to safe, nutrient-dense urban food systems. Dose–response screening (16, 32, and 48 J cm^{-2}) revealed a clear hormetic pattern, with the intermediate dose (32 J cm^{-2}) emerging as optimal by simultaneously maximizing fresh biomass (≈47% increase over control), chlorophyll a and b accumulation, dry matter content (≈2.2 fold), and DPPH-based antioxidant capacity, while higher energy input conferred no proportional gains, indicating physiological saturation. Subsequent pattern analysis at 32 J cm^{-2} showed that fractionated irradiation (four pulses of 8 J cm^{-2}) preferentially enhanced yield and chlorophyll an accumulation, whereas a single-pulse treatment more strongly stimulated chlorophyll b synthesis, lowered the chlorophyll a/b ratio, and elicited greater accumulation of phenolics, flavonoids, and carotenoids, highlighting scheduling-dependent modulation of pigment and secondary metabolic pathways. Both irradiation modes significantly enriched the ascorbate system (total, reduced, and oxidized forms), activated antioxidant enzymes (superoxide dismutase, peroxidase, catalase, and ascorbate peroxidase), and reduced malondialdehyde levels, indicating effective eustress-induced priming with reduced oxidative damage rather than injury. Total antioxidant capacity increased under both patterns, with assay-specific sensitivity showing stronger ABTS responses under single-pulse UVA, reflecting shifts in antioxidant composition. Critically, UVA exposure significantly reduced nitrate accumulation relative to untreated controls, irrespective of delivery pattern, directly addressing a major food-safety concern in leafy microgreens. Collectively, this study establishes preharvest UVA LED management-particularly a 32 J cm^{-2} dose-as a technically sound, energy-efficient, and residue-free strategy to coordinately enhance yield, pigment-based quality, antioxidant nutrition, and nitrate safety in microgreens, reinforcing the role of spectral elicitation as a key tool in future precision horticulture and nutritional security frameworks.

Poudel et al. [52] provides a technically rigorous demonstration that Zn biofortification via fertigation and LED PPFD management can be deployed as largely independent, complementary levers to enhance mineral nutrition, phytochemical density, and resource-use efficiency in pea and radish microgreens under controlled environments. Across both species, Zn rate × PPFD interactions were consistently non-significant for Zn concentration, bioaccessible Zn, bioaccessible fraction, yield traits, mineral composition, and antioxidant parameters, establishing that Zn nutrition and light intensity can be optimized without complex interaction-specific prescriptions. Zn fertigation was the dominant determinant of nutritionally relevant Zn delivery, with pea microgreens showing increases in Zn content from ~72 to ~350 mg kg^{-1} DW and bioaccessible Zn from ~4.3 to ~25.4 mg kg^{-1} fresh weight (FW) as Zn supply rose from 0 to 15 mg L^{-1}, corresponding to an increase in estimated Zn RDA contribution from ~2% to ~11.5%/50 g serving, while radish microgreens exhibited an even stronger response, with Zn content rising from ~51 to ~717 mg kg^{-1} DW, bioaccessible Zn from ~2.0 to ~40.1 mg kg^{-1} FW, and RDA contribution from <1% to ~18%, largely independent of PPFD. In contrast, PPFD primarily structured biomass partitioning and quality, increasing dry matter, pigments, and phytochemical–antioxidant traits while often reducing fresh yield and nitrate concentration and increasing water use, revealing a predictable trade-off between fresh mass productivity and nutritional density. Zn supply exerted secondary effects on dry matter and mineral balance, reflecting nutrient interaction and dilution–concentration dynamics. Multivariate analyses (heatmaps and principal component analysis) confirmed this functional separation, with Zn rate aligning strongly with Zn nutrition and bioaccessibility traits and PPFD aligning with chlorophylls, carotenoids, phenolics, antioxidant capacity, and lower nitrate levels. Collectively, this case study establishes a scalable, nutrition-sensitive microgreen production framework in which Zn biofortification reliably enhances bioaccessible Zn intake from small servings, while PPFD tuning independently modulates phytochemical quality and resource efficiency, offering an evidence-based pathway for designing mineral- and antioxidant-rich microgreens for urban and global food and nutritional security.

A hydroponic biofortification study by Spyrou et al. [53] provides a technically robust, nutrition-sensitive framework for enhancing dietary Se supply through controlled-environment cultivation of neglected and underutilized leafy greens-purslane (*Portulaca oleracea* L.), dandelion (*Taraxacum officinale* L.), and iceplant (*Mesembryanthemum crystallinum* L.)-using sodium selenite/selenium dioxide (SeO_2) supplementation of the nutrient solution. SeO_2 elicited strongly species- and dose-dependent responses, with purslane exhibiting high Se tolerance and consistent fresh biomass gains (≈14 - 19%) across treatments with minimal disruption of dry matter and macronutrient balance, dandelion showing a clear optimum at 4 µM SeO_2 with substantial fresh yield, leaf number, and leaf area increases despite a modest reduction in dry matter, and iceplant displaying a threshold response in which intermediate doses (1 - 2 µM) enhanced growth while 4 µM induced growth suppression associated with nutrient and ionic imbalance. Mineral profiling revealed that Se biofortification could be achieved with limited macronutrient perturbation in purslane, whereas dandelion and iceplant showed Se-dose-dependent shifts in nitrate-N and selected minerals, underscoring the need for crop-specific dose optimization. Se accumulation in edible tissues increased predictably with SeO_2 concentration, with dandelion and iceplant accumulating more Se than

purslane at higher doses, and a 50 g fresh-weight serving of biofortified greens contributing substantially to daily Se requirements (up to ~76% in dandelion, ~67% in iceplant, and ~42% in purslane) while maintaining a low health risk index, indicating nutritional adequacy without exceeding safety thresholds. Antioxidant responses, assessed via FRAP and trolox equivalent antioxidant capacity, were selectively enhanced by SeO_2, with purslane and iceplant responding optimally at lower doses (≈1 μM) and dandelion at higher Se supply, alongside species-specific modulation of phenolic profiles. Collectively, this case study establishes hydroponic Se biofortification of underutilized leafy greens as a technically sound, safe, and scalable strategy to improve micronutrient density and functional quality of diets, particularly within urban and controlled-environment food systems aimed at strengthening food and nutritional security.

Rao et al. [54] provides a technically rigorous food-safety case study demonstrating that seed-borne contamination constitutes a primary and persistent entry route for major foodborne pathogens in controlled-environment microgreen production systems. Using dip-inoculated seeds of four Brassicaceae microgreens (daikon, broccoli, mustard, and red cabbage) with defined low (~3 log CFU g^{-1} seed) and high (~5 log CFU g^{-1} seed) inocula of *S. enterica*, *E. coli* O157:H7, or *L. monocytogenes*, and growing them under standardized warm, humid conditions typical of commercial microgreen production, the authors showed consistent transfer of all pathogens from seed to edible shoots and their persistence through harvest (14 days). Pathogen populations on shoots declined between day 7 and day 14 but remained readily detectable across all crops, with high-inoculum treatments sustaining ~4 - 5 log CFU g^{-1} for *E. coli* and *Salmonella* and similarly elevated levels for *Listeria*, indicating that time alone is insufficient for microbial inactivation under these conditions. Between-crop differences were generally minor and often not statistically significant, suggesting that within a single botanical family and uniform production environment, initial seed contamination level exerts a stronger influence on risk than species identity. Critically, pathogens also disseminated into the initially pathogen-free soil–compost substrate, establishing a secondary reservoir that persisted across the production cycle, particularly for *E. coli* and *Salmonella*, thereby increasing the risk of cross-contamination within and between batches. This study highlights a fundamental constraint for scaling microgreens in nutrition-sensitive food systems: the environmental conditions that optimize rapid biomass accumulation simultaneously favor pathogen survival, making preventive controls at the seed stage, strict sanitation, and substrate hygiene indispensable prerequisites for the safe expansion of microgreen-based strategies aimed at global food and nutritional security.

Ivey et al. [55] provides a technically critical synthesis of food-safety intervention evidence in hydroponic fresh-produce systems, with direct implications for the scalable and safe expansion of microgreens as nutrition-dense controlled-environment crops. From an initial corpus of 1,195 records, 131 studies met inclusion criteria, over half of which were published after 2015, reflecting rapid but still immature growth of the evidence base. The literature is heavily skewed toward bacterial hazards (≈90%), particularly *Salmonella* spp., Shiga toxin-producing *E. coli*, and *L. monocytogenes*, while viral pathogens and several relevant foodborne agents remain under-represented; moreover, widespread reliance on indicator organisms or surrogates raises concerns about ecological validity, as surrogate behavior often fails to predict pathogen persistence in plant-hydroponic interfaces. Crop coverage is similarly unbalanced, with lettuce dominating leafy-green studies, whereas sprouts and microgreens are sparsely represented despite their high-risk production traits and growing nutritional prominence. A major methodological limitation identified is incomplete reporting of hydroponic system design, with over one-third of studies not specifying system type and many using produce from unknown commercial systems, undermining system-specific risk interpretation critical for microgreens, where recirculating water, dense canopies, and biofilm-prone materials shape contamination dynamics. Only 32 studies evaluated interventions, encompassing 53 strategies largely dominated by chemical sanitizers (chlorine and peroxyacetic acid), followed by physical treatments (UV, irradiation, pressure, heat, and plasma), with minimal exploration of biological controls; intervention efficacy was highly context-dependent and frequently limited on roots and hydroponic surfaces, consistent with biofilm protection and structural complexity, and no single approach reliably eliminated pathogens once established. Critically, only five intervention studies met stringent quality benchmarks for reproducibility and data transparency, constraining evidence-based recommendations. Collectively, this case study underscores that the nutritional promise of microgreens can only be realized at scale through prevention-focused, system-specific food-safety frameworks and the development of biologically informed, multi-hurdle control strategies, rather than reliance on downstream sanitization in hydroponic environments.

Conclusion

Microgreens represent a unique convergence of high nutritional value, production efficiency, and socioeconomic opportunity, making them increasingly relevant for future food and nutrition strategies. Their rapid growth cycle, minimal resource requirements, and compatibility with diverse production systems ranging from household trays to advanced vertical farms provide practical pathways for improving dietary diversity and access to fresh vegetables in both urban and rural settings. Their nutrient richness, particularly in vitamins, minerals, antioxidants, and bioactive compounds, positions them as effective tools for combating micronutrient deficiencies and reducing risks of diet-related NCDs. Continued innovation in substrates, LED lighting, nutrient management, and AI-driven environmental control will further enhance yield, quality, and the precision tailoring of nutrient profiles. At the same time, microgreens offer scalable livelihood opportunities for women, youth, and smallholders through low-cost, rapid-return enterprises and value-added products. Integrating microgreens into urban agriculture policies, school feeding programs, and community nutrition initiatives could significantly strengthen local food systems. As global populations grow and climate pressures

intensify, microgreens are poised to evolve from specialty crops into essential components of resilient, nutrition-sensitive agriculture worldwide.

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None.

Conflict of Interest

None.

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