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Microgreens for nutritional resilience: A comprehensive review

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Abstract
Microgreens, the tender young seedlings of vegetables and herbs, have garnered significant attention in recent years due to their rapid growth, dense nutrient composition, and applications in urban agriculture. Harvested typically within 7 to 21 days after germination, they are consumed at the cotyledonary leaf stage. This review synthesizes available literature on the taxonomic diversity, cultivation practices, nutritional and phytochemical composition, health benefits, postharvest management, and future prospects of microgreens. Emerging evidence suggests that microgreens possess significantly higher concentrations of vitamins, minerals, and antioxidants than their mature counterparts. Studies also highlight their potential role in reducing the risk of chronic diseases and their promising integration into biofortification and sustainable farming systems. For instance, a comparative analysis revealed that radish microgreens contained 147 mg of vitamin C per 100g fresh weight—substantially higher than mature radish leaves. Another study demonstrated that mustard microgreens exhibit high total phenolic content and antioxidant capacity, contributing to improved lipid metabolism in obese rat models. Nutritional profiling data shows that red cabbage microgreens contain 147 mg/100 g FW of vitamin C, red amaranth microgreens offer up to 50 mg/100 g FW of iron, and sunflower microgreens provide around 65 mg/100 g FW of calcium, indicating their immense potential to enhance micronutrient intake in human diets.

Keywords: Microgreens, nutritional resilience, urban agriculture, phytochemicals

1. Introduction
Microgreens are young vegetable greens harvested just after the cotyledon leaves have developed and before the first true leaves appear. Their rapid growth cycle, high nutritional density, and ease of cultivation have propelled them into prominence as functional foods and dietary supplements (Kyriacou *et al.*, 2016; Benincasa *et al.*, 2019) [6, 1]. Microgreens have emerged as a novel functional food category, bridging the gap between sprouts and mature leafy vegetables. Their cultivation aligns with modern demands for fresh, nutrient-rich, and space-efficient crops. These young greens are typically harvested between 7 to 21 days after germination, when they have developed their cotyledonary leaves and sometimes their first true leaves. Unlike sprouts, microgreens are grown in soil or soilless media and are harvested without roots, which contribute to better food safety. Their popularity stems from multiple converging trends including the rise of gourmet cuisine, urban agriculture, and growing awareness of the health benefits of phytonutrients. The minimal space requirement, fast growth cycle, and low input needs make microgreens suitable for sustainable agriculture, particularly in urban settings and controlled environments. In the context of global food security, especially in urban areas with limited agricultural space, microgreens provide a promising avenue for improving both dietary quality and agricultural sustainability. As such, they have the potential to contribute to nutrition-sensitive agriculture strategies aimed at combating micronutrient deficiencies and promoting health.

2. What are microgreens?
Microgreens encompass a wide range of plant species spanning various botanical families, each offering distinct sensory attributes and nutrient profiles. This diversity allows growers and

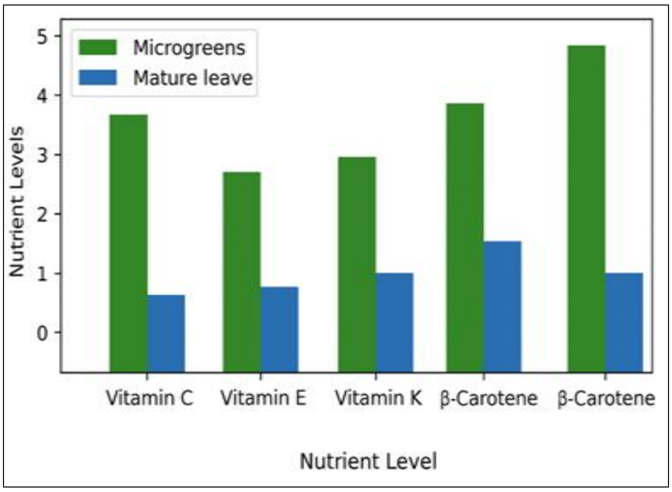
consumers to choose from a broad palette of colors, flavors, and textures. Common plant families used for microgreen production include Brassicaceae (e.g., broccoli, mustard, kale, arugula), Amaranthaceae (e.g., beet, amaranth), Fabaceae (e.g., pea, chickpea, fenugreek), Asteraceae (e.g., lettuce, chicory, sunflower), and Lamiaceae (e.g., basil, mint). These species vary in their germination rates, growth duration, biomass yield, and tolerance to environmental conditions, influencing their suitability for different growing systems. Brassicaceae members are particularly popular due to their rapid growth and high concentrations of glucosinolates, while Amaranthaceae microgreens are known for vibrant pigmentation and antioxidant capacity. Understanding the taxonomic background helps in selecting suitable species based on target nutrients, flavor profiles, and agronomic compatibility. Such diversity not only offers culinary and nutritional variety but also enables year-round cultivation and functional blending to enhance dietary benefits. Research continues to evaluate lesser-known species for microgreen cultivation to further broaden the diversity and nutritional potential of this crop category (Treadwell *et al.*, 2010) [14].

3. Cultivation Practices

Microgreen cultivation can be carried out in a range of systems including traditional soil beds, soilless media (coconut coir, peat moss), and hydroponic systems (e.g., NFT, DWC). Environmental parameters such as light intensity and spectrum, humidity, temperature, and irrigation frequency are critical for optimizing growth and nutrient content. The use of artificial lighting, particularly LEDs, has revolutionized microgreen production by allowing precise control over photoperiod and light quality, thereby influencing morphology and phytochemical composition. Red and blue wavelengths are often used to stimulate chlorophyll synthesis and enhance antioxidant production. Light quality, particularly LED spectral composition, significantly affects microgreen morphology and phytochemical accumulation. Recent studies have shown that tailored LED light combinations can enhance both yield and the synthesis of bioactive compounds like flavonoids and glucosinolates (Zhou *et al.*, 2023) [21]. Hydroponic cultivation minimizes soil-borne disease risks and is efficient in water and nutrient usage, making it ideal for vertical farming and urban agriculture. Seed density, sowing depth, and harvest timing significantly impact yield and quality. Standard practices recommend high seed density and shallow sowing to ensure uniform germination. Regular misting is used to maintain adequate moisture levels during germination, followed by controlled irrigation. These practices must be tailored to the specific needs of different species. Moreover, organic cultivation methods are increasingly favored for reducing chemical input and appealing to health-conscious consumers. Cultivation success is therefore dependent on an integrative approach involving cultivar selection, system design, and environmental control (Graamans *et al.*, 2018) [4].

4. Nutritional and Phytochemical Composition

Microgreens are reported to have significantly higher concentrations of vitamins, minerals, and antioxidants compared to their mature counterparts. For instance, microgreens of red cabbage, cilantro, and garnet amaranth have shown elevated levels of ascorbic acid, tocopherols, and polyphenols (Renna *et al.*, 2018) [12]. These findings emphasize their potential role in addressing micronutrient deficiencies and oxidative stress-related disorders. Microgreens are renowned for their rich concentration of nutrients and bioactive compounds, which are generally higher than in their mature counterparts. Research indicates that microgreens contain elevated levels of essential vitamins such as A, C, E, and K; important minerals including calcium, magnesium, potassium, iron, and zinc; and a variety of secondary metabolites like polyphenols, carotenoids, flavonoids, and glucosinolates. For instance, red cabbage microgreens were found to contain six times more vitamin C and forty times more vitamin E compared to mature leaves (Xiao *et al.*, 2012) [16]. These compounds contribute to the antioxidant, anti-inflammatory, and anti-cancer properties attributed to microgreens. The concentration and type of nutrients vary with species, growth conditions, and developmental stage. Light quality, especially exposure to blue and UV-A wavelengths, can significantly enhance antioxidant content. Microgreens from the Brassicaceae family are rich in glucosinolates, which are metabolized into isothiocyanates with potential anti-cancer properties. Carotenoid-rich species such as amaranth and basil also offer significant provitamin A activity. A study by Choe *et al.* (2018) [3] reported that broccoli microgreens had significantly higher levels of lutein and zeaxanthin compared to mature heads, enhancing their role in eye health. These attributes position microgreens as a potent dietary intervention for enhancing nutrient intake and supporting disease prevention, especially in urban populations with limited access to fresh produce (Zhang *et al.*, 2021) [18].



5. Functional and Therapeutic Benefits

The bioactive constituents of microgreens endow them with multiple health-promoting properties. The presence of bioactive compounds such as sulforaphane, lutein, and anthocyanins contributes to the functional value of microgreens. These compounds have been associated with anti-inflammatory, anti-cancer, and cardioprotective effects (Renna *et al.*, 2018; Benincasa *et al.*, 2019) [12, 1]. Antioxidants such as polyphenols and flavonoids neutralize reactive oxygen species, reducing oxidative stress and preventing cellular damage. This has implications in mitigating the progression of chronic conditions like cardiovascular disease, diabetes, and certain cancers. Animal model studies have provided preliminary evidence of these benefits. For example, fenugreek microgreens significantly improved glucose tolerance and lipid profiles in diabetic rats, suggesting potential antidiabetic properties (Mir *et al.*, 2021) [8]. Similarly, red cabbage microgreens reduced hepatic cholesterol and systemic inflammation in mouse models, demonstrating cardioprotective effects (Xiao *et al.*, 2012) [16]. Glucosinolates in Brassicaceae microgreens degrade into isothiocyanates that modulate detoxification enzymes and inhibit tumor cell proliferation. A study by Chandra *et al*. (2021) [2] showed that microgreens of mustard and radish exhibit notable antimicrobial activity due to their high phytochemical content. Additionally, microgreens contribute to gut health by delivering fiber and prebiotic compounds. Despite promising results, human clinical trials are needed to validate these effects. Nonetheless, the integration of microgreens into daily diets offers a practical and appealing strategy to augment nutrient intake and reduce the risk of diet-related noncommunicable diseases. Their ease of incorporation into salads, smoothies, and garnishes makes them an accessible functional food for a wide demographic (Pérez-López *et al*., 2021) [10].

6. Postharvest Physiology and Shelf-Life Management

Postharvest handling of microgreens is critical due to their high metabolic rate and moisture content, which predispose them to rapid deterioration. Physiological factors such as respiration rate, ethylene sensitivity, and tissue fragility impact their shelf life. To maintain freshness and nutritional integrity, several preservation strategies are employed. Modified atmosphere packaging (MAP) helps reduce oxygen levels and increase carbon dioxide concentration, slowing respiration and microbial growth. Edible coatings made from natural polymers like chitosan or aloe vera form a protective barrier against moisture loss and oxidation. Cold storage at 4°C remains the standard practice to retard enzymatic activity and microbial proliferation. Storage conditions significantly influence the shelf life and quality of microgreens. For example, radish microgreens stored at 5°C under micro-perforated films maintained better texture and antioxidant content over 14 days (Xiao *et al*., 2014) [17]. Additionally, color and phytochemical retention in broccoli microgreens are greatly affected by temperature and duration of storage (Zhang *et al*., 2016) [19]. Additionally, non-thermal treatments such as UV-C irradiation have shown efficacy in preserving antioxidant levels and reducing spoilage organisms without compromising sensory quality (Liu *et al*., 2022) [7]. Optimal postharvest practices must also include hygienic harvesting, proper drainage to avoid microbial contamination, and minimal handling to prevent mechanical damage. From a safety standpoint, microgreens are susceptible to microbial contamination due to their dense canopy and high humidity environments. Therefore, rigorous hygienic practices are essential from cultivation through postharvest handling (Riggio *et al*., 2019) [13]. Pereira *et al*. (2020) [9] demonstrated that microgreens coated with aloe vera and stored at low temperatures retained higher chlorophyll content and showed reduced microbial load over a 7-day period. Further innovations in packaging materials, smart sensors, and cold chain logistics could improve shelf stability and reduce postharvest losses, enhancing the commercial viability of microgreens (Zhou *et al*., 2022) [20].

7. Few Case Studies

Case Study 7.1: Diversity and Nutrient Density in Brassicaceae

A study conducted at the University of Maryland evaluated 25 varieties of microgreens across five families. The results showed that Brassicaceae members (e.g., red cabbage, mustard, broccoli) had the highest concentrations of ascorbic acid and total phenolics. Red cabbage, in particular, stood out with its high vitamin C and E content (Xiao *et al*., 2012) [16]. This diversity supports targeted functional food development based on health benefits and consumer preference.

Case Study 7.2: Hydroponic Microgreen Production in Urban India

A startup in Bengaluru, India, implemented hydroponic vertical farming for growing microgreens such as basil, mustard, and sunflower. With LED lighting and automated nutrient dosing, the company achieved harvests every 10-12 days and reported a 25% increase in antioxidant levels under red-blue light spectra. The project also reduced water use by 90% compared to conventional soil systems and became a local supplier to premium restaurants (Rai *et al*., 2023) [11].

Case Study 7.3: Red Cabbage Microgreens and Antioxidant Potential

Xiao *et al*. (2012) [16] studied red cabbage microgreens and found that they contained up to 147 mg/100 g FW of vitamin C, which is six times higher than that of mature red cabbage. Additionally, they had elevated levels of polyphenols and carotenoids. The results confirmed their superior nutritional status, positioning them as potential candidates for functional food applications and health interventions.

Case Study 7.4: Anti-obesity Effects of Mustard Microgreens

A 2021 study conducted by Mir *et al*. investigated the effects of mustard microgreens on obese rat models. The rats that consumed microgreen-enriched feed showed a significant reduction in total cholesterol, LDL cholesterol, and body fat percentage. Liver enzyme levels also improved, suggesting hepatoprotective activity. The study attributed these effects to the presence of flavonoids and glucosinolates, reinforcing their functional food value.

Case Study 7.5: Antidiabetic Activity of Fenugreek Microgreens

In a randomized animal trial, diabetic rats fed with fenugreek microgreens (500 mg/kg) exhibited improved blood glucose regulation and insulin sensitivity compared to the control group (Mir *et al*., 2021) [8]. This suggests that these microgreens could be explored as dietary supplements in managing type2 diabetes.

Case Study 7.6: Aloe Vera Coating to Extend Shelf Life

Pereira *et al*. (2020) [9] applied aloevera gel coating to sunflower and radish microgreens and stored them at 4°C. The coated microgreens retained over 90% of chlorophyll content after 7 days, compared to 60% retention in uncoated controls. The microbial load was also significantly lower in coated samples, proving the efficacy of edible coatings for commercial shelf-life extension.

Case Study 7.7: Selenium Biofortification in Broccoli Microgreens

Kyriacou *et al*. (2021) [5] tested selenium enrichment in broccoli microgreens through foliar application of sodium selenate. The selenium-enriched microgreens demonstrated a 2-3 fold increase in antioxidant activity without adverse effects on growth. This method could address selenium deficiency in human diets, especially in regions with selenium-poor soils.

Case Study 7.8: Microgreens in School Nutrition Programs

In a pilot initiative by a school district in California, microgreens were introduced into student meals via indoor classroom growing kits. Students engaged in planting, tending, and harvesting microgreens, which were later included in salads and sandwiches. This increased vegetable acceptance and improved nutrition awareness, supporting microgreens as tools for nutrition education and behavior change.

8. Future Perspectives and Challenges

The future of microgreens lies in their integration into sustainable food systems, urban agriculture, and health-oriented diets. Biofortification presents a promising opportunity; for instance, selenium-enriched broccoli and basil microgreens have demonstrated improved antioxidant potential and nutrient density (Kyriacou *et al*., 2021) [5]. Urban farming initiatives, including rooftop gardens and container-based systems, benefit from the short growth cycle and high turnover rate of microgreens, making them ideal for local, fresh produce supply chains. As microgreens continue to gain popularity, future research should focus on optimizing controlled-environment agriculture (CEA) parameters, developing nutrient-specific cultivars, and exploring novel substrates. The rise of plant factories and vertical farming systems offers new avenues for year-round, clean production (Kyriacou *et al*., 2016; Zhou *et al*., 2023) [6, 21]. However, challenges persist. The lack of standardized cultivation protocols and nutritional labeling regulations limits their market potential. Variability in nutrient content due to genetic and environmental factors complicates health claims. Additionally, large-scale production faces obstacles related to automation, cost-efficiency, and postharvest preservation. A study by Weber (2017) [15] highlighted the economic viability of microgreens in urban agriculture, noting high yield per unit area and consumer willingness to pay a premium for freshness and nutritional value. Recent advancements in precision agriculture, IoT-based monitoring, and data-driven cultivation models have begun to address some of these barriers (Rai *et al*., 2023) [11]. More interdisciplinary research is needed to understand genotype-environment interactions, consumer preferences, and long-term health outcomes. Policymaking support in terms of subsidies, training programs, and quality certification can enhance adoption. In summary, while microgreens offer substantial nutritional, economic, and environmental benefits, addressing the existing gaps through innovation, regulation, and education will be critical to realizing their full potential.

9. Conclusion

Microgreens have emerged as a promising component of sustainable and health-oriented food systems due to their rapid growth cycle, high nutrient density, and adaptability to various cultivation environments. This review highlights their taxonomic diversity, efficient agronomic practices, and significant concentrations of vitamins, minerals, and phytochemicals, which collectively contribute to their functional and therapeutic potential. Despite their early developmental stage, microgreens exhibit superior nutritional profiles compared to mature vegetables, offering considerable benefits in the prevention of diet-related chronic diseases. Advances in controlled environment agriculture, hydroponic technologies, and postharvest management have further strengthened the viability of microgreens as a commercial crop. However, challenges remain, including the need for standardized production protocols, improved shelf-life strategies, and comprehensive clinical studies to substantiate health claims. Future research should focus on genotype-environment interactions, biofortification strategies, and consumer acceptance to optimize both agronomic performance and nutritional outcomes. With appropriate scientific, technological, and policy support, microgreens hold significant potential for integration into urban agriculture, functional food development, and public health nutrition strategies.

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