

Growing Techniques and Applications of Microgreens

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Abstract

Microgreens are young, edible seedlings harvested shortly after the development of cotyledons and the emergence of the first true leaves. They have gained considerable attention in recent years because of their attractive appearance, distinctive flavours, short production cycle, and potential nutritional benefits. A wide range of plant species, including cereals, legumes, leafy vegetables, herbs, and cruciferous crops, can be cultivated as microgreens. Their production requires limited space and can be adapted to indoor farming, greenhouse cultivation, vertical farming, and household gardening. Successful cultivation depends on seed quality, growing media, water availability, temperature, light intensity, and harvesting practices. Microgreens are reported to contain various vitamins, minerals, phenolic compounds, carotenoids, and other phytochemicals, although their composition varies considerably among species and growing conditions. They are used in salads, sandwiches, soups, garnishes, functional food products, and sustainable urban food systems. However, microbial contamination, short shelf life, production costs, and the lack of standardized cultivation practices remain important challenges. This review discusses the cultivation techniques, environmental requirements, nutritional properties, harvesting and post-harvest management, food and health applications, and major challenges associated with microgreen production. The review highlights the potential of microgreens as nutrient-rich foods and promising crops for sustainable agriculture, while emphasizing the need for improved production protocols, food safety measures, and further scientific research.

1. Introduction

Microgreens are young vegetable greens

produced from the seeds of vegetables, herbs, and other edible plants. They are generally

harvested when the cotyledons are fully developed and the first true leaves have appeared, usually within approximately 7–21 days after sowing, depending on the species and growing conditions. They are distinct from sprouts, which are commonly consumed at an earlier developmental stage, and baby greens, which are grown for a longer period before harvest. Microgreens are cut above the growing medium, and their roots are generally not included in the harvested product (Xiao *et al.*, 2012). The growing interest in microgreens is associated with their short production cycle, high market value, diverse flavours, attractive colors, and potential contribution to dietary diversity. Species belonging to the families Brassicaceae, Amaranthaceae, Fabaceae, Apiaceae, and Asteraceae are commonly used for microgreen production. Popular crops include radish (*Raphanus sativus*), broccoli (*Brassica oleracea*), mustard (*Brassica juncea*), red amaranth (*Amaranthus* spp.), sunflower (*Helianthus annuus*), pea (*Pisum sativum*), and coriander (*Coriandrum sativum*). Microgreens have attracted scientific interest because certain species contain appreciable concentrations of vitamins, carotenoids, phenolic compounds, and other bioactive constituents. Xiao *et al.* (2012) demonstrated that the nutritional composition of microgreens varies considerably among species and that some microgreens contain higher concentrations of selected vitamins and carotenoids than their mature counterparts on a

fresh-weight basis. However, these differences are species-specific and should not be generalized to all microgreens. Microgreen cultivation can be undertaken in homes, schools, research laboratories, commercial greenhouses, and controlled-environment farms. Production can take place in soil-based media, soilless substrates, or hydroponic systems. Because the crop can be harvested within a short period, successive sowing allows growers to maintain a regular supply throughout the year. This makes microgreens potentially useful in urban agriculture, educational activities, and localized food production. According to Kyriacou *et al.* (2016), microgreens represent an emerging horticultural crop with considerable potential for improving dietary diversity and supporting innovative production systems. Nevertheless, commercial development requires attention to seed selection, environmental management, crop hygiene, harvesting methods, and post-harvest storage. The present review examines the principal cultivation methods and applications of microgreens, with particular emphasis on their horticultural, nutritional, commercial, and sustainability-related significance.

2. Classification and Selection of Microgreen Crops

Microgreens can be produced from a wide range of edible plant species. The choice of crop depends on seed availability, germination

percentage, growth rate, flavour, color, nutritional composition, market demand, and ease of cultivation. Some species produce harvestable microgreens within a week, whereas others require two to three weeks or longer. Crop-specific differences in seed size, seed coat characteristics, root development, and shoot growth influence the selection of appropriate production techniques (Kyriacou *et al.*, 2016; Teng *et al.*, 2023).

2.1 Major groups of microgreens

Brassicaceae microgreens: Broccoli, radish, mustard, cabbage, kale, and cauliflower are widely cultivated because of their rapid germination, characteristic flavours, and phytochemical composition. Brassicaceae species are particularly interesting because they contain glucosinolates and related compounds, although their concentrations vary according to species, cultivar, and growth conditions.

Amaranthaceae microgreens: Amaranth, beet, and Swiss chard are valued for their colourful stems, leaves, and attractive appearance. Red amaranth is especially useful in salad preparation and culinary decoration because of its reddish-purple pigmentation.

Fabaceae microgreens: Pea, chickpea, lentil, and other edible legumes can be cultivated for their tender shoots and distinctive flavours. Pea shoots are commonly used in salads, stir-fried dishes, and sandwiches.

Apiaceae microgreens: Coriander, carrot, celery, and fennel are grown for their characteristic aromas and flavours. These crops

may require comparatively longer germination periods than radish or mustard. Other crops: Sunflower, wheat, buckwheat, basil, and lettuce are also cultivated as microgreens. Sunflower microgreens produce succulent shoots, while basil provides aromatic leaves suitable for culinary applications. Xiao *et al.* (2012) reported considerable variation in the nutrient profiles of different microgreen species. Consequently, selecting a diverse range of crops can improve the sensory and nutritional variety of microgreen products.

2.2 Selection of seeds

Seed quality is one of the most important determinants of successful microgreen production. Seeds should have high germination capacity, good vigour, uniform size, and freedom from visible mould, insect damage, and foreign materials. Seeds intended for edible microgreen production should be obtained from reliable suppliers and handled according to food-safety requirements. Seeds treated with chemicals that are not approved for edible seedling production should not be used. Similarly, untreated seeds are not necessarily free from pathogens. Seed-borne microorganisms can multiply under moist growing conditions, making seed sourcing and sanitation essential components of production management (Turner *et al.*, 2020).

3. Growing Techniques and Production Systems

Microgreens can be cultivated using conventional soil-based methods, soilless substrates, hydroponics, and controlled-environment systems. The appropriate technique depends on the scale of production, available resources, target crop, water quality, and intended market. Teng et al. (2023) reviewed the use of microgreens in household, commercial, and space-farming systems and highlighted the flexibility of these crops across different production environments.

3.1 Soil-based cultivation

Soil-based cultivation is one of the simplest methods for producing microgreens. Shallow trays or containers are filled with clean, well-drained growing soil or a suitable growing mixture. Seeds are distributed evenly over the surface and covered lightly when required by the species. Gentle irrigation maintains moisture during germination without waterlogging the medium. A suitable soil mixture should provide physical support, sufficient aeration, moisture retention, and appropriate drainage. Excessively compacted or contaminated soil can reduce germination and increase the likelihood of root diseases and microbial contamination. Clean containers and potable irrigation water should be used to minimize contamination risks. Soil-based cultivation is particularly suitable for household gardens, educational institutions, and small-scale growers because it requires relatively simple equipment. However, soil variability, weed seeds, pests, and difficulties in

maintaining uniform moisture can limit consistency in commercial production (Turner *et al.*, 2020).

3.2 Soilless substrate cultivation

Soilless cultivation involves growing microgreens in substrates such as coco coir, peat-based mixtures, perlite-containing media, vermiculite, and suitable biodegradable fibre mats. These materials provide physical support and influence water retention, aeration, drainage, and root development. Coco coir is commonly used because of its water-holding capacity and availability in many tropical regions. Fibre mats offer a relatively uniform growing surface and may simplify harvesting and handling. Peat-based substrates can also provide favourable physical properties, although environmental considerations associated with peat extraction have encouraged the evaluation of alternative materials. The performance of a substrate depends on its physical structure, chemical characteristics, cleanliness, and ability to maintain moisture without restricting oxygen supply. Di Gioia et al. (2017) investigated sustainable substrates for microgreen production, illustrating the importance of evaluating alternative materials for crop growth and production efficiency. Substrates should be selected based on their suitability for edible crop production rather than appearance alone. Reusing growing media without validated cleaning or treatment can introduce pathogens and compromise crop safety (Turner *et al.*,

2020).

3.3 Hydroponic cultivation

Hydroponics is a soilless production technique in which plants receive water and, where required, dissolved mineral nutrients through a managed solution. Microgreens can be grown on inert supports, fibre mats, or other suitable substrates supplied with water or nutrient solution. Hydroponic systems offer several potential advantages, including reduced dependence on agricultural soil, easier management of irrigation, and improved uniformity when environmental and nutrient conditions are properly controlled. They can be adapted to small indoor units or larger commercial production facilities. However, microgreens have a short growth cycle, and the need for added fertilizer varies by species, substrate, seed reserves, and water quality. Nutrient supplementation should therefore be based on crop requirements rather than automatically applying concentrations designed for mature leafy vegetables. Excessive nutrient supply can increase production costs and affect crop quality. Water quality, solution composition, irrigation frequency, and drainage must be carefully managed. Recirculating systems require particular attention because contaminated water can distribute microorganisms throughout the growing area. Hydroponics should not be considered inherently safer than soil cultivation; hygiene and monitoring remain essential in either system

(Turner *et al.*, 2020; Teng *et al.*, 2023).

3.4 Indoor cultivation and vertical farming

Indoor microgreen production allows growers to control light, temperature, irrigation, and other environmental factors. Trays can be arranged on shelves or racks to increase production per unit of floor area. Vertical farming systems may incorporate automated irrigation, programmable LED lighting, temperature control, and environmental monitoring. This technique is useful in urban areas where agricultural land is limited. Production can continue throughout the year, reducing dependence on seasonal outdoor conditions. Indoor cultivation also offers opportunities for standardized sowing, harvesting, and quality control. Nevertheless, artificial lighting, cooling, ventilation, and automation require energy and capital investment. Poor ventilation and excessive humidity can encourage fungal growth, while inadequate cleaning can allow contamination to persist. The economic and environmental performance of indoor systems therefore depends on efficient resource management and appropriate facility design (Teng *et al.*, 2023).

4. Environmental Factors Influencing Growth and Yield

Successful microgreen production depends on the interaction of environmental conditions, seed characteristics, and cultivation practices. Managing these factors improves germination,

shoot development, color, texture, biomass production, and nutritional composition. Kyriacou et al. (2016) and Teng et al. (2023) emphasize the importance of optimizing growing conditions for consistent crop quality.

4.1 Light intensity and quality

Light is essential for photosynthesis, chlorophyll development, and normal seedling growth. Microgreens can be cultivated under natural sunlight, artificial lighting, or a combination of both. In indoor systems, light-emitting diodes (LEDs) are commonly used because they permit control over light intensity, photoperiod, and spectral composition. Red and blue wavelengths influence photosynthesis and plant morphology, while the effects of other wavelengths depend on the species and production conditions. Light exposure can also modify concentrations of pigments and secondary metabolites, including carotenoids, anthocyanins, and phenolic compounds. Insufficient light may produce elongated, pale seedlings with weak stems. Excessive light intensity can cause stress, reduce growth, or increase energy costs without providing a proportional increase in yield. The optimum lighting regime should therefore be determined for each crop rather than applying a single standard to all species (Kyriacou *et al.*, 2016; Teng *et al.*, 2023).

4.2 Temperature and humidity

Temperature influences seed germination, enzyme activity, respiration, and seedling

growth. Most commonly cultivated microgreens grow well under moderate temperatures, but the optimum range varies according to species. Cool-season crops and warm-season crops may respond differently to the same temperature regime. Relative humidity affects water loss, seedling hydration, and the development of fungal diseases. High humidity combined with poor ventilation can favour damping-off and other microbial problems. Very low humidity may accelerate drying and reduce seedling quality. A suitable balance between temperature, humidity, and airflow is therefore essential. Growers should monitor the actual growing environment and modify irrigation or ventilation when condensation and persistent surface moisture occur (Turner *et al.*, 2020; Teng *et al.*, 2023).

4.3 Water and nutrient management

Water is required for seed imbibition, germination, nutrient transport, and cellular expansion. Both inadequate irrigation and excessive watering can reduce crop quality. Water deficiency may result in poor germination and wilting, whereas waterlogging restricts oxygen availability around roots and can encourage microbial growth. Bottom watering, in which water is supplied beneath the growing tray or substrate, may reduce direct wetting of leaves and help maintain a relatively dry canopy. However, the method does not eliminate the risk of contamination if the water or substrate is contaminated. Because microgreens are

harvested young, seed reserves can support much of their initial growth. Additional nutrients may be useful in some production systems, but their requirement varies with crop species, seed size, substrate, water composition, and harvest stage. Nutrient management should aim to achieve satisfactory yield and quality without unnecessary fertilizer use (Kyriacou *et al.*, 2016; Teng *et al.*, 2023).

4.4 Seed density and ventilation

Sowing density determines how closely seedlings grow together. High density can increase the number of shoots harvested per tray, but excessive crowding may reduce airflow, encourage moisture retention, and produce uneven growth. Low density can improve individual plant development but reduce yield per unit area. The appropriate sowing rate depends on seed size, germination percentage, species, tray dimensions, and production objectives. Large seeds, such as pea and sunflower, generally require different spacing and handling from small seeds such as mustard and amaranth. Maintaining uniform seed distribution, suitable irrigation, and adequate ventilation helps reduce competition and supports consistent growth. Crop trials should be conducted to determine the most productive density for each species (Teng *et al.*, 2023).

5. Nutritional Composition and Phytochemical Properties of Microgreens

Microgreens are recognized as a promising

source of dietary nutrients and plant-derived bioactive compounds. Their nutritional composition depends on plant species, cultivar, seed quality, growing medium, light exposure, temperature, water availability, and harvesting stage. Although some microgreens contain high concentrations of selected nutrients, their nutritional superiority over mature vegetables is not universal (Xiao *et al.*, 2012; Turner *et al.*, 2020).

5.1 Vitamins and minerals

Microgreens may contain vitamin C, vitamin E, vitamin K, carotenoids, and various minerals. Xiao *et al.* (2012) examined the nutrient profiles of 25 commercially available microgreen species and documented substantial differences among species in ascorbic acid, carotenoids, phyloquinone, and tocopherols. The nutrient concentration of a particular microgreen should be interpreted in relation to the plant species, fresh-weight or dry-weight basis, growing conditions, and analytical method. Differences in water content can influence comparisons expressed per unit of fresh weight. Microgreens can contribute to dietary diversity, but they should be consumed as part of a balanced diet rather than treated as replacements for all mature vegetables.

5.2 Phenolic compounds and antioxidant activity

Phenolic compounds are plant secondary metabolites associated with antioxidant activity and several other biological functions.

Flavonoids and related phenolic constituents may contribute to the colour, taste, and chemical properties of microgreens. Their concentrations can vary with genotype, environmental stress, light quality, and the developmental stage at harvest. Antioxidant capacity is commonly assessed using laboratory methods such as DPPH, ABTS, or FRAP assays. These tests provide information about chemical antioxidant activity under experimental conditions, but they do not directly establish the magnitude of health benefits in humans. Kyriacou et al. (2016) discussed the potential to manipulate growing conditions to influence the nutritional and sensory characteristics of microgreens. Further research is needed to establish how these changes affect nutrient bioavailability and long-term health outcomes.

5.3 Carotenoids and pigments

Carotenoids are pigments involved in photosynthesis and photoprotection. They include compounds such as beta-carotene, lutein, and zeaxanthin. Their concentrations vary among species and are affected by light conditions and leaf development. Green microgreens generally contain chlorophyll, while red and purple varieties may contain anthocyanins and other pigments. These compounds contribute to visual appeal and may also influence antioxidant activity. Coloured microgreens are particularly useful in food preparation because they provide a combination of nutritional interest and attractive presentation

(Xiao *et al.*, 2012).

5.4 Glucosinolates and other bioactive constituents

Microgreens belonging to the Brassicaceae family, including broccoli, radish, mustard, and cabbage, may contain glucosinolates. These sulphur-containing compounds can be converted into biologically active products through enzymatic processes, including the formation of isothiocyanates from particular glucosinolates. The quantity and composition of these compounds differ between species and developmental stages. Other microgreens may contain different phytochemical groups, including flavonoids, phenolic acids, and aromatic compounds. Although these constituents have attracted attention for their potential biological activities, evidence from chemical analyses and experimental models should not be interpreted as proof that consuming microgreens prevents or treats specific diseases. Turner et al. (2020) emphasized the importance of interpreting microgreen nutrition in the context of differences in species, growing conditions, and analytical methods.

5.5 Factors affecting nutritional quality

The nutritional quality of microgreens can be influenced by several production variables:

- **Genotype:** Different species and cultivars possess different capacities to accumulate vitamins, minerals, pigments, and phenolic compounds.

- Light conditions: Light intensity, spectral composition, and photoperiod can influence photosynthesis and secondary metabolism.
- Growing medium: Substrate properties affect water availability, nutrient supply, root development, and mineral uptake.
- Nutrient management: Appropriate nutrient supplementation can modify growth and the accumulation of selected minerals.
- Harvesting stage: Concentrations of some compounds change during seedling development.
- Storage conditions: Temperature, humidity, packaging, and storage duration influence the retention of quality and selected nutrients.

Consequently, microgreen production can be optimized not only for biomass yield but also for specific nutritional characteristics. Such optimization should consider the balance between yield, quality, resource consumption, and food safety (Kyriacou *et al.*, 2016; Teng *et al.*, 2023).

6. Harvesting, Post-Harvest Handling and Storage

Harvesting and post-harvest management are critical stages in microgreen production because these young plants are delicate, have a high surface-area-to-volume ratio, and lose moisture readily. Their quality can deteriorate rapidly

when temperature, humidity, handling, and packaging are poorly controlled (Turner *et al.*, 2020).

6.1 Harvesting techniques

Microgreens are generally harvested by cutting the shoots above the growing medium using clean scissors, knives, or specialized harvesting equipment. The appropriate stage is determined by the species, shoot development, cotyledon expansion, and appearance of the first true leaves. Harvesting should be carried out using clean tools and food-contact surfaces. Workers should follow appropriate personal hygiene practices, and harvested material should be protected from contact with soil, dirty containers, and other potential contamination sources. Mechanical harvesting may be appropriate for larger commercial operations, but delicate shoots require careful handling to prevent crushing and tissue damage. Uniform cutting and removal of damaged seedlings improve the appearance and consistency of the final product.

6.2 Cleaning and preparation

After harvesting, microgreens should be inspected to remove damaged, discolored, or visibly contaminated material. Washing practices should be selected according to the production system, food-safety requirements, and intended market. Washing with contaminated water can introduce microorganisms rather than remove them. Likewise, ordinary rinsing cannot guarantee the

elimination of pathogens that are attached to plant tissues. If washing is undertaken, potable water and validated hygiene procedures are essential. For products intended to be sold ready to eat, growers and processors should follow applicable food-safety standards. The need for washing, sanitization, and drying should be established through an appropriate process rather than assumed to be identical for every product (Turner *et al.*, 2020).

6.3 Packaging methods

Microgreens may be packed in food-grade plastic containers, clamshell packages, or other suitable packaging materials. Packaging protects the crop from physical damage, reduces contamination during handling, and helps maintain product appearance. Modified-atmosphere packaging may help preserve quality when the gas composition, film permeability, temperature, and product respiration are properly matched. However, unsuitable packaging can result in condensation, oxygen depletion, off-odours, or microbial growth. Some producers also market microgreens as living plants in their growing trays. This method allows consumers to harvest the shoots when needed and may reduce some handling steps, but it does not remove the need for hygienic production and storage (Turner *et al.*, 2020).

6.4 Storage temperature and shelf life

Low-temperature storage is important for maintaining freshness, slowing deterioration,

and limiting the growth of many microorganisms. Harvested microgreens should be cooled promptly and maintained under an appropriate refrigerated cold chain. Storage temperature, relative humidity, packaging, and crop type determine the actual shelf life. Excessive moisture, poor ventilation within packages, mechanical damage, and temperature fluctuations can accelerate deterioration. Some microgreens wilt quickly, while others retain acceptable quality for longer periods under suitable conditions. Turner *et al.* (2020) identified rapid post-harvest quality deterioration as an important limitation to the commercialization of microgreens. Further research into packaging, cooling, and other post-harvest treatments is necessary to improve storage stability without compromising food safety or nutritional quality.

7. Applications of Microgreens in Food, Health, Agriculture and Education

Microgreens have applications extending beyond culinary decoration. Their short production cycle, diverse sensory characteristics, and potential nutritional value make them useful in food preparation, controlled-environment agriculture, educational programmes, and small-scale entrepreneurship.

7.1 Culinary and food-processing applications

Microgreens are widely used in restaurants, hotels, catering services, and household

kitchens. Their bright colors, delicate textures, and distinctive flavours can enhance the appearance and sensory characteristics of different dishes.

Common culinary applications include:

- Fresh salads and vegetable bowls.
- Sandwiches, wraps, and burgers.
- Soups and cooked dishes, where suitable.
- Garnishes for rice dishes, pasta, and other main courses.
- Smoothies and selected blended food products.
- Specialty foods and innovative restaurant preparations.

Different species provide different flavours. Mustard and radish microgreens may have a peppery taste, while pea shoots are relatively mild and sweet. Coriander and basil provide characteristic aromatic notes. The choice of species depends on the intended recipe and consumer preference (Kyriacou *et al.*, 2016; Turner *et al.*, 2020).

7.2 Functional foods and nutritional applications

Microgreens are being investigated as ingredients in functional foods because they may provide vitamins, pigments, phenolic compounds, and other phytochemicals. Selected species can be incorporated into fresh food preparations and, following appropriate processing studies, into certain value-added products. However, the nutritional contribution

of a product depends on the amount consumed, the species used, its composition, and the processing method. Heating, drying, blending, and storage can alter particular nutrients and bioactive compounds. Therefore, the nutritional quality of processed microgreen products should be established experimentally. Research on microgreens has identified opportunities to improve nutrient composition through species selection and controlled growing conditions (Xiao *et al.*, 2012; Teng *et al.*, 2023). Nevertheless, claims of disease prevention or therapeutic efficacy require appropriate clinical evidence and should not be based solely on laboratory antioxidant assays.

7.3 Urban agriculture and household gardening

Microgreens are suitable for urban agriculture because they can be cultivated in shallow trays, on balconies, near windows, and in small indoor growing areas. They do not require the same land area or cultivation period as many mature vegetable crops. Household cultivation can improve access to fresh greens and provide opportunities for families to explore a wider variety of edible plants. Successive sowing at intervals can help maintain a regular supply. Indoor systems may also be useful in locations where outdoor growing space is restricted. Teng *et al.* (2023) discussed the potential of microgreens for home and commercial production, emphasizing their adaptability to different growing environments. However,

household growers should still use appropriate seeds, clean growing materials, safe water, and hygienic harvesting practices.

7.4 Sustainable agriculture and resource-efficient production

Microgreens offer opportunities for localized food production, particularly when grown close to consumers. Their short crop cycle and compact growing systems can support frequent harvests and reduce the need for long-distance transportation in some supply chains. Hydroponic and vertical farming systems may use land and water efficiently when designed and managed appropriately. However, their environmental performance depends on electricity consumption, lighting efficiency, cooling requirements, substrate sourcing, packaging, and nutrient management. The use of locally available, safe, and renewable substrates may improve sustainability. Nevertheless, alternative substrates must be evaluated for their physical properties, crop performance, microbial quality, and environmental impact. Sustainable production should be assessed across the entire production system rather than inferred from the short crop cycle alone (Teng *et al.*, 2023).

7.5 Educational and research applications

Microgreen cultivation is a useful practical activity in schools, colleges, and botanical laboratories. The rapid growth of seedlings allows students to observe germination, cotyledon development, photosynthesis, and

early plant growth within a relatively short period.

Microgreens can also support student research projects involving:

- Comparison of seed germination and seedling vigour among plant species.
- Evaluation of soil-based and soilless growing media.
- Effects of light intensity and photoperiod on growth.
- Comparison of irrigation methods and sowing densities.
- Estimation of chlorophyll, pigments, and selected phytochemicals.
- Assessment of fresh biomass and growth rates under different treatments.

These activities can introduce students to experimental design, data collection, horticultural techniques, and sustainable food production. They are especially useful for demonstrating how environmental conditions influence plant development and product quality.

7.6 Commercial and entrepreneurial opportunities

Microgreens provide opportunities for small-scale entrepreneurship because they can be grown in relatively limited spaces and supplied to local restaurants, retailers, caterers, and individual consumers. Potential business models include fresh-cut microgreen sales, living trays, subscription deliveries, and customized mixes for culinary use. Commercial success depends

on reliable seed supply, production planning, consistent quality, hygienic handling, packaging, customer relationships, and market demand. Producers must also account for labour, electricity, water, substrate, packaging, transport, and crop losses when calculating profitability. Because harvested microgreens are perishable, local marketing and planned harvesting can help reduce unsold inventory. A small-scale producer should assess local demand and conduct pilot production before investing in large indoor facilities (Turner *et al.*, 2020; Teng *et al.*, 2023).

8. Challenges, Limitations and Future Prospects

Despite their promising nutritional and commercial potential, microgreens face several challenges related to production costs, food safety, storage, standardization, and market development. Addressing these limitations is essential for establishing reliable and sustainable production systems.

8.1 Microbial contamination and food safety

Microbial contamination is one of the most important concerns in microgreen production. Seeds, irrigation water, growing substrates, containers, equipment, and handling surfaces may introduce microorganisms into the production system. Warm and moist conditions that favour seed germination may also support the multiplication of certain foodborne pathogens when contamination occurs.

Although microgreens are harvested above the growing medium, this does not guarantee that their edible portions are free from microorganisms. Pathogens may be introduced through contaminated seeds, water, hands, or equipment and may persist during production and storage. High standards of hygiene and preventive management are therefore essential (Turner *et al.*, 2020). Appropriate measures include sourcing seeds from reliable suppliers, using potable water, cleaning and sanitizing reusable equipment, maintaining worker hygiene, preventing cross-contamination, and controlling storage temperatures. Sanitation treatments should be validated for their effectiveness and suitability for the crop. No single treatment can compensate for inadequate hygiene throughout the production chain (Xiao *et al.*, 2014; Turner *et al.*, 2020).

8.2 Short shelf life and post-harvest losses

Microgreens have tender leaves and stems that are susceptible to wilting, moisture loss, tissue damage, and decay. Their short shelf life restricts long-distance distribution and may result in substantial losses when production exceeds demand. Improvements in rapid cooling, refrigerated transport, packaging design, humidity management, and harvest scheduling may help preserve quality. Modified-atmosphere packaging and other preservation approaches require crop-specific validation because inappropriate conditions can promote deterioration or create food-safety

concerns (Turner *et al.*, 2020).

8.3 Production costs and economic limitations

Commercial microgreen cultivation may require expenditure on seeds, trays, growing media, irrigation equipment, lighting, ventilation, cooling, packaging, and labour. Indoor and vertical systems can be particularly expensive when electricity and climate control account for a substantial proportion of operating costs. Profitability also depends on local demand, selling price, production consistency, and the amount of product lost before sale. Small growers can reduce financial risks by starting with a limited number of crops, monitoring production costs, and establishing regular buyers before expanding their facilities.

8.4 Lack of standardized cultivation protocols

Differences in seed varieties, growing media, irrigation, lighting, sowing density, and harvesting stages make it difficult to compare results among studies. A treatment that improves growth in one species may not produce the same effect in another. Standardized protocols are needed for germination testing, seed density, substrate selection, environmental monitoring, yield measurement, nutritional analysis, and post-harvest assessment. Research should also report growing conditions and analytical methods in sufficient detail to allow reproducibility (Kyriacou *et al.*, 2016; Teng *et al.*, 2023).

8.5 Future research directions

Future investigations should focus on developing crop-specific cultivation protocols that improve yield, nutritional quality, food safety, and resource-use efficiency simultaneously. Promising research areas include:

- Improved growing media: Evaluation of locally available, biodegradable substrates and agricultural by-products that are suitable for edible crop production.
- Optimized LED lighting: Identification of suitable light intensities, spectra, and photoperiods for different species.
- Nutrient management: Determination of appropriate nutrient concentrations and application schedules for hydroponic microgreens.
- Food-safety interventions: Development and validation of effective methods to reduce microbial contamination without damaging product quality.
- Post-harvest technologies: Improvement of cooling, packaging, and storage procedures to extend marketable life.
- Automation and precision cultivation: Use of sensors and automated irrigation and environmental monitoring to improve production consistency.
- Nutritional research: Assessment of nutrient bioavailability, phytochemical

stability, and the effects of processing and storage.

- Commercial feasibility: Evaluation of production costs, market demand, energy requirements, and environmental impacts under local conditions.

Teng et al. (2023) highlighted the potential of microgreens for controlled-environment agriculture and future space farming. These applications demonstrate the versatility of microgreens, but further work is required to resolve technical challenges, improve resource efficiency, and establish reliable production standards. In India, microgreen cultivation may offer opportunities for household nutrition, urban gardening, educational institutions, and small-scale agricultural entrepreneurship. Research on locally adapted crops, affordable substrates, low-cost irrigation, and energy-efficient growing systems could help make production more accessible. The development of suitable standards and reliable marketing channels would further support the growth of this emerging horticultural sector.

9. Conclusion

Microgreens represent an important emerging category of edible plants with applications in nutrition, horticulture, food processing, education, and sustainable agriculture. Their short growth cycle, diverse flavours, attractive colours, and adaptability to soil-based, soilless, hydroponic, and controlled-environment

systems make them suitable for household and commercial production. Their nutritional composition, including vitamins, minerals, pigments, and phytochemicals, varies with species, genotype, cultivation conditions, and harvesting stage. Therefore, crop selection and appropriate environmental management are essential for achieving satisfactory yield and quality. Although microgreens offer promising opportunities for localized food production and agricultural entrepreneurship, microbial contamination, rapid post-harvest deterioration, production costs, and inconsistent cultivation practices remain significant limitations. Improved seed quality, hygienic cultivation, optimized lighting and irrigation, appropriate packaging, and efficient resource management can help overcome these challenges. Further research is needed to establish standardized production protocols, verify nutritional and health-related claims, improve storage stability, and evaluate the economic and environmental sustainability of different cultivation systems. Overall, microgreens have considerable potential as a complementary component of diversified diets and innovative horticultural production, provided that their cultivation and marketing are supported by sound scientific practices and appropriate food-safety measures.

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