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Microgreen production in vegetable crops: A comprehensive review

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Abstract

Microgreens are tender, immature greens harvested at the cotyledon stage or immediately after the development of the first true leaves. During the last decade, microgreens have emerged as an important component of modern horticulture due to their high nutritional value, short production cycle, attractive sensory qualities, and suitability for controlled environment agriculture. Vegetable crop species such as broccoli, cabbage, kale, radish, mustard, beetroot, lettuce, fenugreek, coriander, and pea are widely cultivated as microgreens because of their superior nutritional composition and rapid growth characteristics. Numerous studies have demonstrated that microgreens contain significantly higher concentrations of vitamins, minerals, carotenoids, phenolic compounds, glucosinolates, and antioxidants than their mature counterparts. Their cultivation requires limited land, water, and agricultural inputs, making them particularly suitable for urban agriculture, vertical farming, hydroponics, and indoor production systems. Increasing consumer awareness regarding healthy diets and functional foods has further accelerated the commercial expansion of the microgreen industry worldwide. Despite these advantages, several challenges remain, including seed quality management, microbial contamination, postharvest deterioration, standardization of production practices, and economic feasibility under large-scale cultivation. This review critically examines the origin, classification, production technologies, nutritional significance, health-promoting properties, cultivation practices, environmental requirements, harvesting methods, postharvest management, economic prospects, and future research opportunities associated with microgreen production in vegetable crops. The review highlights the growing importance of microgreens as sustainable nutrient-dense foods capable of contributing to food security, nutritional well-being, and climate-resilient urban agriculture systems.

Keywords: Microgreens, vegetable crops, controlled environment agriculture, hydroponics, vertical farming, functional foods, nutritional quality, sustainable agriculture

Introduction

The global agricultural sector is under increasing pressure due to population growth, urbanization, climate change, shrinking arable land, and rising demand for nutritious food (FAO, 2022; United Nations, 2023) [37]. By 2050, the global population is expected to exceed 9 billion, significantly intensifying the demand for efficient and sustainable food production systems. At the same time, growing awareness of the link between diet and health has increased consumer preference for nutrient-rich foods containing vitamins, minerals, antioxidants, and other bioactive compounds (Kyriacou & Rouphael, 2018; Hasan *et al.*, 2017) [13, 10, 30]. These challenges have encouraged interest in alternative horticultural crops, among which microgreens have emerged as a promising innovation in modern vegetable production systems (Xiao *et al.*, 2012; Kyriacou *et al.*, 2017) [40, 18].

Microgreens are young edible seedlings harvested at an early growth stage, typically 7–21 days after germination, when cotyledons are fully expanded and first true leaves begin to appear (Treadwell *et al.*, 2010) [35]. Unlike sprouts, which are consumed entirely including seed and root, microgreens are harvested above the growing medium, making them safer and more suitable for fresh consumption (Weber, 2017) [39]. The term “microgreens” originated in California during the 1990s, where chefs introduced them into gourmet cuisine for their color, texture, and flavor enhancement (Xiao *et al.*, 2012) [40]. Since then, they have evolved into functional foods due to their high nutritional density and health-promoting properties (Kyriacou & Rouphael, 2018) [13, 30].

The overall production chain of microgreens, from seed selection and cultivation to harvesting, packaging, and consumer utilization, is illustrated in Figure 1.

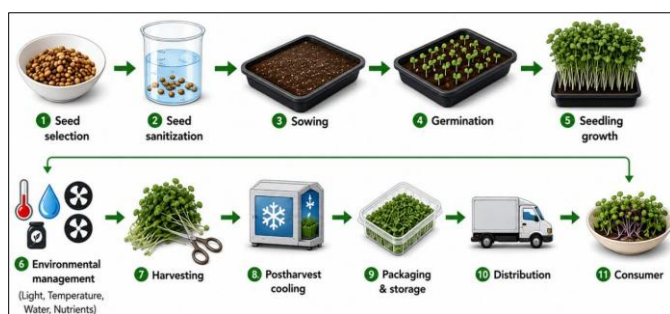


Fig 1: Production chain of microgreens from seed to consumer

Research has shown that microgreens contain significantly higher concentrations of vitamins (C, E, K), carotenoids, phenolic compounds, and antioxidants compared to mature vegetables (Xiao *et al.*, 2012; Pires *et al.*, 2019) [40, 26]. These bioactive compounds contribute to antioxidant activity, immune support, and prevention of chronic diseases such as cardiovascular disorders, diabetes, and cancer (Liu *et al.*, 2016; Kyriacou *et al.*, 2017) [21, 18]. As a result, microgreens are increasingly recognized as functional foods in human nutrition (El-Nakhel *et al.*, 2020) [7]. A wide range of vegetable crops are suitable for microgreen production, particularly *Brassicaceae* species such as broccoli, kale, mustard, radish, and cabbage due to their rapid growth and high glucosinolate content (Xiao *et al.*, 2014; Waterland *et al.*, 2017) [41, 38]. Other commonly used species include beetroot, fenugreek, coriander, lettuce, basil, spinach, and pea (Pinto *et al.*, 2015) [25]. These crops are selected based on growth rate, nutritional quality, and consumer preference. Microgreens are highly compatible with controlled environment agriculture (CEA), including hydroponics, vertical farming, greenhouse systems, and indoor cultivation (Treadwell *et al.*, 2010; Toulaitos *et al.*, 2016) [35, 34]. These systems allow year-round production with efficient use of water and land resources, making microgreens ideal for urban agriculture (Kyriacou *et al.*, 2017) [18]. Their short production cycle ensures rapid turnover and continuous supply to markets.

Microgreens are increasingly valued as functional foods due to their rich content of polyphenols, flavonoids, carotenoids, vitamins, and essential minerals such as potassium, calcium, iron, and magnesium (Xiao *et al.*, 2012; Zhang *et al.*, 2020) [40, 42]. These compounds contribute to antioxidant, *anti-inflammatory*, and immunomodulatory effects, reducing the risk of chronic diseases (Hasan *et al.*, 2017; Kyriacou & Rouphael, 2018) [10, 13, 30]. From an economic perspective, microgreens offer strong commercial potential due to high market value, short production cycle, and increasing demand from restaurants, supermarkets, and health-conscious consumers (Kyriacou *et al.*, 2017) [18]. Advances in LED lighting, hydroponics, and vertical farming have further improved commercial feasibility (Bantis *et al.*, 2018) [1]. However, challenges such as seed cost, microbial contamination, short shelf life, and lack of standardized protocols still limit large-scale adoption (Weber, 2017; El-Nakhel *et al.*, 2020) [39, 7].

Therefore, this review aims to provide a comprehensive overview of microgreen production in vegetable crops, including origin, classification, production technologies, environmental requirements, nutritional composition, health benefits, cultivation systems, economic potential, challenges, and future research directions.

Historical Development and Global Status of Microgreens

The commercial history of microgreens is relatively recent compared with conventional vegetable cultivation. Although young seedlings have been consumed for centuries, the concept of microgreens as a distinct horticultural product emerged during the late 1980s and early 1990s in Southern California, USA, where upscale restaurants sought visually attractive, flavorful, and nutrient-rich garnishes (Weber, 2017; Treadwell *et al.*, 2010) [39, 35]. Initially, only a few species such as arugula, basil, beetroot, kale, and mustard were cultivated. However, increasing consumer interest in healthy diets and advances in cultivation techniques rapidly expanded the range of crops used for microgreen production (Pinto *et al.*, 2015; Xiao *et al.*, 2014) [25, 41]. During the early

2000s, scientific investigations revealed that many microgreens contain higher concentrations of vitamins, antioxidants, and phytochemicals than their mature counterparts, leading to growing recognition of their value as functional foods (Xiao *et al.*, 2012; Kyriacou *et al.*, 2017) [40, 18]. Over the past decade, the global microgreen industry has expanded considerably, driven by increasing awareness of nutrition, health, and sustainable food production. North America remains one of the leading markets, supported by strong consumer demand and the rapid growth of indoor farming enterprises. Similarly, European countries such as the Netherlands, Germany, Italy, Spain, and the United Kingdom have invested heavily in greenhouse cultivation, hydroponics, and vertical farming technologies for year-round production (Bantis *et al.*, 2018; Kyriacou & Rouphael, 2018) [1, 13, 30]. In Asia, countries including China, Japan, South Korea, Singapore, and India are witnessing growing demand for fresh, nutrient-dense vegetables produced through controlled-environment agriculture (Liu *et al.*, 2016) [21].

India possesses significant potential for microgreen cultivation owing to its large population, expanding urban markets, and increasing health consciousness. Crops such as fenugreek, coriander, mustard, radish, beetroot, and amaranth are particularly well suited to local conditions and can be produced with relatively low investment, making them attractive for urban households and small-scale entrepreneurs (Hasan *et al.*, 2017; Zhang *et al.*, 2020) [10, 42]. Looking ahead, the global microgreen market is expected to continue expanding due to increasing demand for functional foods and sustainable production systems. Emerging technologies such as LED lighting, vertical farming, artificial intelligence, precision agriculture, and automation are likely to further improve production efficiency, quality, and profitability in the coming years (Toulaitos *et al.*, 2016; Kyriacou *et al.*, 2017) [34, 18].

Classification and Characteristics of Microgreens

Microgreens are young edible seedlings harvested at an early stage of growth, usually when the cotyledons are fully expanded and the first true leaves begin to emerge. They are classified based on botanical family, growth duration, pigmentation, flavor characteristics, and nutritional composition (Xiao *et al.*, 2012; Kyriacou & Rouphael, 2018) [40, 13, 30]. A wide range of vegetable species can be cultivated as microgreens, with major families including *Brassicaceae*, *Amaranthaceae*, *Apiaceae*, *Fabaceae*, *Chenopodiaceae*, and *Lamiaceae* (Pinto *et al.*, 2015) [25]. Among these, *Brassicaceae* crops such as broccoli, kale, cabbage, cauliflower, mustard, radish, arugula, and turnip are the most widely cultivated due to their rapid germination, high productivity, and abundance of health-promoting glucosinolates and antioxidants (Waterland *et al.*, 2017; Xiao *et al.*, 2014) [38, 41]. Similarly, *Amaranthaceae* species including beetroot, amaranth, Swiss chard, and spinach are valued for their attractive

pigmentation and high concentrations of betalains and anthocyanins, while Apiaceae crops such as coriander, parsley, dill, celery, and fennel contribute unique flavors and aromatic compounds (El-Nakhel *et al.*, 2020; Pires *et al.*, 2019) ^[7, 26].

Microgreens exhibit considerable diversity in appearance, taste, and nutritional quality. Depending on the species and cultivar, they may possess green, red, purple, or multicolored cotyledons and stems, with flavor profiles ranging from mild and sweet to spicy, peppery, bitter, or aromatic (Kyriacou *et al.*, 2017) ^[18]. Unlike mature vegetables, microgreens are harvested during a phase of intense metabolic activity when stored seed nutrients are rapidly converted into vitamins, amino acids, antioxidants, and other bioactive compounds. Consequently, they often contain higher concentrations of these health-promoting constituents than their mature counterparts (Liu *et al.*, 2016) ^[21]. Their growth cycle generally ranges from 7 to 21 days, with fastgrowing species such as radish, broccoli, and mustard harvested within a week, while coriander, beetroot, and celery may require up to three weeks (Treadwell *et al.*, 2010; Zhang *et al.*, 2020) ^[35, 42]. This short production cycle, combined with high nutritional value and diverse sensory characteristics, makes microgreens an attractive component of modern horticultural production systems.

Vegetable Crops Suitable for Microgreen Production

A diverse range of vegetable crops can be cultivated as microgreens, with species selection largely influenced by germination ability, growth rate, nutritional value, market demand, and adaptability to different production systems. Among the various crop groups, members of the *Brassicaceae* family are the most widely cultivated because of their rapid growth, ease of production, and abundance of health-promoting phytochemicals (Treadwell *et al.*, 2010; Xiao *et al.*, 2014) ^[35, 41]. Broccoli microgreens are particularly valued for their high concentrations of glucoraphanin and sulforaphane, compounds associated with antioxidant, antiinflammatory, and anticancer properties. Similarly, radish, red cabbage, kale, and mustard microgreens are popular due to their attractive pigmentation, distinctive flavors, and rich contents of vitamins, carotenoids, glucosinolates, and phenolic compounds that contribute to improved human health (Kyriacou *et al.*, 2017; Waterland *et al.*, 2017) ^[18, 38].

In addition to *Brassicaceae* crops, several non-*Brassicaceae* species have gained commercial importance. Beetroot and amaranth microgreens are appreciated for their vibrant coloration and high levels of betalains and antioxidants. Fenugreek microgreens are widely consumed in Asian countries because of their pleasant flavor and richness in proteins, dietary fiber, minerals, and bioactive compounds. Coriander microgreens are valued for their characteristic aroma and essential oil content, while pea microgreens and pea shoots are favored for their tender texture, sweet flavor, and relatively high protein concentration (Pinto *et al.*, 2015; Hasan *et al.*, 2017; Bian *et al.*, 2020) ^[25, 10, 2]. Lettuce microgreens are also popular owing to their mild taste and versatility in salads and garnishes. Furthermore, crops such as spinach, Swiss chard, basil, celery, fennel, dill, and parsley have demonstrated considerable potential for commercial production due to their desirable sensory and nutritional attributes. The wide diversity of vegetable crops available for microgreen cultivation enables producers to create specialized product mixtures that meet consumer preferences for flavor, appearance, and health benefits, thereby supporting the growing market for functional and value-added horticultural products (Kyriacou & Rouphael, 2018; El-Sayed *et al.*, 2021) ^[13, 15].

Production Technologies for Microgreen Cultivation

Successful microgreen production depends on the use of quality

seeds, suitable growing media, efficient irrigation, and proper environmental management. High-quality seeds with good germination, genetic purity, and freedom from pathogens are essential for uniform seedling establishment and biomass production. In crops such as pea, sunflower, beetroot, and fenugreek, seed pre-soaking is often practiced to promote rapid and uniform germination (Xiao *et al.*, 2012; Di Gioia *et al.*, 2017) ^[40]. The choice of growing medium is equally important. Common substrates include cocopeat, peat moss, vermiculite, perlite, rockwool, and biodegradable mats. Among these, cocopeat is widely preferred because of its excellent moisture retention, aeration, sustainability, and availability. Proper sowing density should also be maintained to avoid overcrowding, poor air circulation, and disease incidence (Kyriacou *et al.*, 2016; Renna *et al.*, 2018) ^[19, 13].

Microgreens require careful irrigation because of their shallow root systems. Misting, capillary mats, and bottom-watering systems are commonly used to maintain adequate moisture while minimizing microbial contamination. Although seedlings largely depend on seed reserves for nutrition, dilute nutrient solutions are often supplied in hydroponic systems to improve growth and phytochemical content (Riggio *et al.*, 2019; El-Nakhel *et al.*, 2021) ^[28, 6, 8]. Environmental factors such as temperature, humidity, light, and air circulation also influence crop performance. Harvesting is usually performed when cotyledons are fully expanded, after which the microgreens are cooled and packaged to maintain freshness and shelf life. Therefore, integrating quality seed, suitable substrates, proper irrigation, environmental control, and post-harvest management is essential for producing high-quality microgreens (Rouphael *et al.*, 2018; Choe *et al.*, 2018; Khan *et al.*, 2024) ^[30, 3].

Growing Media and Substrate Management

Growing media play a fundamental role in microgreen production by influencing seed germination, root development, water availability, nutrient uptake, and overall crop performance. An ideal substrate should possess adequate aeration, moisture-holding capacity, drainage, structural stability, and freedom from pathogens and contaminants to ensure healthy seedling growth and food safety (Kyriacou *et al.*, 2016; Mir *et al.*, 2017) ^[19, 22, 18]. Traditionally, peat-based substrates have been widely used because of their favorable physical and chemical properties. However, environmental concerns regarding peat extraction have increased interest in sustainable alternatives. Among these, cocopeat has emerged as one of the most preferred growing media due to its renewable nature, excellent water retention, good aeration, and suitability for root development. Studies have demonstrated that cocopeat-based substrates enhance germination, seedling vigor, and biomass production in various microgreen crops (Renna *et al.*, 2018; Sharma *et al.*, 2022) ^[27, 33]. To optimize substrate performance, materials such as perlite and vermiculite are frequently incorporated into growing media. Perlite improves aeration and drainage, while vermiculite enhances moisture retention and nutrient-holding capacity, thereby creating favorable conditions for root growth and seedling establishment (Treadwell *et al.*, 2010; Di Gioia *et al.*, 2017) ^[35]. In hydroponic and controlled-environment systems, inert substrates including rockwool, hemp mats, cellulose fiber mats, and biodegradable fabrics are commonly used to support seedlings while allowing precise control of water and nutrient supply (Rouphael *et al.*, 2018) ^[30]. Increasing emphasis on sustainable agriculture has also encouraged the development of renewable substrates derived from agricultural residues, recycled fibers, composted organic materials, and biochar (Pescarini *et al.*,

2023)^[24]. Furthermore, microbial activity within the substrate can influence crop performance and food safety, with beneficial microorganisms promoting nutrient availability and root growth, while pathogenic microbes may reduce germination and increase contamination risks. Therefore, proper substrate selection, sanitation, and moisture management are essential for achieving high productivity, quality, and sustainability in commercial microgreen production systems (Riggio *et al.*, 2019; O'Sullivan *et al.*, 2024; Khan *et al.*, 2024)^[28, 23].

Environmental Factors Affecting Microgreen Growth and Quality

Environmental conditions greatly influence the growth, yield, nutritional quality, and marketability of microgreens. Since microgreens are harvested at an early growth stage, factors such as temperature, light, relative humidity, carbon dioxide concentration, and air circulation significantly affect seed germination, biomass production, pigmentation, and phytochemical accumulation (Kyriacou *et al.*, 2016; Mir *et al.*, 2017)^[19, 22, 18]. Temperature is a key factor regulating germination and seedling growth, with most microgreens performing best between 18-25 °C. Lower temperatures delay growth, whereas excessively high temperatures can reduce yield and quality (Treadwell *et al.*, 2010; Sharma *et al.*, 2022)^[35, 33]. Light influences photosynthesis, morphology, and nutritional composition. The use of LED lighting, particularly red and blue spectra, has been shown to enhance chlorophyll, carotenoids, antioxidants, phenolic compounds, and vitamin content in microgreens (Samuolienė *et al.*, 2013; Rouphael *et al.*, 2018)^[30, 31]. The major environmental factors and their interactions affecting microgreen growth, yield, and nutritional quality are illustrated in Figure 2.

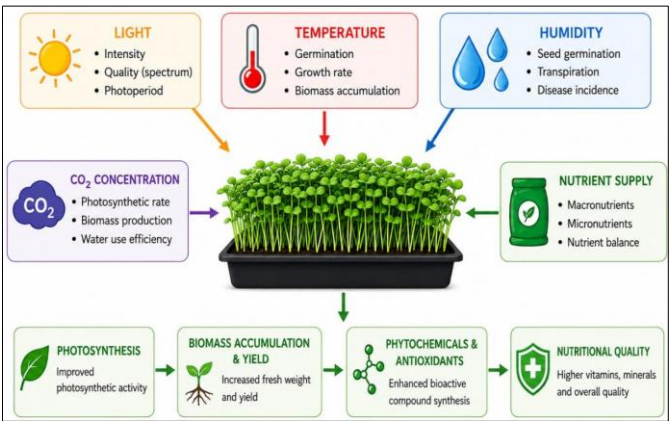


Fig 2: Schematic representation of factors influencing microgreen growth and quality

Relative humidity levels of 50–70% are generally considered optimal. Excess humidity encourages fungal diseases and microbial contamination, while low humidity may cause moisture stress (Riggio *et al.*, 2019; Turner *et al.*, 2020)^[28, 36]. Elevated CO₂ concentrations can improve photosynthesis and biomass production under controlled-environment conditions (Kyriacou *et al.*, 2020). In addition, adequate air circulation helps maintain uniform temperature and humidity, strengthens seedlings, and minimizes disease incidence. The optimum ranges of major environmental factors and their effects on microgreen growth and quality are summarized in Table 1. Therefore, effective management of environmental factors is essential for achieving high productivity, superior nutritional quality, and consistent microgreen production (Rouphael *et al.*, 2021; Khan *et al.*, 2024)^[29].

Table 1: Influence of environmental factors on growth and quality of microgreens

Environmental factor	Optimum range	Effect on growth and quality	References
Temperature	18–25 °C	Enhances germination and biomass accumulation	Treadwell <i>et al.</i> (2010); Sharma <i>et al.</i> (2022) ^[35, 33]
Relative humidity	50–70%	Reduces water stress and disease incidence	Riggio <i>et al.</i> (2019)
Light intensity	100–300 μmol m ⁻² s ⁻¹	Improves photosynthesis and growth	Samuolienė <i>et al.</i> (2013)
Photoperiod	12–18 h day ⁻¹	Enhances biomass and phytochemical production	Rouphael <i>et al.</i> (2018)
CO ₂ concentration	600–1000 ppm	Increases photosynthetic efficiency	Kyriacou <i>et al.</i> (2020)
Air circulation	Adequate ventilation	Minimizes pathogen development	Turner <i>et al.</i> (2020)

Light Quality and LED Technology in Microgreen Production

Light is a critical factor in microgreen production, serving as both an energy source for photosynthesis and a regulator of plant growth, morphology, and phytochemical synthesis. Light quality, intensity, and duration significantly influence biomass accumulation, pigmentation, nutritional composition, and overall crop quality (Kyriacou *et al.*, 2016; Rouphael *et al.*, 2018)^[19, 30, 13]. While traditional greenhouse production relies on natural sunlight, controlled-environment agriculture increasingly utilizes artificial lighting to ensure consistent growth and year-round production (Mir *et al.*, 2017)^[22]. Among available lighting systems, light-emitting diodes (LEDs) are widely preferred because of their high energy efficiency, low heat emission, long lifespan, and ability to provide specific light spectra according to crop requirements (Samuolienė *et al.*, 2013; O'Sullivan *et al.*, 2024)^[23, 31]. Red light promotes photosynthesis, biomass accumulation, and chlorophyll synthesis, whereas blue light enhances chlorophyll production, antioxidant activity, and the accumulation of secondary metabolites. Consequently, combinations of red and blue LEDs are commonly used to improve both yield and nutritional quality in microgreens

(Samuolienė *et al.*, 2017)^[32]. Light spectrum manipulation can significantly influence phytochemical composition. Increased blue light often enhances phenolic compounds, flavonoids, anthocyanins, and antioxidant activity, while red light supports vigorous growth. Proper photoperiod management, generally between 12 and 18 hours per day, further improves photosynthetic efficiency and biomass production (Treadwell *et al.*, 2010; Sharma *et al.*, 2022)^[35, 33]. Therefore, LED technology has become an essential tool in modern microgreen production, enabling growers to optimize crop productivity, nutritional quality, and energy efficiency (Kyriacou *et al.*, 2021; Khan *et al.*, 2024)^[15].

Nutritional Composition of Microgreens

Microgreens are highly valued for their exceptional nutritional quality and are often considered functional foods because they contain concentrated levels of vitamins, minerals, antioxidants, and other bioactive compounds. Studies have shown that many microgreens possess higher nutrient concentrations than their mature vegetable counterparts, making them important components of healthy diets (Xiao *et al.*, 2012; Kyriacou *et al.*, 2016)^[40, 19]. Their nutritional composition varies with species,

cultivar, growing conditions, and harvest stage, but they generally exhibit remarkable nutrient density (Mir *et al.*, 2017) ^[22]. Microgreens are rich sources of vitamins C, E, K, and provitamin A carotenoids. *Brassica* microgreens such as broccoli, kale, red cabbage, and mustard contain particularly high levels of vitamin C and antioxidant compounds, while carotenoids such as β -carotene, lutein, and zeaxanthin contribute to eye health, immune function, and protection against oxidative stress (Xiao *et al.*, 2012; Choe *et al.*, 2018) ^[40, 3]. They also provide essential minerals including potassium, calcium, magnesium, iron, zinc, and phosphorus, which are important for metabolic functions, bone health, and cardiovascular well-being (Pinto *et al.*, 2015; Kyriacou *et al.*, 2021) ^[25, 15]. In addition, leguminous microgreens

such as pea, fenugreek, lentil, and chickpea contain relatively high levels of protein and dietary fiber. Beyond conventional nutrients, microgreens are rich in phytochemicals such as phenolic compounds, flavonoids, glucosinolates, anthocyanins, and other antioxidants that exhibit *anti-inflammatory*, cardioprotective, and anticancer properties (Samuolienė *et al.*, 2017; Kyriacou *et al.*, 2021) ^[32]. The nutritional composition, major bioactive compounds, and associated health benefits of selected microgreen species are summarized in Table 2. Owing to their high nutrient density and healthpromoting compounds, microgreens represent a valuable dietary source of functional ingredients and contribute significantly to modern health-conscious nutrition (Rouphael *et al.*, 2021; Khan *et al.*, 2024) ^[29].

Table 2: Nutritional composition of selected microgreens and associated health benefits

Microgreen species	Major nutrients	Important bioactive compounds	Potential health benefits	References
Broccoli	Vitamin C, K, Ca, Fe	Glucosinolates, sulforaphane	Anticancer, antioxidant activity	Xiao <i>et al.</i> (2012); Kyriacou <i>et al.</i> (2016) ^[40, 19]
Red cabbage	Vitamin C, K	Anthocyanins, polyphenols	Cardiovascular protection	Xiao <i>et al.</i> (2012) ^[40]
Kale	Vitamin A, C, E	Carotenoids, flavonoids	Eye health, immune support	Pinto <i>et al.</i> (2015) ^[25]
Radish	Vitamin C, K	Anthocyanins, glucosinolates	Antioxidant activity	Choe <i>et al.</i> (2018) ^[3]
Amaranth	Fe, Ca, Mg	Betalains, carotenoids	Anti-inflammatory effects	Di Gioia <i>et al.</i> (2017) ^[40]
Pea	Protein, fiber	Phenolic compounds	Metabolic health improvement	Mir <i>et al.</i> (2017) ^[22]
Fenugreek	Protein, Fe	Flavonoids, saponins	Antidiabetic potential	Sharma <i>et al.</i> (2022) ^[33]

10. Phytochemicals and Bioactive Compounds in Microgreens

Microgreens are not only rich in essential nutrients but also contain high concentrations of phytochemicals and bioactive compounds that contribute to human health and disease prevention. Important bioactive constituents found in microgreens include polyphenols, flavonoids, glucosinolates, anthocyanins, betalains, and carotenoids, which possess strong antioxidant and protective properties (Xiao *et al.*, 2012; Kyriacou *et al.*, 2016) ^[40, 19]. Polyphenols and flavonoids are among the most abundant phytochemicals in microgreens and are known for their antioxidant, *anti-inflammatory*, and cardioprotective effects. Compounds such as quercetin, kaempferol, and rutin help protect cells from oxidative damage and may reduce the risk of chronic diseases (Mir *et al.*, 2017; Choe *et al.*, 2018) ^[22, 3]. In *Brassicaceae* microgreens, including broccoli, kale, mustard, and radish, glucosinolates are particularly important. These compounds are converted into biologically active isothiocyanates such as sulforaphane, which exhibit anticancer, antioxidant, and *anti-inflammatory* activities (Xiao *et al.*, 2012; Di Gioia *et al.*, 2017) ^[40]. Natural pigments such as anthocyanins and betalains contribute to the attractive coloration and functional value of many microgreens. Anthocyanins, abundant in red cabbage and purple radish microgreens, possess strong antioxidant activity, while betalains in beetroot and amaranth microgreens are associated with *anti-inflammatory* and health-promoting effects (Pinto *et al.*, 2015) ^[25]. In addition, carotenoids such as β -carotene, lutein, and zeaxanthin support eye health, immune function, and protection against oxidative stress. The combined presence of these bioactive compounds enhances the functional and therapeutic value of microgreens, making them an important component of health-oriented diets and functional food systems (Rouphael *et al.*, 2021; Khan *et al.*, 2024) ^[29].

Health Benefits of Microgreens

The increasing popularity of microgreens is largely due to their exceptional nutritional value and potential health benefits. Rich in

vitamins, minerals, antioxidants, and bioactive compounds, microgreens are increasingly recognized as functional foods that support human health and help prevent chronic diseases. Studies have shown that many microgreens contain higher concentrations of health-promoting compounds than their mature vegetable counterparts (Xiao *et al.*, 2012; Kyriacou *et al.*, 2016) ^[40, 19].One of the major health benefits of microgreens is their strong antioxidant activity. They are rich in phenolic compounds, flavonoids, carotenoids, anthocyanins, and vitamins C and E, which help neutralize reactive oxygen species (ROS) and reduce oxidative stress associated with aging and chronic diseases (Mir *et al.*, 2017; Choe *et al.*, 2018) ^[22, 3]. Regular consumption of microgreens may also support cardiovascular health by improving endothelial function, reducing inflammation, and regulating lipid metabolism. Essential minerals such as potassium and magnesium further contribute to maintaining normal blood pressure and heart function (Pinto *et al.*, 2015; Rouphael *et al.*, 2021) ^[25, 19]. *Brassicaceae* microgreens, including broccoli, kale, mustard, and radish, are particularly valued for their glucosinolate content. These compounds are converted into isothiocyanates such as sulforaphane, which possess anticancer, *anti-inflammatory*, and detoxifying properties (Xiao *et al.*, 2012; Di Gioia *et al.*, 2017) ^[40]. In addition, microgreens may improve metabolic health, support immune function, and contribute to healthy aging due to their high nutrient density and diverse phytochemical profile. Consequently, microgreens represent a valuable dietary component for promoting overall health and disease prevention (Kyriacou *et al.*, 2021; Khan *et al.*, 2024) ^[15].

Hydroponic Systems for Microgreen Production

Hydroponics has become one of the most efficient production systems for commercial microgreen cultivation. In this method, plants are grown without soil and supplied with nutrientenriched water directly to the root zone. Hydroponic cultivation offers several advantages, including efficient water use, precise nutrient management, rapid growth, and uniform crop quality, making it particularly suitable for microgreens with their short production

cycle of 7–21 days (Di Gioia *et al.*, 2017; Rouphael *et al.*, 2018)^[30]. Various hydroponic systems, such as nutrient film technique (NFT), deep water culture (DWC), floating rafts, and capillary mat systems, have been successfully used for microgreen production. These systems provide controlled growing conditions that promote uniform germination and vigorous seedling development. Precise nutrient delivery allows growers to enhance biomass production, mineral accumulation, and phytochemical content, often resulting in higher nutritional quality compared with conventional cultivation methods (Kyriacou *et al.*, 2021; El-Nakhel *et al.*, 2021)^[8, 6, 15]. Hydroponic systems are highly water-efficient because nutrient solutions can be recycled, significantly reducing water losses.

They are also well suited to urban agriculture, indoor farming, and vertical farming systems where space is limited. Furthermore, the absence of soil minimizes problems associated with weeds and soil-borne pathogens, reducing the need for chemical inputs (Pescarini *et al.*, 2023; O'Sullivan *et al.*, 2024)^[24, 23]. A comparison of the major advantages and limitations of different microgreen production systems, including hydroponics, is presented in Table 3. Although hydroponic production requires careful management of nutrients, pH, water quality, and sanitation, advances in automation and environmental control technologies continue to improve its sustainability and commercial viability for microgreen production (Rouphael *et al.*, 2021; Khan *et al.*, 2024)^[29].

Table 3: Advantages and limitations of different microgreen production systems

Production system	Major advantages	Major limitations	References
Soil-based cultivation	Low investment cost, simple operation	Disease and weed problems	Di Gioia <i>et al.</i> (2017) ^[40]
Hydroponics	Water efficiency, precise nutrient control	High technical requirement	Rouphael <i>et al.</i> (2018) ^[13]
Vertical farming	High productivity per unit area	High energy consumption	Pescarini <i>et al.</i> (2023) ^[24]
Indoor farming	Year-round production	Initial infrastructure cost	O'Sullivan <i>et al.</i> (2024) ^[23]
Controlled environment agriculture	Consistent quality and yield	Skilled management required	Khan <i>et al.</i> (2024) ^[3]

Vertical Farming and Controlled Environment Agriculture
Vertical farming and Controlled Environment Agriculture (CEA) have emerged as advanced technologies for microgreen production, particularly in urban areas where land resources are limited. These systems utilize vertically stacked growing units and precisely controlled conditions such as temperature, humidity, light, carbon dioxide, and nutrient supply to maximize productivity. Due to their short growth cycle, compact size, and high market value, microgreens are especially suitable for vertical farming systems (Kyriacou *et al.*, 2016; Mir *et al.*, 2017)^[19, 22, 18]. One of the major advantages of vertical farming is its ability to produce high yields within a limited space. By utilizing multiple cultivation layers, growers can substantially increase production per unit area while ensuring year-round cultivation independent of seasonal climatic variations. Controlled environmental conditions improve crop uniformity, productivity, and nutritional quality while reducing losses caused by adverse weather conditions (Di Gioia *et al.*, 2017; Rouphael *et al.*, 2021)^[29]. The integration of LED lighting, automated irrigation, nutrient delivery systems, and environmental monitoring technologies further enhances resource-use efficiency and crop performance. Vertical farms can also be established near urban consumers, reducing transportation costs, postharvest losses, and carbon emissions. Although high initial investment and energy requirements remain challenges, advances in automation, artificial intelligence, and renewable energy technologies are expected to improve the economic feasibility and sustainability of vertical farming. Consequently, vertical farming is increasingly recognized as a promising approach for sustainable microgreen production and future urban food security (Pescarini *et al.*, 2023; O'Sullivan *et al.*, 2024)^[24, 23].

Food Safety Considerations in Microgreen Production
Food safety is a critical concern in microgreen production because microgreens are generally consumed fresh without cooking. The warm and humid conditions required for germination can also favor the growth of harmful microorganisms, making strict hygiene and sanitation practices essential throughout the production process (Riggio *et al.*, 2019; Turner *et al.*, 2020)^[28, 36]. Seeds are considered the primary source of microbial contamination, as pathogens such as *Salmonella spp.*, *Escherichia coli* O157:H7, and *Listeria monocytogenes* may be present on

contaminated seed lots. Therefore, the use of certified pathogen-free seeds and appropriate seed sanitation treatments is highly recommended. Water quality is equally important, particularly in hydroponic systems, where contaminated irrigation water can rapidly spread pathogens throughout the production unit (Xiao *et al.*, 2012; Di Gioia *et al.*, 2017)^[40]. Proper sanitation of growing trays, equipment, packaging materials, and production facilities is essential to minimize contamination risks. Worker hygiene, including handwashing, protective clothing, and safe handling practices, also plays a significant role in maintaining product safety. The adoption of Good Agricultural Practices (GAPs), Good Manufacturing Practices (GMPs), and Hazard Analysis and Critical Control Point (HACCP) systems provides an effective framework for ensuring safe production and compliance with food safety regulations (Mir *et al.*, 2017; Khan *et al.*, 2024)^[22]. Overall, maintaining food safety in microgreen production requires an integrated approach involving high-quality seeds, safe water, proper sanitation, worker training, and continuous monitoring. These measures are essential for producing safe, high-quality microgreens that meet consumer expectations and market standards (Turner *et al.*, 2020; O'Sullivan *et al.*, 2024)^[36, 23].

Harvesting and Postharvest Management
Harvesting and postharvest handling are crucial for maintaining the quality, nutritional value, and marketability of microgreens. Owing to their tender tissues, high moisture content, and active metabolism, microgreens are highly perishable and require careful management after harvest (Mir *et al.*, 2017; Turner *et al.*, 2020)^[22, 36]. Most species are harvested 7–21 days after sowing when cotyledons are fully expanded and the first true leaves begin to emerge. Harvesting at this stage ensures optimum flavor, texture, appearance, and nutrient content (Xiao *et al.*, 2012; Choe *et al.*, 2018)^[40, 3]. Microgreens are generally harvested manually using sanitized scissors or knives to minimize mechanical damage and microbial contamination. Immediate cooling after harvest is essential to reduce respiration, water loss, and microbial growth, thereby extending shelf life. Packaging systems, particularly modified atmosphere packaging (MAP), help maintain freshness by regulating gas exchange and reducing moisture loss (Di Gioia *et al.*, 2017; Rouphael *et al.*, 2021)^[29].

Storage at low temperatures (1–5 °C) and high relative humidity can extend shelf life from one to three weeks depending on the species and packaging method. Recent innovations such as biodegradable packaging, edible coatings, antimicrobial treatments, and intelligent packaging technologies are being explored to further improve shelf life, food safety, and product quality while supporting sustainable production systems (Pescarini *et al.*, 2023; O'Sullivan *et al.*, 2024) ^[24, 23].

Economics and Market Potential of Microgreens

Microgreens have become a rapidly expanding sector of the horticultural industry due to increasing consumer demand for nutritious, functional, and sustainably produced foods. Their short production cycle (7–21 days), high market value, and suitability for year-round cultivation make them an attractive enterprise for urban growers, greenhouse operators, and commercial producers (Kyriacou *et al.*, 2016; Mir *et al.*, 2017) ^[19, 22, 18].

A major economic advantage of microgreens is the ability to achieve multiple crop cycles annually, resulting in rapid returns and efficient utilization of land, water, and other resources. Growing consumer awareness of health and wellness has expanded market demand through restaurants, supermarkets, specialty stores, and direct marketing channels. Their attractive appearance, unique flavors, and nutritional benefits make them highly desirable in both culinary and health-food markets (Di Gioia *et al.*, 2017; Choe *et al.*, 2018) ^[3].

Urban agriculture, vertical farming, and e-commerce platforms have further strengthened the commercial potential of microgreens by enabling local production and direct access to consumers. However, profitability depends on efficient management of key production costs, particularly seeds, labor, packaging, and energy used in controlled-environment systems. Continued advances in automation, LED technology, and resource-efficient production methods are expected to improve economic sustainability and support future growth of the global microgreen industry (Rouphael *et al.*, 2021; Pescarini *et al.*, 2023; Khan *et al.*, 2024) ^[29, 24].

Challenges and Constraints in Microgreen Production

Despite their nutritional and economic advantages, several challenges limit the largescale adoption of microgreens. One of the primary concerns is the availability of high-quality seeds with good germination, genetic purity, and freedom from pathogens. Poor seed quality can result in uneven germination, reduced growth, and lower productivity, directly affecting profitability (Treadwell *et al.*, 2010; Sharma *et al.*, 2022) ^[35, 33]. Food safety is another major challenge because the warm and humid conditions required for microgreen cultivation favor microbial growth. Contamination by pathogens such as *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes* can threaten consumer health and market acceptance. Therefore, strict sanitation measures, quality assurance programs, and Good Agricultural Practices (GAPs) are essential (Riggio *et al.*, 2019; Turner *et al.*, 2020) ^[28, 36].

Microgreens are highly perishable due to their tender tissues and high moisture content, making postharvest deterioration a significant constraint. Wilting, discoloration, and microbial spoilage can reduce shelf life and market value. Additionally, the lack of standardized production protocols often leads to variability in crop quality and yield. High investment and operational costs, particularly in indoor and vertical farming systems, further challenge commercial viability. Increasing consumer awareness and developing cost-effective production technologies are therefore critical for expanding the microgreen

industry (Kyriacou *et al.*, 2016; O'Sullivan *et al.*, 2024) ^[19, 23].

Recent Innovations in Microgreen Research

Recent technological advances have significantly improved the productivity, nutritional quality, and sustainability of microgreen production. Precision agriculture tools, including sensors, Internet of Things (IoT) devices, and automated environmental control systems, enable real-time monitoring of temperature, humidity, light, and nutrient conditions, resulting in improved resource-use efficiency and crop performance (O'Sullivan *et al.*, 2024; Khan *et al.*, 2024) ^[23]. Artificial intelligence (AI) and machine learning technologies are increasingly being used to optimize irrigation, nutrient management, environmental regulation, and harvest scheduling. These data-driven approaches improve productivity while reducing operational costs. Similarly, advances in programmable LED lighting systems allow precise manipulation of light spectra to enhance biomass production and increase concentrations of antioxidants, vitamins, carotenoids, and phenolic compounds in microgreens (Samuolienė *et al.*, 2013; Samuolienė *et al.*, 2017) ^[31, 32].

Biofortification has emerged as another promising research area, with studies focusing on increasing essential minerals such as iron, zinc, selenium, and iodine through nutrient management and hydroponic techniques. Researchers are also developing sustainable substrates derived from agricultural residues, biochar, and biodegradable materials. Furthermore, innovations in edible coatings, antimicrobial treatments, biodegradable packaging, and modified atmosphere packaging are helping to extend shelf life and reduce postharvest losses. Together, these advancements are enhancing the sustainability, nutritional value, and commercial potential of microgreens while supporting the future growth of the industry (Rouphael *et al.*, 2021; Pescarini *et al.*, 2023) ^[29, 24].

Future Research Directions

Although considerable progress has been made in microgreen research, several areas require further investigation to enhance productivity, nutritional quality, food safety, and sustainability. Future studies should focus on evaluating genetic diversity among vegetable species and cultivars to identify genotypes with superior yield, nutrient content, phytochemical accumulation, and adaptability to controlled-environment systems. Breeding programs specifically targeting microgreen production could contribute to the development of improved cultivars with enhanced commercial value (Xiao *et al.*, 2012; Sharma *et al.*, 2022) ^[40, 33].

Additional research is needed to better understand the interactions among environmental factors such as light, temperature, humidity, carbon dioxide, and nutrient management. Optimizing these factors through advanced environmental control technologies can improve crop performance and resource-use efficiency. Clinical studies are also required to validate the longterm health benefits of microgreens and strengthen their role as functional foods. Furthermore, continued research on food safety, pathogen control, sustainable substrates, biofortification, automation, artificial intelligence, and life-cycle assessment will support environmentally responsible and economically viable production systems. Collaborative efforts integrating horticulture, nutrition, engineering, and biotechnology will be essential for advancing the microgreen industry in the future (Rouphael *et al.*, 2021; O'Sullivan *et al.*, 2024) ^[29, 23].

Conclusion

Microgreens represent a rapidly emerging category of specialty crops characterized by exceptional nutritional value, short

production cycles, and adaptability to modern agricultural systems. Vegetable crops such as broccoli, kale, cabbage, radish, mustard, beetroot, fenugreek, coriander, lettuce, and pea have demonstrated significant potential for microgreen production owing to their rapid growth and abundance of health-promoting compounds. Scientific investigations have consistently demonstrated that microgreens contain elevated concentrations of vitamins, minerals, antioxidants, carotenoids, glucosinolates, phenolic compounds, and other bioactive constituents compared with many mature vegetables. These attributes contribute to their recognition as functional foods capable of supporting human health and reducing the risk of chronic diseases. The compatibility of microgreens with hydroponics, vertical farming, and controlled-environment agriculture further enhances their significance within contemporary food systems. Their efficient use of land and water resources aligns with global efforts to promote sustainable agriculture and improve urban food security. Nevertheless, challenges related to food safety, postharvest management, production costs, and standardization must be addressed to ensure long-term industry sustainability. Future advances in genetics, precision agriculture, biofortification, automation, artificial intelligence, and postharvest technologies are expected to further enhance the productivity and quality of microgreens. As consumer demand for nutrient dense and environmentally sustainable foods continues to grow, microgreens are likely to play an increasingly important role in future horticultural production systems and public health strategies.

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