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Microgreens for Home, Commercial, and Space Farming: A Comprehensive Update of the Most Recent Developments

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Abstract

Microgreens are edible young plants that have recently attracted interest because of their color and flavor diversity, phytonutrient abundance, short growth cycle, and minimal space and nutrient requirements. They can be cultivated in a variety of systems from simple home gardens to sophisticated vertical farms with automated irrigation, fertilizer delivery, and lighting controls. Microgreens have also attracted attention from space agencies hoping that their sensory qualities can contribute to the diet of astronauts in microgravity and their cultivation might help maintain crew physical and psychological health on long-duration spaceflight missions. However, many technical challenges and data gaps for growing microgreens both on and off Earth remain unaddressed. This review summarizes recent studies on multiple aspects of microgreens, including nutritional and socioeconomic benefits, cultivation systems, operative conditions, innovative treatments, autonomous facilities, and potential space applications. It also provides the authors' perspectives on the challenges to stimulating more extensive interdisciplinary research.

1. INTRODUCTION

Microgreens, the miniaturized plants that are harvested at full cotyledon expansion and emergence of true leaves (Xiao et al. 2012, Xu et al. 2020), have recently gained increasing popularity. These seedlings exhibit advantages over mature plants given their short growth cycle and attractive colors and flavors, etc. Moreover, microgreens are rich in phytonutrients with highly species-dependent nutrient profiles (Mir et al. 2017, Teng et al. 2021, Turner et al. 2020, Xiao et al. 2012). Microgreens can be produced by procedures with all levels of sophistication, ranging from at-home cultivation on potting mix or capillary mat (Işık et al. 2020, Kyriacou et al. 2020, Wieth et al. 2020) to mass production with state-of-the-art controlled environment agriculture (CEA) technologies (Guntaka et al. 2021, Jiang et al. 2021, Rankothge et al. 2021).

The multitude of benefits of microgreens has incited extensive studies and technological advancement, a trend that has accelerated in the 2020s. Several underutilized species and cultivars have been investigated for their nutritional composition and health benefits (Altuner et al. 2021, Lenzi et al. 2019, Schayot 2021, Senevirathne et al. 2019). Several comprehensive in vitro and in vivo studies (de la Fuente et al. 2020, Mohamed et al. 2022, Truzzi et al. 2021) yielded more insight at the level of molecular nutrition. Continuous efforts have been made to optimize the growth conditions with a focus on light input (Appolloni et al. 2022) and nutrient management (Islam et al. 2020, Patras 2021, Phornvillay et al. 2022). Moreover, microgreen production has benefited from a variety of emerging cultivation systems (Kizak & Kapaligoz 2019, Ma et al. 2019), innovative treatments (Phornvillay et al. 2022, Saengha et al. 2021, Supapvanich et al. 2020), and the revolutionary Internet of Things (IoT) (Guntaka et al. 2021, Jiang et al. 2021, Turchenko et al. 2020).

Beyond the Earth, microgreens have been considered as a possible diet component for crew members in the space station(s). The rich flavor and unique nutrient profile of microgreens may help promote appetite and maintain the homeostasis of astronauts (Cahill & Hardiman 2020, Taylor et al. 2020). In addition, the convenient cultivation and vibrant color make microgreens a good choice for horticultural therapy (Kyriacou et al. 2017). Although space farming faces many challenges from the microgravitational environment (Hirai & Kitaya 2009, Kitaya et al. 2010), various technologies and growth systems are being developed or conceptualized to achieve successful space cultivation (Chandrika et al. 2019, Kalossaka et al. 2021, Rai & Kaur 2012, Xu et al. 2020).

This review aims to summarize the latest research and development on multiple aspects of microgreens, including the nutritional and socioeconomic aspects, cultivation systems and techniques, critical growth conditions, quality and safety improvement technologies, IoT and autonomous gardening, and the potential of microgreen space farming. It also provides the authors' perspectives on the trends and research opportunities in this area with the intent to stimulate more comprehensive and interdisciplinary research. The fact that most of the references covered in this review were published in the 2020s signifies the increasing interest and momentum in microgreen-related research.

1.1. Nutritional Profile of Microgreens

Microgreens are densely packed with nutrients and health-promoting phytochemicals. The past four years (2019–2022) have seen a surge in research on the nutritional aspects of microgreens. Two subjects are highlighted in these recent studies: (*a*) the nutritional composition of uncommon or underutilized microgreen species and (*b*) mechanistic investigations via in vitro and in vivo studies. Readers are referred to review articles for studies published prior to 2019 (see Mir et al. 2017, Teng et al. 2021, Turner et al. 2020).

1.1.1. Nutritional composition. **Table 1** summarizes recent studies regarding the nutritional composition and antioxidative activities of microgreens. Many microgreen species are excellent sources of essential nutrients (amino acids, vitamins, minerals, etc.) as well as nonessential, health-beneficial phytonutrients (mainly phenolics and glucosinolates). Whether microgreens or their mature counterparts provide more nutrients depends on the species and the type of nutrients. For instance, parsley microgreens have more phosphorous and potassium but less calcium, magnesium, sulfur, and sodium than baby greens (El-Nakhel et al. 2021a). For vitamins, fenugreek and roselle microgreens have higher α-tocopherol but lower β-carotene levels than mature plants (Ghoora et al. 2020b). In addition, certain microgreen species exhibit high levels of nitrate (Lenzi et al. 2019) or an inadequate nitrogen balance index (Altuner et al. 2021). Regarding the phytonutrients, although lettuce (Martínez-Ispizua et al. 2022) microgreens exhibit higher total phenolic content (TPC) than mature plants, Chinese basil (Dimita et al. 2022), radish, jute, and water spinach (Yadav et al. 2019) show greater TPC at maturity. Moreover, as discussed in Section 3, the nutritional profile of microgreens is greatly influenced by the growth environment and nutrient input. As such, the comparison between microgreens and mature plants should be conducted under reasonably similar growth conditions. Considering all these factors, it is recommended that microgreen species be investigated discriminatively for their nutritional properties and included in nutritionally balanced meals to realize maximal nutritional benefits.

1.1.2. Antiproliferative and antidiabetic effects of certain microgreens. There have been several recent studies on the antiproliferative effect of microgreens and their underlying mechanisms (**Table 2**). In vitro studies revealed remarkable and selective inhibition against cancer cells by broccoli, kale, mustard, radish, green pea, soybean, barley, beetroot, and amaranth microgreens (de la Fuente et al. 2020, Truzzi et al. 2021). Studies show that the antiproliferative effects of microgreens may be attributed to two factors. First, microgreens in general are an abundant source of antioxidants, including vitamins A, C, and E, as well as phenolics. Those compounds scavenge excessive ROS (reactive oxygen species) and help maintain normal signaling, thus preventing cell damage induced by cancer cells (do Carmo et al. 2018). Second, it has been found that certain polyphenols such as epigallocatechin-3-gallate (EGCG), trans-resveratrol, quercetin, and curcumin may act as pro-oxidants. Those compounds produce hydrogen peroxide and kill cancer cells without significantly damaging normal tissues (D'Angelo et al. 2017, León-González et al. 2015). Recently, two comparative studies (Drozdowska et al. 2020, 2021) reported more potent antiproliferative effects of red-headed cabbage microgreens than mature plants. The authors attributed the difference to the greater levels of polyphenolic compounds, especially flavonoids in microgreens. However, more studies are needed to conclude whether microgreens in general exhibit greater antiproliferative effects than their mature counterparts. In addition, knowledge gaps remain as to which role of the phenolics is predominant under given conditions and in certain pathways.

More recently, barley (Mohamed et al. 2022) and broccoli (S. Ma et al. 2022, Theodorou et al. 2021) microgreens have been reported to exhibit significant antidiabetic effects. Such an effect is achieved by broccoli microgreens through blood lipid status improvement, anti-inflammatory

Table 1 Recent studies on the nutritional properties of microgreens

Species	Nutrients/indices	Findings	Reference
Parsley	Minerals, carotenoids, TPC	Microgreens have more P and K, less Ca, Mg, S, and Na than baby greens Microgreens have more lutein and carotenoid but fewer phenolics than baby greens	El-Nakhel et al. 2021a
Beet	Ascorbic acid, TPC, betalains	The pigment betalains unique to Caryophyllales are the primary contributors to antioxidant ability	Acharya et al. 2021
Choy sum	Amino acids, sugars, minerals, vitamins, glucosinolates	Amino acids, carotenoids, vitamin K, folate, and most minerals, except Na, are more concentrated in microgreens than in adult plants	Zou et al. 2021
Hemp	Minerals, cannabinoids, TPC, and delta-8 THC	Good source of P and Mg; low levels of THC; cannabinoids accumulate over time; slightly more phenolics and antioxidants than other microgreens	Schayot 2021
Wild leafy species *Sanguisorba minor* Scop., *Sinapis arvensis* L., and *Taraxacum officinale* Weber ex F.H. Wigg.	Macronutrients, vitamins, anthocyanins, carotenoids, nitrate	Competitive yield; high levels of anthocyanins and carotenoids; nitrate level is concerning	Lenzi et al. 2019
Kose and Kirik wheat landraces	Macronutrients, phenolics, flavonoids, carotenoids, total antioxidant ability	Wheat landraces have significantly higher total antioxidant ability than wheat cultivars, barley, and oat, but the nitrogen balance index is low	Altuner et al. 2021
Borage and purslane	Yield, minerals, TPC, carotenoids	Purslane has high TPC and ascorbic acid and potential good β-carotene bioavailability Borage microgreens have a high fresh yield and a more balanced phenolic profile	Corrado et al. 2021
Lettuce (microgreens, baby leaves, and mature plants), various landraces and cultivars	TPC, ascorbic acid, minerals	Microgreens have 42% more ascorbic acid, 79% more phenolics, and more Ca, K, and Fe than adult lettuce; red-leaf varieties show the greatest variation between growth stages	Martínez-Ispizua et al. 2022
Chinese basil microgreens and mature plants	VOCs and TPC	Fragrance does not correlate to phenolics Microgreen basil has higher content of VOCs but lower TPC than mature plants	Dimita et al. 2022

(*Continued*)

Table 1 *(Continued)*

Species	Nutrients/indices	Findings	Reference
Beetroot, radish, kale, amaranth, green peas, in comparison to sprouts	Phenols, antioxidants, pigments, organic acids, sugars, pectin, antioxidant activity	Microgreens are higher in carotenoids, chlorophylls, and organic acid Sprouts are higher in amino acids, pectin, and sugars Overall, sprouts show stronger antioxidant capacities than microgreens	Wojdyło et al. 2020
Amaranthus, bottle gourd, cucumber, jute, palak, poi, pumpkin, radish, water spinach, in comparison to mature plants	TPC, total flavonoids, ascorbic acid, antioxidant activity	Microgreens have higher Zn and K content Mature plants have higher TPC and antioxidant activity No specific trend in ascorbic acid, Fe, Cu, or Mn	Yadav et al. 2019
Fourteen species from Brassicaceae, Fabaceae, Pedaliaceae, Polygonaceae, Convolvulaceae, and Malvaceae	Macronutrients, vitamins, TPC, anthocyanins	Lentil has most proteins, ascorbic acid, and carotenoids Buckwheat shows highest TPC Anthocyanins found only in purple radish and red cabbage	Kowitcharoen et al. 2021
Carrot, fennel, fenugreek, French basil, mustard, onion, radish, roselle, spinach, sunflower	Phytochemicals, OPCI, APCI	Roselle and fennel microgreens have highest APCI; other species have greater or similar APCI and OPCI compared to mature spinach leaves	Ghoora et al. 2020b
Carrot, fennel, fenugreek, French basil, mustard, onion, radish, roselle, spinach, sunflower	NQS based on 11 desirable and 2 to-be-limited nutrients	Fenugreek, spinach, and roselle microgreens have higher α-tocopherol but lower β-carotene contents than mature plants Oxalate levels are much lower in the microgreens All studied microgreens have higher NQS than mature spinach leaves	Ghoora et al. 2020a
Daikon, mustard, rocket salad, watercress, broccoli	Pigments, antioxidants, reducing sugars, antioxidant activity	Mustard has more ascorbic acid and total sugar content Broccoli is richer in polyphenol and carotenoid	Marchioni et al. 2021
Kale, red cabbage, kohlrabi, radish	Metabolomic composition and in vitro bioaccessibility	470 phytochemicals identified, including glucosinolates and phenolics Bioaccessibility (8–14%) depends highly on chemical type and species	Tomas et al. 2021

Abbreviations: APCI, antioxidant potential composite index; NQS, nutrient quality score; OPCI, overall phytochemical composite index; THC, tetrahydrocannabinol; TPC, total phenolic content; VOC, volatile organic compound.

Table 2 Recent studies on the antiproliferative and antidiabetic effects of selective microgreens

Species (preparation)	Health benefit(s)	Mechanism(s)	Reference(s)
Broccoli, kale, mustard, and radish (bioaccessible fraction)	Antiproliferative – reduced Caco-2 cell proliferation by up to 41.9% (Trypan blue method)	Pro-oxidation – increasing ROS and decreasing GSH, altering redox status and causing mitochondrial membrane dissipation, followed by a general cell cycle arrest and apoptosis	de la Fuente et al. 2020
Green pea, soybean, radish, Red Rambo radish, and rocket (sterilized aqueous extract)	Antiproliferative – Red Rambo radish and green pea show low toxicity to healthy L929 fibroblasts and up to 70% inhibition of 3D spheroid culture of RD-ES Ewing sarcoma cells (MTT)	Pro-oxidation – same as above; heat-resistant polyphenols are considered as major contributors (no mechanism is discussed)	Truzzi et al. 2021
Red cabbages, microgreen versus mature plants (juice)	Antiproliferative – microgreens show more potent inhibition of prostate cancer cell growth (DU145 and LNCaP)	Antioxidation – ROS scavenging and cell signaling normalization Cell signaling modulation – apoptosis induction through multiple mitochondrial pathways involving NF-κβ and Akt inhibition and stress-activated protein kinases	Drozdowska et al. 2020, 2021
Barley (incorporated in diet)	Antidiabetic – reverted the change in glucose and insulin levels, β-cell function, and liver and kidney function deterioration in rats caused by streptozotocin Amelioration of aflatoxin toxicity	Wistin (flavonoid) – activates peroxisome proliferator-activated receptors; PPAR-γ is crucial in adipogenesis regulation, energy balance, and insulin sensitivity Phytanic acid (branched fatty acid) – mediates insulin sensitizing, improves glucose homeostasis	Mohamed et al. 2022
Broccoli (incorporated in diet)	Hypoglycemic – improved body weight and glucose homeostasis of mice treated with high-fat diet	Blood lipid status improvement Anti-inflammatory and antioxidant functions Insulin sensitization Gut microbiota modulation	Ma et al. 2022
Broccoli (juice incorporated in diet)	Body weight control – reduced white adipose tissues and increased water intake for mice treated with high-fat diet	Insulin sensitization Gut microbiota modulation Glucose tolerance improvement	X. Li et al. 2021
Beetroot, radish, kale, amaranth, green peas, in comparison to sprouts (methanolic extract)	Microgreens overall have greater antidiabetic, antiobesity, and anticholinergic effects than sprouts; however, this is not a strict pairwise comparison between microgreens and sprouts of same species	Antidiabetic, antiobesity, and anticholinergic: in vitro inhibition of α-amylase, β-glucosidase, pancreatic lipase, AChE, and BuChE	Wojdyło et al. 2020

Abbreviations: AChE, acetylcholinesterase; BuChE, butylcholinesterase; GSH, glutathione; PPAR-γ, peroxisome proliferator-activated receptor gamma; ROS, reactive oxygen species.

and antioxidant functions, insulin sensitization, and modulation of gut microbiota. The effect observed in barley is attributed to two compounds, wistin (4′,6-dimethoxyisoflavone-7-O-β-D-glucopyranoside) and phytanic acid. Both compounds activate proliferator-activated receptors (PPAR-α and PPAR-γ subunits), which are major regulators of adipocyte differentiation and glucose metabolism (Roca-Saavedra et al. 2017, Sanada et al. 2016). Wistin has not been reported as indigenous to mature barley plants or grains, which suggests different antidiabetic mechanisms for mature and microgreen barleys (Zeng et al. 2020). Similar to the case of antiproliferative effects, there is limited research on the comparison between the antidiabetic functions of microgreens, baby leaves, sprouts, mature plants, and mature edible parts (e.g., grains) (Wojdyło et al. 2020). Further research is recommended to address this knowledge gap.

1.2. Role in Physical and Mental Well-Being

The ongoing COVID-19 pandemic has caused not only psychological stress but also a general reduction in daily physical activities. Gardening is a cost-effective activity that enhances a feeling of connectedness with nature and addresses the problem of a sedentary lifestyle (Theodorou et al. 2021). Growing microgreens has emerged as a favored home gardening activity. The convenient growth procedure, short growth cycle, vibrant color, and rich flavor make microgreens an excellent choice for first-time home gardeners, who may be more hesitant to try growing mature plants because of the complexity of maintenance and potential failure. Microgreens' positive effects on physical and mental health are demonstrated in two studies in the United Kingdom (Gittins & Morland 2021) and United States (Kelley et al. 2017), respectively, which suggested that participants experienced less depression and better physical health by growing microgreens, and they would continue to grow plants as a hobby.

1.3. Role in Food Security

Food insecurity is a growing concern as the world urbanizes. Microgreens may be a suitable addition to urban farms that improves food security owing to their ability to provide households with a timely supply of nutrients in the case of emergency (Di Gioia et al. 2017). Moreover, the minimal space requirement and relatively high price make microgreens a profitable choice for CEA and urban/vertical farms, which allow year-round production under various climatic conditions. Those advantages have made microgreens a main food product in global urban farming according to a recent survey (Armanda et al. 2019). Furthermore, microgreens have proven to be a great educational tool for improving nutrition awareness (Haslund-Gourley et al. 2022) and stimulating indoor food farming practices in local communities (Herrmann et al. 2020). However, it is worth noting that microgreen production requires a large volume of seeds with relatively low biomass yield per seed in comparison to mature plants.

2. MAIN AND EMERGING CULTIVATION SYSTEMS FOR MICROGREENS

Microgreens have been grown in various systems with diverse levels of precision and sophistication. Many of these systems are discussed in this section and can be used in CEA facilities that allow precise climate, nutrient, and light control in all locations and seasons. Compared to conventional open farm production, CEA enables energy-efficient and year-round production of crops with greater and more consistent yield, nutritional value, quality, and safety (Shamshiri et al. 2018).

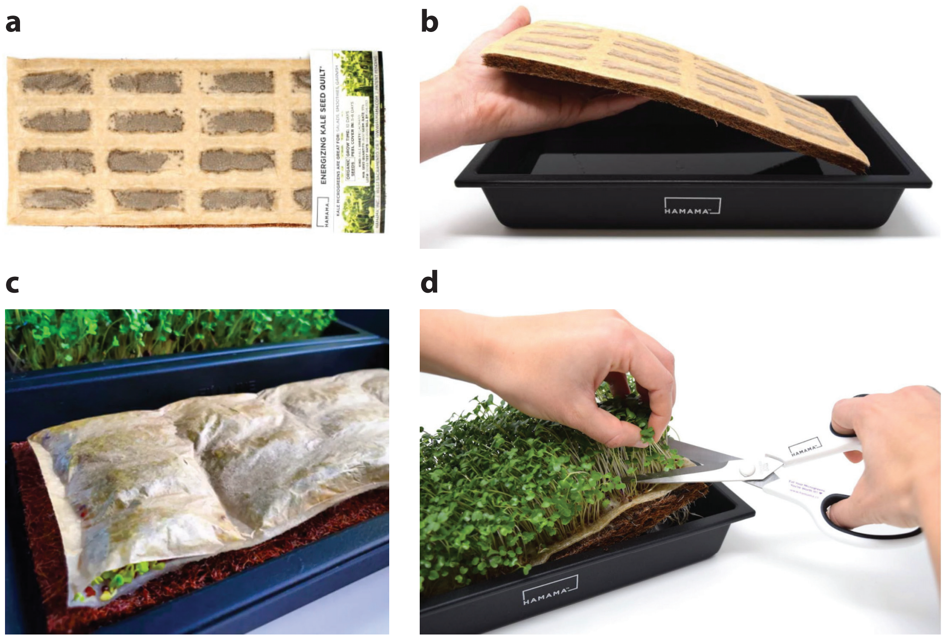

Figure 1

A home-friendly microgreen growth kit. (*a*) A proprietary germination mat with seeded pockets. (*b*) Placing the germination mat after one-time watering. (*c*) Seedlings emerging from the pockets. (*d*) Harvesting the microgreens. Photos courtesy of Hamama, Inc.

2.1. Soilless Substrate–Based Farming

Soilless substrate–based farming is the most convenient growth method for noncommercial settings such as home gardening. These systems leverage soilless substrates such as peat moss, coconut coir, hemp mat, rockwool, or other inert porous materials (Di Gioia et al. 2017, Thuong & Minh 2020) and deliver water via either top-down dripping/spraying or bottom-up wicking. A common analogy is made between this approach and the hydroponic cultivation of mature crops. However, microgreen cultivation is unique in that the nutrient solution is optional rather than required (El-Nakhel et al. 2021b), and thus the substrates may function as a nutrient source rather than merely an inert support (Thuong & Minh 2020).

To date, various user-friendly growth kits have been developed based on soilless substrates and gained popularity among home gardeners. One example is the Microgreen Growth Kit™ by Hamama (**Figure 1**), which consists of a pre-seeded mat and a coconut coir substrate. This system only requires laying the seeded mat on the substrate and watering once. Microgreens can grow with an adequate level of water supply and be harvested typically in two weeks. Another example is the Cell One™, which is an enclosed system with pre-seeded pods and LED illumination. A user-friendly mobile application allows users to monitor the water level and adjust lighting conditions.

2.2. Hydroponic Systems

Hydroponic techniques such as deep-water culture (DWC) and nutrient film technique (NFT) feature higher water efficiency at the expense of higher instrument/energy/space costs. In DWC systems, seeds are sown on an inert substrate floating on a deep reservoir of circulated water or nutrient solution, where the roots develop to seek nourishment. DWC systems require active aeration of the reservoir. A recent study reported that proper aeration improved the productivity of lentil and wheat microgreens, while insufficient aeration led to root hypoxia and poor growth (Grishin et al. 2021). On the other hand, excessive agitation and aeration were found to cause root damage and reduced yield for Swiss chard (Baiyin et al. 2021).

NFT systems deliver the nutrient solution continuously as a shallow, recirculating stream through an inclined growth tray. NFT is advantageous due to minimal root submersion, which boosts root zone aeration and benefits plant development. However, it is susceptible to pump failure, which leads to rapid root dehydration. Recently, NFT has been reported to provide significantly improved yield of table beet microgreens compared to substrate-based methods (Murphy et al. 2010). Moreover, home-friendly NFT systems such as Grow Wall™ are available for household cultivation of microgreens and mature plants.

2.3. Aeroponic Systems

Aeroponic methods deliver the nutrient solution via fine aerosol droplets (10–100 μm) through various atomization techniques (Eldridge et al. 2020). These minute droplets offer two major advantages, namely the highest water efficiency among all growth methods and excellent root zone oxygenation. However, aeroponic systems require sophisticated instrumentation for precise environmental control and are vulnerable to power outages or suboptimal nutrient recipes. Aeroponic techniques have been adopted for commercial microgreen production in emerging corporations such as AeroFarms (**Figure 2**). Miniaturized aeroponic microgreen growth towers (Agrotonomy 2019) and prototype root chambers (Gnauer et al. 2019) have also been reported.

2.4. Aquaponic Systems

Aquaponic systems feature the simultaneous cultivation of fish (aquaculture) and plants (hydroponics). They leverage the conversion of fish waste to plant nourishment via naturally occurring microbes (Yep & Zheng 2019), followed by remediation and recirculation of water consumed by plants. This system is highly water/nutrient efficient and improves plant growth via its unique dissolved organic matter and microbiota (Nicoletto et al. 2018). However, it requires constant monitoring and adjustment of nutrient composition due to the mismatch between the nutrient

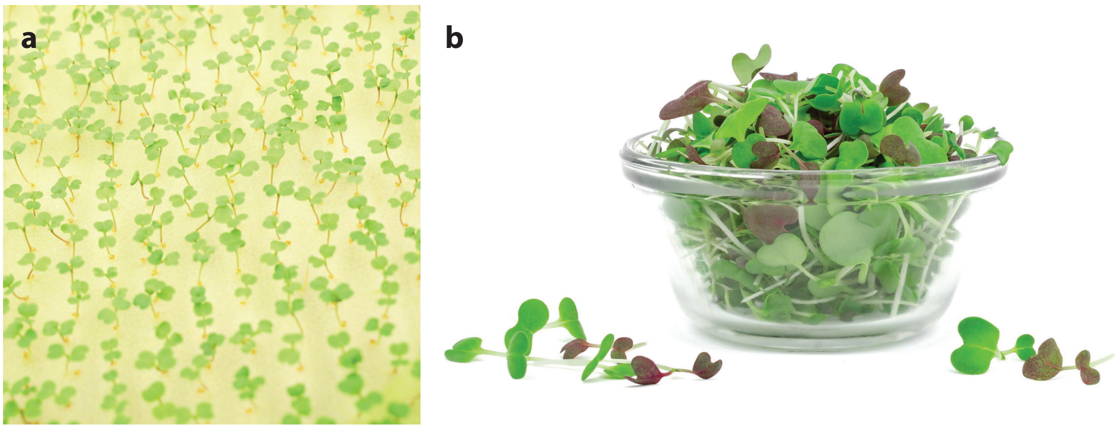

Figure 2

Microgreens produced by aeroponic technology. (*a*) Seedlings growing on a proprietary fabric suitable for aeroponic operation. (*b*) A final product containing several varieties of microgreens. Photos courtesy of AeroFarms, Inc.

requirements of fish, nitrifying bacteria, and plants (Nicoletto et al. 2018). Currently, there is only one academic publication on aquaponic production of arugula microgreens (Kizak & Kapaligoz 2019). However, it is foreseeable that this technology could gain more attention in the future and become a sustainable, visually appealing, and economically viable method for producing microgreens or other miniaturized plants.

3. KEY FACTORS AFFECTING MICROGREEN GROWTH

The growth and quality of microgreens can be influenced by many environmental and operational factors, including substrate, light, and nutrient input. These factors need to be considered and optimized on a species-specific basis to achieve optimal yield and product quality, as is discussed in this section.

3.1. Substrates

Substrates can serve as a nutrient source and/or as an interface between plants and the nutrient solution. Thus, substrates may affect microgreen growth by physical (mechanical strength and support, water holding/wicking capacity, air-filled porosity, etc.), chemical (dissolution of nutrients and/or antinutrients from substrate), or microbiological (initial microbial load or susceptibility to microbial growth) means. **Table 3** summarizes recent studies comparing the performance of various microgreen growth substrates. These results suggest that the performance of a substrate is dependent on the species and the goals (fresh yield, dry yield, nutrient level, etc.). In addition, it is noteworthy that all those studies employed similar fertilizers or nutrient solutions, and thus the different performances of the substrates were more attributable to their physical property than chemical composition. The role of chemical composition would have been more remarkable if the microgreens had been cultivated in pure water or under nutrient deprivation (see Section 3.3). Moreover, factors such as cost, durability, ease of disinfection, and biodegradability need to be considered. Overall, it is recommended that proper substrates be chosen on a case-specific basis.

3.2. Light Input

Light as the energy source for plant growth is the core parameter controlled by CEA as well as the factor most extensively studied for microgreen production (Alrifai et al. 2019, Appolloni et al. 2022, Zhang et al. 2020). In brief, the light spectrum affects yield and the contents and profile of secondary metabolites (glucosinolates, phenolics, etc.) in a highly species-dependent manner (Alrifai et al. 2020). The photoperiod interacts with the circadian rhythm of plants, regulates nutrient uptake and growth, and alters the production of secondary metabolites (Liu et al. 2022). The blockage and subsequent exposure to light cause physiological and biochemical changes referred to as etiolation and de-etiolation, respectively; modulation of such processes by manipulating the timing of first light exposure alters the yield, hypocotyl length, and levels of certain nutrients of microgreens (Kong & Zheng 2021, Niroula et al. 2021). Overnight supplementation of blue light may improve microgreen yield without compromising the nutritional values (Ying et al. 2020). Finally, short-term high-intensity light irradiation (Shao et al. 2020) and pulsed LEDs (Miliauskienė et al. 2021, Olvera-Gonzalez et al. 2021) have been reported as effective ways to save energy and induce higher antioxidant levels in microgreens.

3.3. Nutrient Management

Although microgreens can grow without a nutrient solution, their metabolic pathways can be effectively altered by the macro- and microelements in the environment. Therefore, nutrient

Table 3 Recent studies on the effect of substrates on microgreen growth and nutrition

Species	Substrates	Findings	Reference
Radish	Sphagnum peat, coconut coir	Sphagnum peat requires less fertilizer than coconut coir to achieve same yield Microbial load within safe and legal limit	Thuong & Minh 2020
Green basil, rocket, and red basil	Coconut coir, vermiculite, jute	Yield and nutrition depend on both species and substrates Coconut fiber and vermiculite work the best for green and red basil, respectively	Negri et al. 2019
Kohlrabi, pak choi, and coriander	Agave fiber, capillary mat, cellulose sponge, coconut fiber, peat moss	Peat moss provided greatest fresh and dry yield but low dry matter content and phenolic content Natural fiber substrates increase nitrate and macromineral levels	Kyriacou et al. 2020
Mizuna and rapini	*Posidonia* natural residue and peat	Addition of *Posidonia* leaves or fibers increased the I and B content in microgreens without negatively affecting the yield	D'Imperio et al. 2021
Purple cabbage	CSC® vermiculite, Beifiur® S10, Carolina Soil® seedling, Carolina Soil® organic	No effect of substrate type on shoot fresh/dry matter yield or shoot height at harvest	Wieth et al. 2020
Green basil, rocket, and red basil	Coconut coir, vermiculite, jute	Substrate type dictated levels of nitrate, sucrose, anthocyanin, and phenolics	Bulgari et al. 2021
Broccoli, cabbage, kale, mustard, and radish	Biostrate® (felt fiber), hemp mat, jute mat, Micro-Mats (wood fiber)	Substrate type altered fresh, dry shoot weights and mineral nutrients in tested microgreens Microgreens in hemp mat showed highest shoot height and weight and K concentration but lowest N concentration	T. Li et al. 2021a

solutions are commonly used and modified in microgreen production, especially under CEA settings, to boost crop yield and quality. For example, one-time application of a general-purpose fertilizer increases the fresh shoot weight and macro- and micronutrient concentrations of ten microgreen species (amaranth, arugula, broccoli, basil, cabbage, radish, kale, kohlrabi, mustard, and green pea), despite lower levels of minerals that were not present in the fertilizer (T. Li et al. 2021b). In addition, the NH_4^+/NO_3^- ratio in the fertilizer affects the fresh and dry matter, nitrate, protein, and β-carotene content of broccoli, broccoli raab, and cauliflower microgreens (Palmitessa et al. 2020). Regarding trace nutrients, selenium biofortification has been reported as an effective method to enhance the contents of selenium, phenolics, flavonoids, vitamin C, and anthocyanin in microgreen species, including wheat, coriander, tatsoi, green basil, and red basil (Islam et al. 2020, Pannico et al. 2020a).

Although sodium is not an essential element for plants, sodium salts are employed to induce salinity stress and serve as an elicitor. For instance, NaCl (up to 25 mM) significantly increases the levels of β-carotene, phenolic acid, flavonoid, vitamin C, anthocyanin, and antioxidant activity of wheat microgreen extract without compromising the yield (Islam et al. 2019). Likewise, elevated salinity increases the total phenolic content and diphenyl-1-picrylhydrazyl (DPPH) scavenging capacity of white cabbage microgreens (Patras 2021) as well as the glucosinolate content and antioxidant activity of *Brassica carinata* (L.) microgreens (Maina et al. 2021).

Nutrient deprivation has proved to be another effective method to regulate microgreen growth. In a recent study, replacing a quarter-strength Hoagland nutrient solution with pure water reduced the yield of Brussels sprouts, cabbage, and rocket microgreens by 10%, 10%, and 47%, respectively. However, such treatment led to remarkably increased levels of lutein, ascorbic acid, phenolic acid, and total anthocyanins as well as a reduction of nitrate levels by as much as 99% (El-Nakhel et al. 2021b). Very similar results on yield, ascorbic acid, phenolics, and nitrate were reported in another study on lettuce microgreens (Pannico et al. 2020b). In a third study, lowering the strength of Hoagland nutrient solution from 100% to 25% yielded higher anthocyanin content and lower nitrate content in garden cress microgreens, but such treatment reduced the carotenoid, total phenols, and antioxidant activity levels in radish cress microgreens (Keutgen et al. 2021). Finally, nutrient deprivation up to 12 days before harvest reduced the nitrate content and improved the phenolic content of lettuce, rocket, and mustard microgreens at the expense of lower carotenoid content (Kyriacou et al. 2021).

4. TECHNOLOGICAL ADVANCEMENT EMPOWERING MICROGREEN PRODUCTION

Microgreen farming is an epitome of modern agriculture that evolves with greater productivity, precision, and level of automation. Such transition is largely propelled by new technologies, including advanced physical and chemical treatments as well as IoT-enabled autonomous operation. Many of those technologies were invented outside of agricultural science but have demonstrated many beneficial effects in microgreen production. This section discusses the latest technological advancement in microgreen cultivation to highlight and stimulate interdisciplinary collaboration between growers, scientists, and engineers.

4.1. Physical Treatments

Physical treatments improve the yield, quality, and safety of microgreens by inducing abiotic stress and altering plant metabolism. For instance, the advanced oxidation process (AOP) generates highly unstable ROS in the presence of UV-C. AOP is augmented by a solvent containing micro-nano bubbles (50–100 μm diameter), which generate ROS as the bubbles collapse. Combination of the two techniques (AOP and micro-nano bubbles) produced large quantities of free radicals that stress the plants and bacteria, which was reported to improve seed viability and increase the total phenolic content and DPPH antioxidant activity of roselle microgreens (Phornvillay et al. 2022).

Cold plasma is a nonthermal, economical, flexible, and environmentally friendly procedure for food processing. It stresses the plant by oxidative degradation of double bond–containing compounds. Cold plasma seed treatment showed significant improvement in the total phenolic, isothiocyanate, and flavonoid contents; antioxidant activity; and antiproliferative effects for mustard microgreens (Saengha et al. 2021). Similarly, rat-tailed radish seeds (Luang-In et al. 2021) treated with a combination of cold plasma and $CaCl_2$ yielded microgreens with improved dry weight, total isothiocyanate content, and total phenolic content. Recently, a multicorona discharge model was developed to deliver stable plasma to large microgreen growth areas. The novel design exhibited a significant improvement in germination rate of up to 8% and growth rate of up to 3.5 times for rat-tailed radish microgreens (Tanakaran & Matra 2021).

Pulsed electromagnetic field is a noninvasive and ecological method for plant treatment. By improving food reserve utilization, nutrient assimilation, enzymatic activity, and photosynthesis of plants, this technology was reported to improve the fresh weight, dry weight, and greenness of wheat and spinach microgreens (Katsenios et al. 2021).

Low-frequency high-intensity ultrasound (20–40 kHz) inactivates bacterial cells by inducing shear forces, water jets, and shock waves resultant from acoustic cavitation in a liquid. A novel technology was developed to leverage the bactericidal effect of ultrasound without damaging plant tissues. It combines high acoustic power density ultrasound with mild heat and a $CaO/Ca(OCl)_2$ antimicrobial spray. This treatment achieved satisfactory antimicrobial effectiveness on radish, broccoli, and kale microgreens, which was comparable to that accomplished by immersion in a water solution of 20,000 mg/L free chlorine for 20 min. It provides an adequate and environmentally friendly solution for mitigating microbial contamination on microgreens (Dong et al. 2022).

4.2. Chemical Treatments

A variety of chemical treatments have been applied singularly or with physical treatments for improving microgreen quality. The chemicals may impact the quality and safety of microgreens by (*a*) serving as elicitors that trigger plant defense response during growth or (*b*) acting as a preservative that extends shelf life after harvest. For preharvest applications, $CaCl_2$ combined with UV-B radiation improved the glucosinolate level, visual appeal, and shelf life of broccoli microgreens (Lu et al. 2021). A combination of Na_2SeO_3 and UV-A radiation led to significantly improved levels of anthocyanin, glucosinolate, total soluble proteins, total phenolic compounds, and antioxidant activity in broccoli microgreens (Gao et al. 2021). Regarding postharvest treatments, immersion of red amaranth microgreens in a solution of cyanocobalamin (vitamin B_{12}, 0.1 μM) enhanced the betacyanin, betaxanthin, and total betalain concentrations of red amaranth microgreens during storage (Supapvanich et al. 2020). Treatment of sunflower microgreens with citric and ascorbic acids improved the phenolic content and antioxidant activity while lowering the microbial load at the end of storage (Dalal et al. 2020). Finally, aloe vera gel was demonstrated to be effective for both pre- and postharvest treatments. Consisting of polysaccharides, vitamins, and minerals, the gel led to less electrolyte leakage, higher ascorbic acid content, lower microbial load, and better overall acceptability of radish and roselle microgreens (Ghoora & Srividya 2020).

4.3. Autonomous Gardening Empowered by the Internet of Things

The emergence of the IoT has brought unprecedented opportunities for agricultural modernization. IoT-based autonomous growth systems collect extensive, real-time data on plant growth and environmental parameters (climate, plant size, soil/substrate moisture, nutrient solution status, light intensity, photosynthetically active radiation, etc.). These data are utilized to inform end users through interactive interfaces and drive autonomous control systems to operate functional components (fans, humidifiers, LED panels, robotic arms, etc.). These integrated systems minimize the physical intervention by users and thus reduce the risk of human error and human-mediated pathogen contamination. In addition, by precisely delivering optimal growth conditions at desired times and locales, these systems hold promise in improving yield, quality, and energy efficiency (Ragaveena et al. 2021).

Compared to the broader realm of agriculture, microgreen production is still in its early stages of IoT adoption, especially on the consumer end. So far, only a few prototypes of IoT-based microgreen sprouting systems have been reported (**Table 4**). These systems are claimed to have multiple benefits, including precise climate control, uniform temporal/spatial distribution of lighting conditions, energy saving, intuitive operation, and effective inspection over large growth areas. It should be noted that the IoT has found much wider applications in the production of mature plants, with many more successful designs reported since the late 2010s (Sharma et al. 2020). In

Table 4 Internet of Things–enabled autonomous microgreen growth devices reported in the 2020s

Tested crop	Sensors	Function highlights	Findings	Reference
Kale microgreens	Light (RGB and quantum)	LED dimming and red:blue ratio adjustment	Energy savings of up to 34% Precise and uniform light spectrum and distribution in all weathers	Jiang et al. 2021
Kale microgreens	RGB and quantum, humidity, temperature, CO_2, and plant images	Light recipe modification and implementation Automated light positioning	Stable light spectrum and distribution at different sunlight levels Energy saving (projected)	Jiang & Moallem 2020
Microgreens (species undisclosed)	Electric conductivity, dissolved oxygen, CO_2, pH, light intensity, and plant images	LED dimming, water inflow/outflow, and automatic camera positioning	Reported and addressed various anomalies in detection and operation Complete light blockage recommended for irrigation line	Guntaka et al. 2021
Mung bean microgreens	Temperature, humidity, ultrasonic sensor (for growth and water-tank-level monitoring)	Temperature and humidity control Growth curve generation Low water warning	Established optimal temperature, photoperiod, and watering frequency for mung beans	Rankothge et al. 2021
NA (conceptualized protocol)	Temperature, humidity, light	AR-enabled inspection of entire growth space Autonomous watering, lighting, and cooling	AR is anticipated to provide quick access to comprehensive and intuitive growth information in large growth space	Turchenko et al. 2020

Abbreviations: AR, augmented reality; LED, light-emitting diode.
More discussion on the construction of IoT-based microgreen growth systems can be found in an additional reference (Juárez & Agudelo 2021).

addition, this technique has been adopted by several leading commercial CEA companies (AeroFarms, Bowery Farming, Plenty, etc.) for microgreen cultivation. Therefore, it is foreseeable that the IoT technology will be applied more widely in microgreen production, providing growers with more convenience, better energy efficiency, greater yield, and more consistent nutrition quality.

5. MICROGREENS FOR SPACE FARMING

The ability of humans to travel in space on extended missions may depend on growing fresh plants in space. NASA (National Aeronautics and Space Administration) has been testing growing leafy greens to feed astronauts on the International Space Station (Hummerick et al. 2021, Johnson et al. 2021, Massa et al. 2016). But growing plants in space faces many technical challenges because of the microgravity, limited growth areas and crew time, and elevated radiation levels (Johnson et al. 2021). Recently, microgreens have attracted significant attention and are being tested by NASA as an alternative or supplement to other leafy greens (**Figure 3**).

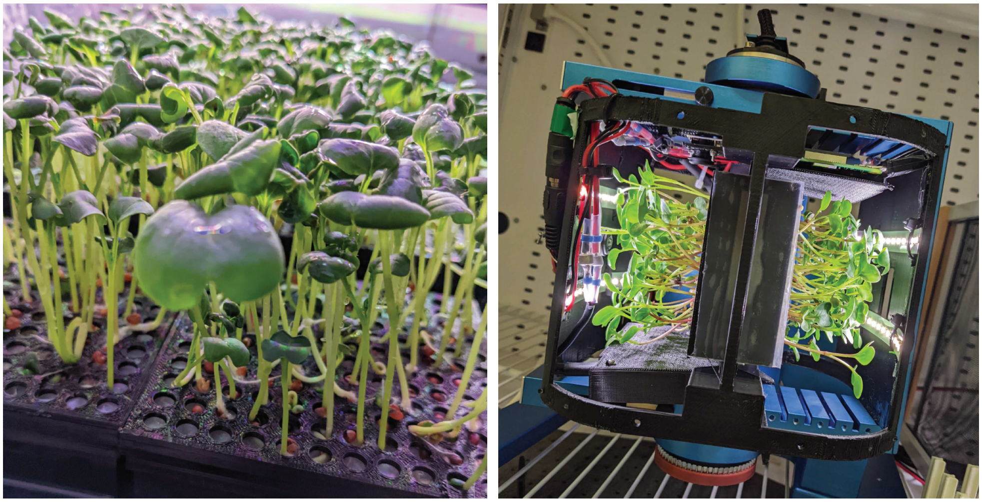

Figure 3

Microgreen tests performed by NASA. (*Left*) Radish microgreens on a parabolic flight simulating temporary microgravity. (*Right*) Radish microgreens on the random positioning machine simulating chronic microgravity. Photos provided by R.M. Wheeler and C.M. Johnson from the NASA Kennedy Space Center.

5.1. Roles of Microgreens in Space Farming

The unique advantages of microgreens discussed in previous sections make them an ideal food ingredient in space. Their short growth period and convenient horticultural procedures allow crew members to focus on critical missions and spend minimal effort on maintaining the plants. Their relatively low light and water requirements are beneficial in a spacecraft environment with limited water and electrical power for artificial lighting. In addition, spacecraft and habitats have limited volumes and the small size of microgreens would be an asset. Microgreens can be picked fresh and are ready-to-eat given proper sanitization measures, and the bold flavor and appealing color could enhance food presentation and astronauts' appetites. Lastly, the high density of nutrients and presence of additional bioactive food factors may improve crew members' health and provide adequate antioxidant and antiproliferative activities, the latter of which counterbalance the oxidative stresses and genotoxicity induced in outer space. The downside of microgreens in space farming lies in (*a*) their inability to produce progenies, leading to a large net consumption of seeds, and (*b*) their low biomass fixation and low oxygen generation as compared to growing larger plants (Kyriacou et al. 2017, Wheeler et al. 2008).

5.2. Major Challenges in Space Farming

The outer space environment is full of challenges not found on Earth. As noted, some challenges are related to the limited volume, resources, and crew time during the flight, which can be addressed more easily with microgreens than with mature plants. However, growing microgreens encounters numerous technical challenges commonly seen with other mature leafy greens plus additional unique challenges.

First, air convection driven by the buoyancy of hot air is lacking under microgravity, which retards the exchange of heat, moisture, and gases (e.g., CO_2 and ethylene) between plants and the environment, sometimes causing metabolic disorders in or damage to plants (Hirai & Kitaya 2009, Kitaya et al. 2010). This issue may be addressed by monitoring cabin gas composition and applying forced-air convection via electric fans. For fractional gravity environments, such as the Moon (1/6 gravity) or Mars (3/8 gravity), the lack of natural convection should not be as severe but requires further research.

Second, irrigation in space environments is extremely difficult, as there is little or no natural drainage of the root zone substrates (Jones et al. 2012, Monje et al. 2003), making rooting media prone to hypoxia (Porterfield 2002). Various watering solutions for microgravity have been tested, including the use of particulate media like arcillite (calcined clay chips) with time-released fertilizer and delivery of water with porous tubes embedded in the media (Massa et al. 2016, Morrow et al. 1993), use of passive, capillary-driven watering as with the NASA Veggie plant chamber (Massa et al. 2016, Morrow et al. 2017), and proposed aeroponics or hydroponic concepts that could contain and recirculate water (Morrow et al. 2017). However, challenges remain and watering plants in weightlessness continues to be an area of research (Johnson et al. 2021, Monje et al. 2003). For partial gravity settings like the Moon and Mars, more conventional watering techniques with solid media and recirculating hydroponics should work, but further research is needed (Jones et al. 2012). In all cases, considerations for sustainable approaches that minimize consumables and generation of wastes and recycling water and nutrients must be considered (Vandenbrink et al. 2014).

Third, reduced gravity may directly affect the physiology of plants and microorganisms (Su et al. 2017, Vandenbrink et al. 2014, Villacampa et al. 2021). In general, the observations from plant experiments in space suggest that if environmental requirements for light, water, CO_2, air circulation, and nutrients are met, plant growth is good (Stutte et al. 2005). And numerous studies have shown that the growth of plant shoots in space can be oriented phototropically (Heathcote et al. 1995, Su et al. 2017). Therefore, providing adequate lighting should allow proper shoot orientation, cotyledon opening, and leaf development for microgreens even in microgravity.

6. PERSPECTIVES AND RESEARCH OPPORTUNITIES

As discussed in this review, microgreen production has benefited greatly from scientific studies and technological advancements. As the microgreen industry is still in its early stages of development, there is plentiful room for technological advancement, and many knowledge gaps remain to be filled by the scientific community.

6.1. Holistic Nutritional Evaluation

As discussed in Section 1.1.1, the nutritional value of microgreens needs to be assessed using a holistic approach instead of focusing on certain families of compounds. Untargeted metabolomic studies may reveal the complex composition of nutrients and antinutrients (Tomas et al. 2021). Moreover, as discussed in Section 1.1.2, the overall health benefits and/or specific nutrient concentrations of microgreens, baby leaves, sprouts, and mature plants can vary largely by plant species, growth stages, and growing conditions. Although many studies have documented the overall high nutrient density of microgreens, more studies are needed that compare the nutritional profiles of microgreens and mature plants of the same species and under similar growth and testing conditions. By the same token, expanded studies are also warranted to exploit the opportunities of growth environment modulations afforded by CEA to produce the targeted phytonutrients in microgreens.

6.2. Artificial Intelligence

As discussed in Section 4.3, autonomous microgreen production systems may benefit significantly from cutting-edge technologies, especially artificial intelligence (AI), that are proven in the production of mature plants. For instance, AI may be used to establish a proper image acquisition procedure based on environment and growth stage (Astapova et al. 2022), calculate leaf area and estimate the fresh weight at harvest (Nagano et al. 2019), predict the yield and nutrition of plants at early stages (Yoosefzadeh-Najafabadi et al. 2021), and predict optimal timing and position for product harvesting (Krishnan & Swarna 2020). In addition, rapid detection platforms may be developed by a matrix chromogenic array coupled with AI to detect the early emergence of human/plant pathogens (Yang et al. 2021).

6.3. Nanotechnology

Nanomaterials have superior capabilities in encapsulating, stabilizing, and delivering small functional molecules. Therefore, nanotechnology presents some unique potential in microgreen production and broader agriculture. For example, seed coating by nanofibers could not only serve as a regulator for moisture and gas exchange but also deliver functional compounds (e.g., antimicrobials and plant hormones) with maximal precision and efficiency (Chandrika et al. 2019, Xu et al. 2020). Nanoparticles and nanoemulsions allow the stabilization and stimulus-responsive release of fertilizer or bioactive compounds (Maluin et al. 2021). Hydrogels can be patterned at micro/nanoscale precision with the latest 3D-printing technology. This technique, combined with novel materials (Tang et al. 2014, Zhang et al. 2017) and gelation processes (Cao & Li 2021, Wang et al. 2018), may provide an attractive growth substrate with desirable physical (particle size, pore size, wettability, air flow, mechanical properties, etc.) and chemical (reactivity and interaction with bioactive compounds) properties that allow optimal microgreen growth and limit microorganism propagation (Kalossaka et al. 2021).

6.4. Microbial Safety

There has been a significant knowledge gap in the safety of microgreen products. To date, no outbreaks associated with microgreens have been reported. However, there have been a few recalls of microgreen products related to human pathogens according to the US Food and Drug Administration (FDA 2022) and Canadian Food Inspection Agency (CFIA 2022). These events underscore the urgent need for risk analyses that identify sources of contamination and critical control points along the farm-to-fork continuum. Lab studies and commercial-scale verification are required to establish the route of bacterial migration and propagation. Recirculated water and nonsterile substrates are two major causes of bacteria propagation (Gombas et al. 2017, Misra 2020); therefore, proper water and substrate treatments need to be developed and validated. Microgreens are harvested at a few centimeters above the substrate, and their delicate structures render them prone to mechanical damage. Both factors may cause substrate-to-product bacteria migration (Gombas et al. 2017). Therefore, safe and effective harvesting methods could help mitigate pathogenic contamination. Finally, novel antimicrobial measures such as biological control may be considered for killing pathogens without inducing drug resistance.

7. CONCLUDING REMARKS

Microgreens are young plants with great potential. These versatile, nutrient-dense crops may play a beneficial role in the health of consumers, food and nutrient security, and bioregenerative support in outer space. The utilization of unconventional species, emerging growth platforms, innovative physical and chemical treatments, and the IoT all have had a profound influence on the development of the microgreen industry. Holistic nutritional evaluation, produce safety, and space farming remain great opportunities for future research. Finally, it is envisioned that AI and nanotechnology may greatly enhance the productivity, quality, value, and pleasure of microgreen production in the future.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. USDA is an equal opportunity provider and employer.

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