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Microgreens in sustainable food systems: A critical review of nutritional quality, production technologies, and security implications

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Abstract

A novel approach to functional foods and sustainable agriculture is microgreens, which are soft, edible seedlings of vegetables and herbs that are collected at the cotyledon or first genuine leaf stage. Known for their vivid hues, strong tastes, and exceptional levels of vitamins, minerals, and antioxidants, microgreens help to reconcile contemporary farming methods with health-conscious eating habits. As conventional agriculture faces challenges from limited arable land and rising urbanization, microgreens provide a highly effective, space-efficient, and water-conserving alternative that may be used in indoor, vertical, and hydroponic growth systems. This review emphasizes the historical evolution, nutritional advantages, health benefits, cultivation methods, and market potential of microgreens, while also discussing issues like contamination risks and limited shelf life. In a world that is changing quickly, microgreens have the potential to completely transform both home-scale and commercial food systems by fostering food security, dietary diversity, and economic sustainability through advancements in controlled environment agriculture (CEA) and rising consumer awareness.

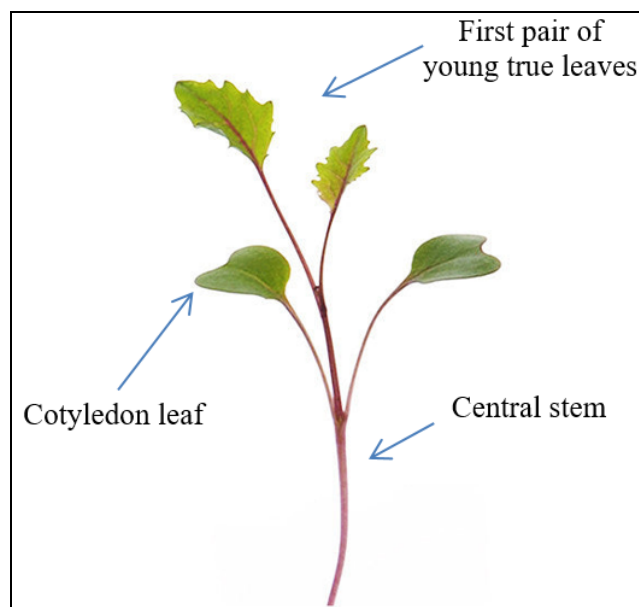
Keywords: Sustainable agriculture, microgreens, functional foods, urban farming, nutrition, health advantages

Introduction

Microgreens are young vegetable, herb, or grain seedlings typically harvested 7-21 days after germination, when the cotyledons are fully developed and the first true leaves may begin to emerge. Despite their small size, microgreens are nutrient-dense, often containing higher concentrations of vitamins, minerals, and antioxidants than their mature counterparts (Kyriacou *et al.*, 2016; Xiao *et al.*, 2021) ^[14, 34]. Their vibrant colors, distinctive flavors, and abundance of health-promoting phytochemicals have contributed to their increasing popularity among culinary professionals and health-conscious consumers.

Microgreens can be cultivated using soil-based systems, hydroponics, or biodegradable substrates, making them well suited for urban agriculture, vertical farming, and indoor production systems (Di Gioia *et al.*, 2020) ^[7]. Their short growth cycle, low input requirements, and high economic return per unit area further enhance their potential as a sustainable and profitable crop.

This production potential is particularly significant in regions with limited agricultural land (Poudel *et al.*, 2022) ^[25]. The rising popularity of microgreens is further driven by a growing global shift toward sustainable food systems and functional foods. Research has demonstrated that microgreens of species such as broccoli, red cabbage, and radish are especially rich in bioactive compounds, including glucosinolates, polyphenols, and carotenoids (Zhang *et al.*, 2023) ^[38]. These phytochemicals are associated with several potential health benefits, such as anti-inflammatory, anticancer, and cardioprotective effects, highlighting the nutritional and therapeutic relevance of microgreens in modern diets.



Historical Development of Microgreens

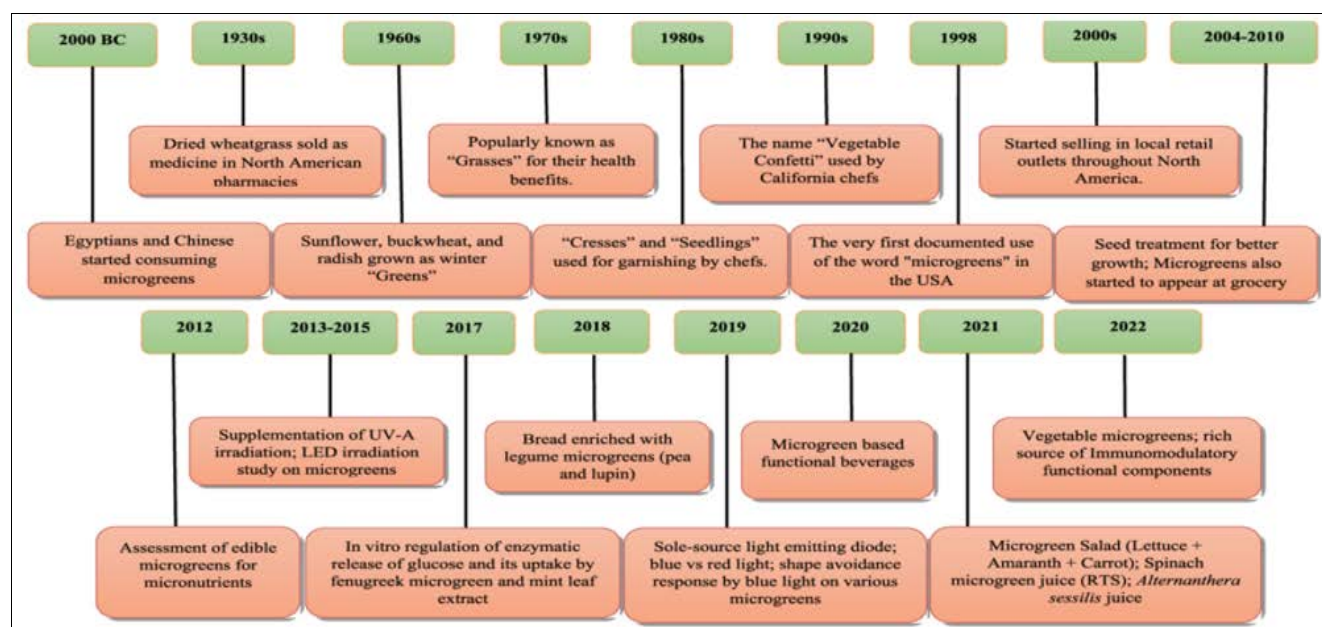
Microgreens, now recognized as a class of functional foods, have evolved from niche culinary garnishes into mainstream health-oriented produce. Their journey reflects growing

consumer awareness of nutrition, sustainability, and innovative food production systems.

The concept of microgreens originated in the United States during the early 1980s, particularly in upscale Californian restaurants, where chefs experimented with young vegetable seedlings for their intense flavors, vibrant colors, and delicate textures (Kyriacou *et al.*, 2016) [14]. Initially, only a limited range of crops such as arugula, basil, beet, and cilantro were cultivated; however, increasing demand soon expanded the diversity of species grown as microgreens.

By the 1990s, microgreens gained widespread recognition in gourmet cuisine due to their aesthetic appeal and concentrated flavours (Xiao *et al.*, 2013) [29]. Their popularity gradually extended beyond fine dining as consumers and researchers alike began to appreciate their nutritional richness, leading to increased scientific interest and advancements in cultivation practices.

During the 2010s, research on microgreens intensified, focusing on their nutritional composition, cultivation techniques, and health-promoting bioactive compounds. This body of evidence supported their classification as superfoods, with studies demonstrating that microgreens often contain higher concentrations of vitamins, minerals, and antioxidants than their mature counterparts (Mir *et al.*, 2023; Brazaitytė *et al.*, 2021) [20, 2].



Recent technological advancements, including LED lighting systems, vertical farming, and controlled environment agriculture, have further accelerated microgreens production and accessibility. These technologies enable year-round cultivation with minimal land and water requirements, making microgreens particularly suitable for urban agriculture and indoor farming systems (Pinto *et al.*, 2021) [24].

Today, microgreens are not merely a culinary trend but represent a sustainable, nutrient-rich food source that contributes to food security, dietary diversity, and human health promotion

What are microgreens?

Young, edible vegetable, herb, or grain seedlings known as microgreens are picked during the cotyledon stage, usually 7-21 days following germination. They are often eaten uncooked and are bigger than sprouts but smaller than baby greens. Microgreens' strong flavour, vivid colour, and high nutritional

content make them popular garnishes or additions to salads, smoothies, and sandwiches.



These tender greens are rich in vitamins (such as C, E, and K), minerals, antioxidants, and various phytochemicals, often present in higher concentrations than those found in mature plants, making microgreens a valuable component of a healthy diet mature plants. Commonly cultivated microgreens include broccoli, radish, beet, kale, arugula, and basil (Kyriacou *et al.*, 2016; Xiao *et al.*, 2021)^[14, 34]. Microgreens can be grown in soil-based or soilless media, such as hydroponic systems or cocopeat, and have gained considerable popularity in urban farming and health food markets due to their rapid growth cycle, minimal space requirements, and significant nutritional and health benefits.



Immature Harvesting Growth Stages of Microgreens

Microgreens are harvested at an early, immature stage of development, typically 7-21 days after germination, depending on the crop species and prevailing environmental conditions. The optimal harvest stage occurs after the full expansion of the cotyledon leaves and just before or at the emergence of the first true leaves (Kyriacou *et al.*, 2016)^[14]. Harvesting at this stage ensures that the plants remain tender, visually vibrant, and rich in nutrients and bioactive phytochemicals, maximizing both

their nutritional quality and consumer appeal.



Stages of Microgreen Growth

The growth and development of microgreens can be broadly divided into the following stages:

- 1. Germination Stage (0-3 days):** During this stage, seeds absorb moisture, initiate metabolic activity, and begin to sprout.
- 2. Cotyledon Stage (4-7 days):** Seedlings develop their first leaves, known as cotyledons, marking the onset of photosynthesis.
- 3. Pre-True Leaf Stage (7-14 days):** Cotyledons are fully expanded, and this stage is considered the optimal harvest period for most microgreens due to maximum tenderness and nutritional quality (Xiao *et al.*, 2021)^[34].
- 4. True Leaf Emergence (>14 days):** The first true leaves begin to appear. Harvesting at this stage may slightly reduce tenderness but can enhance flavor intensity and complexity, depending on the species.



Why Do We Need Microgreens?

Microgreens have gained considerable attention in recent years due to their exceptional nutritional density, rapid growth cycle, and minimal space requirements, making them highly suitable for urban agriculture, health-conscious diets, and food security initiatives.

- 1. Nutrient-Rich Superfoods:** Microgreens are rich sources of vitamins, minerals, and antioxidants, often containing 3-40 times higher concentrations of nutrients than their mature counterparts (Xiao *et al.*, 2012; Brazaitytė *et al.*, 2021)^[35, 2]. This high nutrient density makes microgreens particularly valuable in diets deficient in fresh fruits and vegetables,

especially in urban, peri-urban, and arid regions.

- 2. Sustainable and Space-Efficient:** Microgreens can be cultivated in small spaces using minimal resources, including water and growing substrates, which aligns well with the goals of sustainable agriculture (Chadha *et al.*, 2021). Their adaptability makes them particularly suitable for vertical farming systems and indoor cultivation.
- 3. Short Growth Cycle:** Most microgreens can be harvested within 7-21 days, providing a rapid return on investment and enabling year-round production, even in non-traditional or resource-limited growing environments (Kyriacou *et al.*, 2016)^[34].

4. **Functional Foods and Health Benefits:** Owing to their high content of bioactive phytochemicals, including polyphenols and glucosinolates, microgreens are associated with potential anti-inflammatory, anticancer, and cardioprotective effects (Mir *et al.*, 2023)^[20].
5. **Food Security and Urban Agriculture:** In the context of growing global food security concerns, microgreens present a viable solution for urban and peri-urban agriculture, supporting local food production, enhancing dietary diversity, and reducing dependence on large-scale food supply chains (Pinto *et al.*, 2021)^[24].

Nutritional Importance of Microgreens

Microgreens are considered highly nutritious functional foods due to their high concentrations of vitamins, minerals, antioxidants, and bioactive compounds, which provide multiple health benefits. These young, edible plants are harvested at an early growth stage, typically within 7-21 days after germination, when nutrient density is often at its peak. Their small size, tender texture, and intense flavour make microgreens easy to incorporate into a variety of culinary preparations, including salads, sandwiches, smoothies, and garnishes. The major nutritional attributes of microgreens are outlined below.

1. High Levels of Vitamins and Minerals

Microgreens such as broccoli, red cabbage, and pea shoots are excellent sources of essential vitamins, including vitamin C, vitamin A, vitamin K, and several B-vitamins (Xiao *et al.*, 2012)^[35]. These vitamins play key roles in immune function, skin health, vision, and bone development.

- Vitamin C is essential for collagen synthesis, wound healing, and acts as a potent antioxidant.
- Vitamin A supports vision, immune response, and cellular differentiation.
- Vitamin K is crucial for blood clotting and bone metabolism.

2. Rich in Antioxidants

Microgreens contain high levels of antioxidant compounds, such as flavonoids, polyphenols, and carotenoids, which help combat oxidative stress and reduce the risk of chronic diseases, including cancer and cardiovascular disorders (Xiao *et al.*, 2012; Kyriacou *et al.*, 2016)^[14].

- Carotenoids, including lutein and zeaxanthin, contribute to eye health and lower the risk of age-related macular degeneration.
- Flavonoids, abundant in cabbage and radish microgreens, exhibit anti-inflammatory, antimicrobial, and anticancer properties (Mir *et al.*, 2023)^[20].

3. High Mineral Content

Many microgreens, such as sunflower, amaranth, and beetroot, are rich in essential minerals including calcium, iron, magnesium, potassium, and zinc (Kyriacou *et al.*, 2016)^[14]. These minerals are vital for bone formation, muscle contraction, immune defence, and cellular metabolism.

- **Calcium and magnesium** support bone strength and muscle function.
- **Iron** is necessary for oxygen transport and energy production.
- **Potassium** helps regulate blood pressure and electrolyte balance.

4. Dietary Fiber Content

Microgreens provide a moderate amount of dietary fiber, which

is important for maintaining digestive health. Dietary fiber helps regulate bowel movements, reduce cholesterol levels, and support stable blood glucose levels (Brazaitytė *et al.*, 2021)^[2].

5. Anti-inflammatory and Detoxifying Properties

Several microgreens contain unique bioactive compounds such as sulforaphane (in broccoli microgreens) and betalains (in beetroot microgreens), known for their strong anti-inflammatory and detoxifying effects. These compounds aid in reducing inflammation, enhancing liver detoxification, and supporting healthy metabolic processes (Xiao *et al.*, 2012; Sun *et al.*, 2022)^[35, 30].

6. Low Caloric but Nutrient-Dense

Microgreens are low in calories yet exceptionally nutrient-dense, making them ideal for improving dietary quality without increasing caloric intake. They offer an efficient strategy to enhance nutrition while supporting weight management and overall health (Kyriacou *et al.*, 2016)^[14].

7. Support Heart Health

Due to their high content of antioxidants and polyphenols, certain microgreens, such as radish and sunflower, have been shown to support cardiovascular health by reducing inflammation, oxidative stress, and risk factors associated with cardiovascular diseases (Pinto *et al.*, 2021).

Health Benefits of Microgreens

Microgreens are not only valued for their intense flavor and culinary versatility but also for their substantial health-promoting properties. Their high concentrations of bioactive compounds, vitamins, minerals, and antioxidants confer multiple physiological benefits, making them an important component of a balanced and functional diet.

1. Rich in Antioxidants

Microgreens are recognized for their exceptionally high antioxidant capacity, which helps protect the body against oxidative stress and inflammation. Antioxidants such as flavonoids, polyphenols, and carotenoids play a key role in reducing the risk of chronic diseases, including cardiovascular disorders, diabetes, and certain cancers.

- Broccoli microgreens are particularly rich in sulforaphane, a bioactive compound with strong anticancer properties (Sun *et al.*, 2022)^[30].
- Radish microgreens contain high levels of glucosinolates, which exhibit antioxidant activity and support hepatic detoxification (Mir *et al.*, 2023)^[20].

2. Support Immune Function

The high concentrations of vitamin C and vitamin A in microgreens enhance immune function by stimulating white blood cell production and strengthening cellular defense mechanisms.

- Sunflower microgreens are especially rich in vitamin C, which helps reduce infection severity and promotes wound healing (Kyriacou *et al.*, 2016)^[14].
- Cabbage microgreens, rich in vitamin A, play a vital role in maintaining skin integrity and mucosal barriers, thereby improving immune responsiveness.

3. Anti-inflammatory Effects

Many microgreens exhibit significant anti-inflammatory properties, which may help reduce inflammation-related

disorders such as arthritis, metabolic syndrome, and cardiovascular diseases.

- **Red cabbage and mustard microgreens** contain polyphenols and flavonoids that inhibit pro-inflammatory enzymes, thereby lowering inflammatory responses (Xiao *et al.*, 2012) ^[35].
- **Beetroot and radish microgreens** are rich in betalains, compounds known for their potent anti-inflammatory and antioxidant activities, contributing to improved joint health (Sun *et al.*, 2022) ^[30].

4. Cardiovascular Health

Microgreens contribute to heart health by helping regulate blood pressure, improving lipid profiles, and reducing oxidative damage.

- Pea shoots and sunflower microgreens are rich in potassium and magnesium, minerals that help regulate blood pressure and reduce the risk of hypertension (Xiao *et al.*, 2012) ^[35].
- Antioxidants present in mustard and radish microgreens reduce oxidative stress, a major contributor to cardiovascular disease development (Pinto *et al.*, 2021) ^[24].

5. Weight Management and Digestive Health

Owing to their low calorie content and high dietary fiber, microgreens are beneficial for weight management and gastrointestinal health.

- Dietary fiber in microgreens such as pea and mustard aids in regulating bowel movements, preventing constipation, and lowering cholesterol levels (Kyriacou *et al.*, 2016) ^[14].
- Their low energy density allows for increased consumption without significantly increasing caloric intake, supporting healthy weight control.

6. Skin Health

The abundance of vitamins and antioxidants in microgreens supports skin health by reducing oxidative damage and promoting collagen synthesis.

- Cabbage microgreens are rich in vitamin K, which aids wound healing and improves skin elasticity (Mir *et al.*, 2023) ^[20].
- Broccoli microgreens, with their high antioxidant content, help prevent premature aging by neutralizing free radicals (Xiao *et al.*, 2012) ^[35].

7. Anticancer Properties

Several studies suggest that microgreens, particularly those belonging to the Brassicaceae family, possess significant anticancer potential due to their high levels of glucosinolates and isothiocyanates, which can inhibit cancer cell proliferation and enhance detoxification pathways (Sun *et al.*, 2022; Mir *et al.*, 2023) ^[30, 20].

Anticancer Properties

Microgreens exhibit notable cancer-fighting properties due to their high concentrations of glucosinolates and sulforaphane, which are known to modulate detoxification enzymes, inhibit tumor growth, and reduce oxidative damage.

- Broccoli microgreens are particularly recognized for their strong anticancer potential, as they contain significantly higher levels of sulforaphane compared to mature broccoli, enhancing their chemoprotective effects (Sun *et al.*, 2022) ^[20].
- Radish microgreens, rich in glucoraphanin, help neutralize

carcinogens and may prevent the initiation and progression of cancerous cells (Mir *et al.*, 2023) ^[30].

Growing Process of Microgreens

1. Seed Selection and Variety Choice

Selection of high-quality seeds is critical for successful microgreen production. Crops such as radish, broccoli, sunflower, pea shoots, and mustard are commonly used due to their rapid germination and high nutritional value. Other varieties, including arugula, cilantro, and basil, are preferred for their distinct flavors and added health benefits (Xiao *et al.*, 2012) ^[35].

The cultivation of microgreens involves a series of carefully managed steps, from seed selection to post-harvest handling, to ensure the production of nutrient-dense, high-quality young plants. Microgreens are typically grown within a short production cycle of 7-21 days, depending on the crop species and environmental conditions.



2. Seed Soaking

Certain seeds, particularly sunflower and pea shoots, benefit from pre-soaking to soften the seed coat and enhance germination. Soaking typically lasts 4-12 hours, depending on the seed type, and improves germination uniformity and early seedling vigor (Mir *et al.*, 2023) ^[20].



3. Selection of Growing Medium

Microgreens can be cultivated in soil-based or soilless media, including coconut coir, hydroponic mats, and other inert substrates. Coconut coir is widely used due to its lightweight nature, high water-holding capacity, and good aeration, which promote healthy root growth (Kyriacou *et al.*, 2016). Hydroponic systems are increasingly popular for their water efficiency, though they require precise nutrient management (Pinto *et al.*, 2021) ^[24].



4. Sowing of Seeds

Seeds are sown densely and uniformly over the growing medium to maximize yield in limited space. They are lightly pressed into the substrate or left uncovered, depending on seed size. Proper density is essential to avoid overcrowding, which can restrict airflow and promote disease development (Mir *et al.*, 2023)^[20].



5. Germination and Environmental Conditions

During germination, microgreens require controlled environmental conditions. Optimal temperatures range from 18-22 °C, along with high humidity, often achieved by covering trays with lids or humidity domes (Xiao *et al.*, 2012)^[35]. Light is not essential during germination; however, once seedlings emerge, exposure to light becomes critical for photosynthesis.



6. Lighting

Following germination, microgreens require adequate light for healthy growth and pigment development. LED grow lights are commonly used in indoor systems as they provide an optimal light spectrum. A photoperiod of 12-16 hours per day is generally recommended (Kyriacou *et al.*, 2016)^[14]. Insufficient light may reduce growth and flavor, while excessive light can

cause heat stress.



7. Watering and Nutrient Management

The growing medium should be kept consistently moist but not waterlogged. Gentle misting or light irrigation is preferred to prevent disturbance of seedlings. In some systems, a dilute nutrient solution is applied to support growth. Hydroponic systems rely entirely on nutrient-enriched water to supply essential macro- and micronutrients (Pinto *et al.*, 2021; Mir *et al.*, 2023)^[24, 20].



8. Harvesting

Microgreens are ready for harvest within 7-21 days, when plants reach a height of approximately 2-3 inches and the first true leaves begin to appear. Harvesting is performed by cutting the stems just above the growing medium using sharp scissors or a knife, ensuring minimal damage to surrounding plants (Xiao *et al.*, 2012)^[35].



9. Post-Harvest Handling

After harvest, microgreens should be gently washed to remove substrate residues and excess moisture. They are then drained, packed, and stored under refrigerated conditions to maintain freshness, nutritional quality, and shelf life. Proper post-harvest

handling is essential to reduce microbial contamination and preserve product quality.



After washing, microgreens are carefully dried to remove excess surface moisture and prevent spoilage. The harvested produce should be stored in a cool and dry environment, preferably under refrigerated conditions, to maintain freshness, nutritional quality, and shelf life. Proper packaging, such as ventilated or moisture-absorbing containers, is essential to prevent moisture accumulation, which can otherwise lead to mold growth and decay (Pinto *et al.*, 2021)^[24].

Difference between Sprouts and Microgreens

Sprouts and microgreens are both young, edible forms of plants; however, they differ markedly in their cultivation methods, growth stages, nutritional composition, safety aspects, and culinary uses.

Feature	Sprouts	Microgreens
Growth stage	Germinated seeds (2-7 days)	Cotyledon to pre-true leaf stage (7-21 days)
Growing medium	Grown in water only	Grown in soil or soilless media (cocopeat, hydroponics)
Light requirement	No light required	Light required after germination
Edible part	Whole seedling (seed, root, shoot)	Stem and leaves (roots removed)
Nutritional content	Nutritious but lower than microgreens	Often higher in vitamins, minerals, and antioxidants
Microbial safety	Higher risk of contamination	Safer due to soil-based growth and harvest above medium
Common uses	Used in cooked dishes and salads	Used raw in salads, garnishes, smoothies



Sprouts



Microgreens

Common Types of Microgreens and Their Nutritional Traits

1. Red Cabbage (*Brassica oleracea* var. *capitata*)

Red cabbage microgreens are rich in vitamin C, vitamin E, and anthocyanins. They also contain glucosinolates, which exhibit strong antioxidant and potential anticancer properties (Xiao *et al.*, 2012)^[35].



3. Kale (*Brassica oleracea* var. *acephala*)

Contains beta-carotene, calcium, iron, and polyphenols. Known for its anti-inflammatory and antioxidant properties (Pinto *et al.*, 2021)^[24].



2. Broccoli (*Brassica oleracea* var. *italica*)

Broccoli microgreens are especially valued for their high content of sulforaphane, a powerful antioxidant derived from glucoraphanin. These compounds are associated with anticancer, anti-inflammatory, and detoxifying effects, often present at higher levels than in mature broccoli (Xiao *et al.*, 2012; Sun *et al.*, 2022)^[35, 30].

4. Radish (*Raphanus sativus*)

High in vitamin C, phenolics, and isothiocyanates, supporting detoxification and antioxidant defense (Mir *et al.*, 2023)^[20].



5. Amaranth (*Amaranthus* spp.)

Rich in vitamin K, calcium, iron, and antioxidants such as rutin and quercetin, offering anti-inflammatory effects and supporting cardiovascular health (Kyriacou *et al.*, 2016)^[14].



6. Beetroot (*Beta vulgaris*)

Contains betalains (antioxidants), iron, potassium, and folate, promoting heart health and potentially helping to lower blood pressure (Sun *et al.*, 2022)^[30].



7. Basil (*Ocimum basilicum*)

High in volatile oils (e.g., eugenol), vitamin A, vitamin K, and manganese. Known for its anti-inflammatory and antimicrobial properties (Brazaitytė *et al.*, 2021)^[2].



Cauliflower



Onion



Swiss Chard



Wheat Grass



8. Pea Shoots (*Pisum sativum*)

Rich in protein, vitamin C, folate, and dietary fiber, promoting digestion and immune function (Mir *et al.*, 2023)^[20].



9. Cilantro (*Coriandrum sativum*)

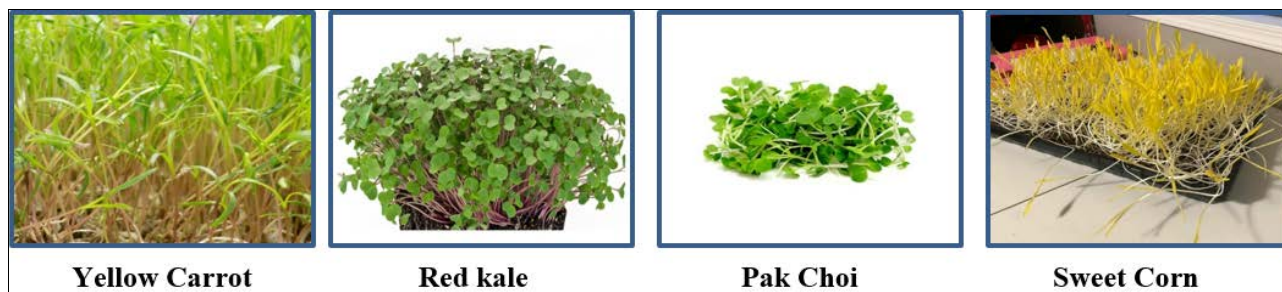
Contains vitamin A, vitamin C, potassium, and essential oils, with detoxifying and digestive benefits (Pinto *et al.*, 2021)^[24].



10. Sunflower (*Helianthus annuus*)

High in zinc, iron, protein, and vitamin E, supporting skin health and acting as a natural antioxidant (Kyriacou *et al.*, 2016)^[14].





Some requirements for growing microgreens

Micro-greens	Seed (g)/Tray (30 x 30 cm^1)	Soaking Time (h)	Depth of media mix (cm)	Temperature ($^{\circ}C$)	Maturity (day)
Amaranth	2.5	NA	2	>22	16-20
Purple Basil	2.5	NA	1	>24	16-20
Beet root	12.5	8-10	2	16-25	16-20
Buckwheat	12.5	10-12	2	20-25	5-6
Cress	8	NA	1	16-25	5-14
Dill	5	NA	1	15-23	16-20
Kale	5	4-8	2	16-28	16-20
Linseed	36	NA	2	16-25	6-8
Mustard	2.5	8	2	16-25	15-20
Pea shoots	100-150	8-12	2	15-25	10-14
Radish	5	6-8	3	16-28	12
Cabbage	5	4-8	2	16-25	3-6
Arugula	3	NA	2	16-25	16-22
Sunflower	50	8-12	2	20-25	8-12

Key Insights

- Brassica microgreens (broccoli, kale, red cabbage) are rich in antioxidants, glucosinolates, and bioactive compounds beneficial for human health (Xiao *et al.*, 2012; Brazaityté *et al.*, 2021) ^[35, 2].
- Amaranth and beetroot microgreens provide pigments such as betalains and anthocyanins, offering strong antioxidant

effects and combating inflammation (Sun *et al.*, 2022) ^[30].

- Pea shoots are an excellent source of protein and fiber, making them valuable in plant-based diets (Mir *et al.*, 2023) ^[2].

Commercially Grown microgreens

Commercial name	Botanical Name	Family	Microgreen colour
Arugula	<i>Eruca sativa</i> Mili	Brassicaceae	Green
Bull's blood beet	<i>Beta vulgaris</i> L.	Chenopodiaceae	Reddish green
Celery	<i>Apium graveolens</i> L.	Apiaceae	Green
Cilantro	<i>Coriandrum sativum</i> L.	Apiaceae	Green
Garnet amaranth	<i>Amaranthus hypochondriacus</i> L.	Amaranthaceae	Red
Golden pea tendrils	<i>Pisum sativa</i> L.	Fabaceae	Yellow
Green basil	<i>Ocimum basilicum</i> L.	Lamiaceae	Green
Green daikon radish	<i>Raphanus sativus</i> L.	Brassicaceae	Green
Magenta spinach	<i>Spinacia oleracea</i> L.	Chenopodiaceae	Red
Mizuna	<i>Brassica rapa</i> L.	Brassicaceae	Green
Opal basil	<i>Ocimum basilicum</i> L.	Lamiaceae	Greenish purple
Opal radish	<i>Raphanus sativus</i> L.	Brassicaceae	Greenish purple
Pea tendrils	<i>Pisum sativum</i> L.	Fabaceae	Green
Pepper cress	<i>Lepidium bonariense</i> L.	Brassicaceae	Green
Popcorn shoots	<i>Zea mays</i> L.	Poaceae	Yellow
Purple kohlrabi	<i>Brassica oleracea</i> L.	Brassicaceae	Purplish green
Purple mustard	<i>Brassica juncea</i> L.	Brassicaceae	Purplish green
Red beet	<i>Beta vulgaris</i> L.	Chenopodiaceae	Reddish green
Red cabbage	<i>Brassica oleracea</i> L.	Brassicaceae	Purplish green
Red mustard	<i>Brassica juncea</i> L.	Brassicaceae	Purplish green
Red orach	<i>Atriplex hortensis</i> L.	Chenopodiaceae	Red
Red sorrel	<i>Rumex acetosa</i> L.	Polygonaceae	Reddish green
Tartary buckwheat	<i>Fagopyrum tataricum</i> L.	Poaceae	Green

Adverse Effects of Microgreens

While microgreens are generally highly nutritious, certain risks may arise from improper handling, contamination, or excessive consumption.

1. Risk of Microbial Contamination

Microgreens are grown in high-moisture environments, which can foster harmful microorganisms such as Salmonella, E. coli, and Listeria. Without strict hygiene and sanitation during

growth, harvest, and storage, these pathogens can contaminate the produce, leading to foodborne illnesses. Leafy greens, including microgreens, have been reported among the top contributors to outbreaks (Manning *et al.*, 2021)^[18].

2. Pesticide Residues

Microgreens grown with chemical pesticides may retain residues, which are not removed during consumption as they are typically eaten raw. Pesticide exposure has been associated with endocrine disruption, neurological damage, and increased cancer risk, highlighting the importance of organic or controlled cultivation methods.

3. Nutrient Overload

Long-term consumption of large amounts of microgreens can lead to nutrient imbalances. For example, varieties rich in vitamin K (like kale and mustard) may interfere with blood-thinning medications such as warfarin (Bertazzoni *et al.*, 2020; Nigg *et al.*, 2021)^[1, 22].

4. Allergic Reactions

Some individuals may be allergic to specific microgreens, particularly those derived from mustard or sunflower seeds. Symptoms can include rashes, itching, and gastrointestinal discomfort (Nabavi *et al.*, 2020)^[21].

5. Oxalates

Certain microgreens, such as spinach and beet greens, contain oxalates, which can bind calcium and contribute to kidney stone formation in susceptible individuals if consumed excessively (Trinder *et al.*, 2019)^[31].

6. Gastrointestinal Disturbances

High fiber content in microgreens may cause bloating, gas, or digestive upset when consumed in large quantities, especially in sensitive individuals (Lo *et al.*).

7. Pesticide Residues

Consumption of microgreens grown with chemical pesticides may expose consumers to endocrine disruptors, neurotoxic compounds, or carcinogens, particularly since microgreens are eaten raw (Nigg *et al.*, 2021)^[22].

Remedies and Safety Measures

To mitigate these adverse effects, the following measures are recommended:

1. Hygienic Cultivation and Handling

Use clean trays, tools, and potable water. Avoid raw manure or compost unless sterilized. Seed sterilization (e.g., food-grade hydrogen peroxide) can reduce microbial risk (Manning *et al.*, 2021)^[18].

2. Organic or Safe Practices

Prefer organic methods or biopesticides to avoid harmful chemical residues (Nigg *et al.*, 2021)^[22].

3. Moderate Consumption

Avoid excessive intake, especially of microgreens high in

vitamin K or oxalates. Individuals on medication should consult a doctor (Bertazzoni *et al.*, 2020)^[1].

4. Proper Storage

Store at 4°C or lower in clean, dry containers. Avoid humid environments that promote microbial growth (Lo *et al.*).

5. Allergy Awareness

Introduce new varieties in small amounts and monitor for allergic reactions (Nabavi *et al.*, 2020)^[21].

6. Trusted Sources

Purchase from certified producers following Good Agricultural Practices (GAP). Home growers should follow extension agency guidelines.

7. Rinse before Consumption

Even homegrown microgreens should be gently rinsed with clean water to remove dust, spores, or residues.

Utility of Microgreens in Home and Commercial Settings

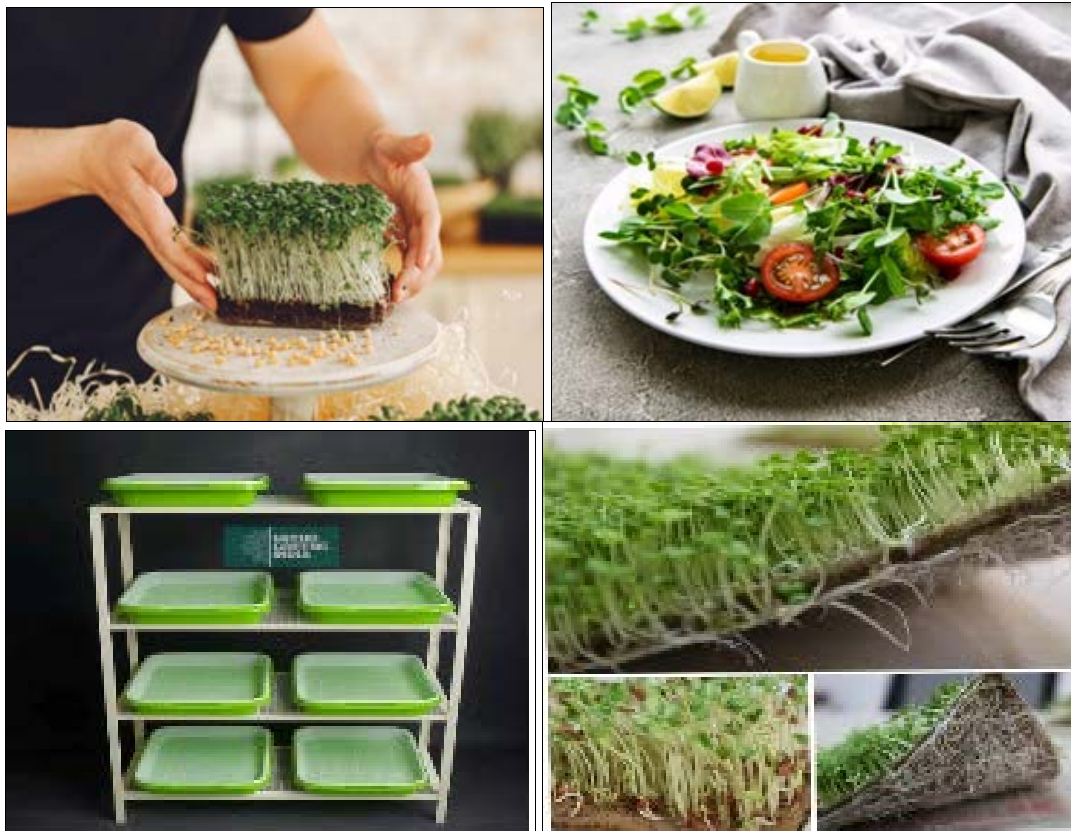
Microgreens are valued for their nutritional density, aesthetic appeal, and rapid growth, making them popular in both home gardening and commercial agriculture:

Home Use

- Ideal for urban gardening and indoor cultivation, requiring minimal space and inputs (Xiao *et al.*, 2022)^[36].
- Allow year-round growth on windowsills, balconies, or small indoor setups.
- Popular among health-conscious consumers for dietary supplementation (Poudel *et al.*, 2021)^[26].

Commercial Use

- Widely used in high-end restaurants, salad mixes, and nutraceutical products.
- Their vibrant colors, intense flavors, and high nutrient content enhance culinary appeal and functional food value.
- Rapid growth cycles and high market value make microgreens a profitable crop for small-scale and urban agriculture enterprises.
- Economic Viability: The short production cycle (7-21 days) makes microgreens profitable for small-scale entrepreneurs and urban farms, especially those using vertical or hydroponic systems (Choe *et al.*, 2022; Kyriacou *et al.*, 2021)^[5, 34].
- Functional Food Markets: Microgreens are valued for their high nutrient density and health-promoting compounds, offering a premium product for restaurants and nutraceutical industries.
- Environmental Sustainability: Microgreens require significantly less water and fertilizer compared to mature crops, making them an eco-friendly and resource-efficient crop (Mehta *et al.*, 2023)^[19].
- Dual Utility: Their combination of nutritional and environmental benefits drives increasing demand across both domestic and commercial sectors.



Troubleshooting in Microgreen Cultivation

Microgreen production, while relatively simple, can face challenges that affect yield, quality, or safety. Early identification and correction are crucial:

1. Poor Germination

- **Causes:** Low-quality seeds, improper moisture, suboptimal temperature.
- **Remedy:** Use high-vigor, pathogen-free seeds; maintain 20-25°C and consistent moisture (Choe *et al.*, 2022; Poudel *et al.*, 2021) [5, 26].

2. Fungal Diseases (Damping-Off)

- **Causes:** Overwatering, poor air circulation, contaminated media.
- **Remedy:** Use sterilized media, ensure ventilation, and apply biological control agents if needed (Kyriacou *et al.*, 2021) [34].

3. Leggy or Elongated Seedlings

- **Causes:** Low light intensity, high temperature.
- **Remedy:** Provide adequate light (200-400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and maintain moderate temperatures (18-22 °C) (Mehta *et*

al., 2023) [19].

4. Uneven Growth / Patchy Stands

- **Causes:** Uneven seeding, poor seed-media contact, inconsistent watering.
- **Remedy:** Evenly distribute seeds and press gently into the medium (Xiao *et al.*, 2022) [36].

5. Yellowing of Leaves (Chlorosis)

- **Cause:** Nutrient deficiencies, particularly nitrogen or iron.
- **Remedy:** Apply balanced dilute nutrient solutions, especially in hydroponics (Chatterjee *et al.*, 2022) [4].

7. Contamination or Food Safety Concerns

- **Cause:** Unsanitary conditions.
- **Remedy:** Use potable water, sanitize equipment, and avoid manure-based composts (Zhang *et al.*, 2021) [37].

8. Mold Growth

- **Cause:** High humidity, dense sowing.
- **Remedy:** Maintain good spacing, airflow, and careful watering (Ghoora *et al.*, 2020) [8].



Poor Germination



Fungal Diseases



Mold Growth

Future Trends in Microgreen Cultivation

1. Integration with Smart Farming and Tool

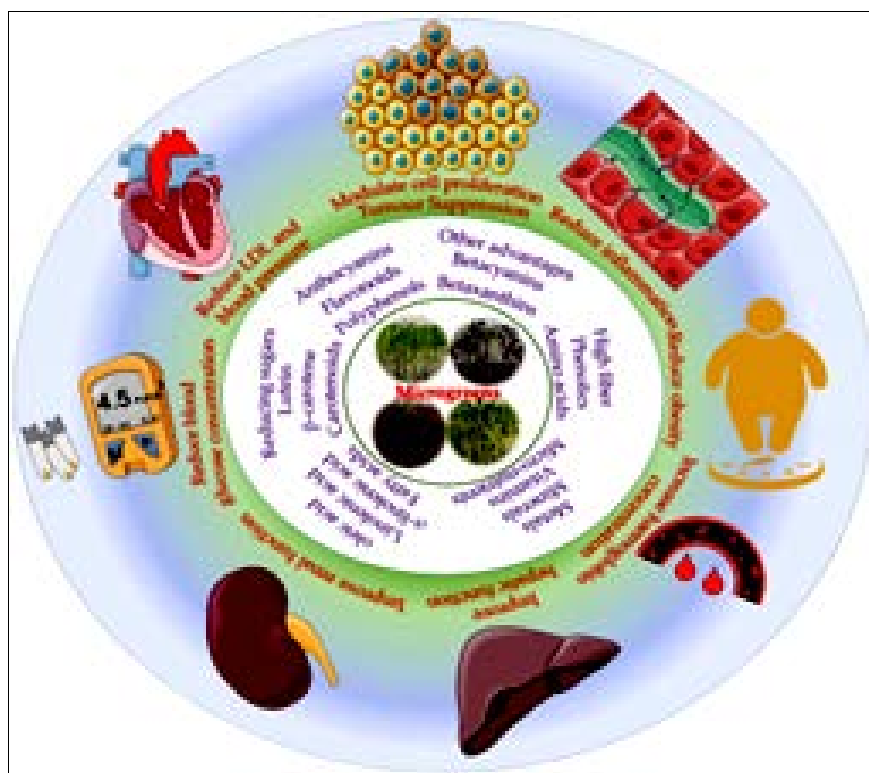
Use of sensors, automated irrigation, and AI-based decision tools for real-time monitoring of light, humidity, nutrients, and growth (Mehta *et al.*, 2023; Choe *et al.*, 2022)^[19, 5].

2. Expansion of Vertical and Urban Farming

Microgreens are ideal for vertical farming and urban agriculture, providing local, fresh, sustainable produce, and reducing transportation costs and carbon footprint (Kyriacou *et al.*, 2021)^[14].

3. Nutritional Biofortification

Research is focusing on enhancing microgreens' nutritional profiles by biofortifying crops with vitamins, minerals, and phytochemicals to combat malnutrition (Chatterjee *et al.*, 2022; Ghoola *et al.*, 2020)^[4, 8].



Organic and Sustainable Cultivation Systems

- **Consumer Preference:** Increasing demand for organically grown microgreens is driving adoption of sustainable practices.
- **Sustainable Practices:** Use of compostable growing mats, biodegradable packaging, and closed-loop hydroponic systems minimizes environmental impact (Xiao *et al.*, 2022)^[35].
- **Resource Efficiency:** Such systems reduce water and nutrient usage while supporting eco-friendly urban agriculture.

Genomic and Breeding Innovations

- **Improved Varieties:** Molecular tools and genomics support breeding for higher yield, longer shelf life, and enhanced nutrient content.
- **Advanced Techniques:** CRISPR gene editing and marker-assisted selection are being explored to develop microgreens with tailored health benefits (Zhang *et al.*, 2021)^[37].



Functional Food and Health Market Expansion

- **Superfood Positioning:** Microgreens are increasingly recognized as functional foods, promoting health beyond basic nutrition.
- **Market Applications:** Used in nutraceuticals, dietary supplements, and functional food products, meeting

growing consumer demand for food as medicine (Kyriacou *et al.*, 2021)^[14].

Customization for Culinary and Aesthetic Appeal

- **Gourmet Use:** Chefs and food designers utilize microgreens for color, flavor, and texture, enhancing culinary presentation.
- **Specialty Varieties:** Breeding programs are developing unique microgreen cultivars to meet the gourmet and aesthetic market demand (Poudel *et al.*, 2021)^[26].



Conclusion

Microgreens represent a dynamic and promising sector in sustainable agriculture due to their:

- **High Nutritional Value:** Dense concentrations of vitamins, minerals, antioxidants, and bioactive compounds make them ideal functional foods.
- **Short Cultivation Cycle:** Rapid growth (7-21 days) supports year-round production and economic viability.
- **Adaptability:** Suitable for urban, vertical, and home-based farming, contributing to food security and local food production.
- **Technological Integration:** Innovations in smart farming, biofortification, and controlled-environment agriculture are expanding potential for nutrition enhancement and production efficiency.
- **Market Potential:** Rising consumer awareness positions microgreens for diversification, commercialization, and incorporation into health-focused industries.

With these attributes, microgreens are poised to play a pivotal

role in future food systems, bridging nutrition, sustainability, and economic opportunity.

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