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Review article

Microgreens on the rise: Expanding our horizons from farm to fork

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A R T I C L E I N F O

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A B S T R A C T

Escalating public health concerns necessitate innovative approaches to food sources. Microgreens, nutrient-rich seedlings of vegetables and herbs, have gained recognition as functional foods. This review explores the evolution of microgreens, cultivation methods, biochemical changes during germination, nutritional content, health benefits, and commercial significance. Comprehensive studies have demonstrated that microgreens have an elevated level of various nutrients. Further, in vitro and in vivo research validated their antioxidant, anticancer, antibacterial, anti-inflammatory, anti-obesity, and antidiabetic properties. Microgreens, termed "desert food," show promise for sustainable food production in climate-vulnerable regions. This paper synthesizes recent research on microgreens, addressing challenges and gaps in understanding their nutritional content and health benefits. It contributes valuable insights for future research, fostering sustainable agriculture and enhancing understanding of microgreens in human health and nutrition.

1. Introduction

Many persistent human diseases and disorders have solid pedigrees. Tobacco use, alcohol use, insufficient physical activity, and sexual activity are all major contributors to the development of chronic impairments [1]. Human development and innovation are reflected in the mutual integration of medical, biological, and nutritional knowledge. Because of the dramatic shifts in general health and the inadequacy of vitamins and minerals in the typical Western diet, there has been a resurgence of interest in the research and developments in organic foods. As the world's urban population grows, so does the need for a reliable, easily accessible, and nutritionally dense food supply. The public and private sectors are showing significant interest in urban farming, particularly in controlled environment farming. This encompasses various techniques such as vertical farms, greenhouses, hydroponics, aquaponics, and more [2]. Data analytics and machine learning are used to monitor, enhance, and even automate the cultivation of crops in a controlled setting. This type of indoor farming may also be more convenient and better for the environment for city dwellers (less water use and soil depletion, for example). Despite the hype, controlled environment agriculture is only applicable to a limited range of crops at the present time.

Experiment-based studies have consistently shown that diets high in plant-based foods have positive health effects. There is evidence that the edible parts of plants in the families of *Brassicaceae*, *Fabaceae*, *Solanaceae*, *Apiaceae*, and *Amaranthaceae* contain compounds that are physiologically active and have health-promoting qualities [3–6]. While it's well-established that humans benefit

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Table 1
Evolution of microgreen definitions across several decades.

Year	Common name	Scientific name	Definition	References
2004	Beet or Chard	*Beta vulgaris* L.	Microgreens have been defined as salad crop shoots harvested for consumption within 10–20 days of seedling emergence. Generally, microgreens have two fully developed cotyledon leaves, with the first pair of true leaves emerged or partially expanded, and during harvest they are cut above the soil line, whereas sprouts are mainly soaked in the water and younger, with the cotyledon not opened or just opened.	Lee et al., 2004
2005	Radish Kale Amaranth	*Raphanus sativus* *Brassica napus* var. *Pabularia* *Amaranthus tricolor*	… salad crop shoots for harvest and consumption within 10–20 days of seedling emergence ("microgreens")	Lee and Pill 2005
2010	Arugula	*Eruca vesicaria* subsp. *sativa*	Microgreens are salad crop shoots harvested for consumption within 10–20 d of seedling emergence.	Murphy et al., 2010
	Table beet	*Beta vulgaris* L.	Microgreens have been defined as salad crop shoots harvested for consumption within 10–20 days of seedling emergence, and they are developmentally classified between "sprouts" and "baby salads."	Murphy et al., 2010
2011	Table beet	*Beta vulgaris* L.	Microgreens are defined as salad crop shoots harvested for consumption within 10–20 days of seedling emergence	Pill et al., 2011
2012	Florida Broadleaf	*(Brassica juncea* L.	Microgreens are a type of specialty leafy green harvested shortly after the first true leaves have emerged. They are harvested just above the roots and consumed fresh as salad greens.	Kopsell et al., 2012
	Broccoli	*Brassica oleracea* var. *italica*	Microgreens are young and tender cotyledonary leafy greens that are found in a pleasing palette of colors, textures and flavors.	Kou et al., 2012
			Harvested at the first true leaf stage and sold with the stem, cotyledons (seed leaves), and first true leaves attached, they are among a variety of novel salad greens available on the market that are typically distinguished categorically by their size and age. Sprouts, microgreens, and baby greens are simply those greens harvested and consumed in an immature state. Based on size or age of salad crop categories, sprouts are the youngest and smallest, microgreens are slightly larger and older (usually 2 in. tall), and baby greens are the oldest and largest (usually 3–4 in. tall).	Treadwell et al., 2012
2013	Broccoli	*Brassica oleracea* var. *italica*	Microgreens are specialty leafy crops harvested just above the roots after the first true leaves have emerged and are consumed fresh.	Kopsell and Sams 2013
	Tomato		Microgreens are seedlings of vegetable and herbs that are grown to fully opened cotyledons or first true leaf stage	Brazaityte et al., 2013
	Borage	*Borago officinalis* L.	Microgreens are a type of specialty leafy greens harvested shortly after the first true leaves have emerged. They are cut just above the roots and consumed fresh as salad greens	Virsile and Sitautas 2013
	Red cabbage Purple kohlrabi Purple mustards Mizuna	*Brassica oleracea* var. *capitata* *B. oleracea* var. *gongylodes* *Brassica juncea* *B. juncea* var. *japonica*	Microgreens are young edible greens produced from vegetables, herbs, or other plants, ranging in size from 5 to 10 cm long including stem and cotyledons (seed-leaves).	Sun et al., 2013
	Broccoli	*Brassica oleracea* var. *italica*	Microgreens are young and tender cotyledon greens harvested within 7–14 d of vegetable seedling emergence	Kou et al., 2014
	Radish	*Raphanus sativus*	Microgreens are a new class of specialty vegetables that are often harvested at the cotyledonary leaf stage without roots and seed coats. They are tender cotyledonary-leaf plants having vivid colors, intense flavors and tender textures …	Xiao et al., 2014a
2015	Mustard Red pak choi Tatsoi	*Brassica juncea* L. *'Red Lion* *Brassica rapa* var. *chinensis 'Rubi F1'* *Brassica rapa* var. *rosularis*	Microgreens are seedlings of vegetables and herbs that are grown to the fully opened cotyledon or first true leaf stages.	Brazaityte et al., 2015a
	Daikon radish	*Raphanus sativus* L.*var. longipinnatus*	They are young seedlings of vegetables, herbs, or other plants, with cotyledons fully developed and the first pair of true leaves emerged or partially expanded.	Xiao et al., 2015a
	Red cabbage	*Brassica oleracea* var. *capitata f. rubra*	Microgreens are tender immature plants produced from the seeds of vegetables (such as red cabbage) and herbs having two fully developed cotyledon leaves with or without the emergence of a rudimentary pair of first true leaves.	Huang et al., 2016
	Rapini	*Brassica rapa* L.	Microgreens, an emerging category of edible greens, are tender seedlings produced from the seeds of different species of vegetables, aromatic herbs and herbaceous plants, including wild edible species. Microgreens are generally harvested 7–21 days after germination, when cotyledonary leaves are fully developed, with or without the emergence of a small pair of true leaves.	Di Gioia et al., 2016
	Arugula Watercress Mustard	*Eruca sativa Mill.* *Nasturtium officinale* L. *Brassica juncea (L.) Czern.*	They are young seedlings of vegetables herbs, harvested when cotyledons are fully developed and the first pair of true leaves are emerging or partially expanded.	Xiao et al., 2016

(*continued on next page*)

Table 1 (*continued*)

Year	Common name	Scientific name	Definition	References
	Dijon Cauliflower	*Brassica oleracea* L. *var. botrytis*		
2016	Purple kohlrabi Mizuna Mustard	*(Brassica oleracea* L. *var. gongylodes* L.*)* *Brassica rapa* L. *var. japonica* *Brassica juncea (L.) Czern. 'Garnet Giant*	Microgreens and baby greens are a relatively new specialty crop appearing in many upscale markets and restaurants. Collectively, these crops consist of vegetables and herbs consumed at a young growth stage. The main difference between the two is that microgreens are harvested at the base of the hypocotyl when the first set of true leaves start to emerge, while baby greens are harvested after the first set of true leaves has developed, generally >21 d after germination	Gerovac et al., 2016
	Rye	*Secale cereale*	A microgreen has a single central stem, which has been cut just above the soil during harvesting …. The seedlings are well suited for local growers because microgreens are harvested just 7–14 days after germination when the cotyledons (seed leaves) have fully developed and before the true leaves have expanded	Lobiuc et al., 2017a
	Garden pea Carrot Amaranth	*Pisum sativum* *Daucus carota* *Amarantuhus tricolor*	vegetables, grains and herbs grown to the phenological phase of cotyledons, or to the development of the first pair of true leaves	Andrejiova et al., 2017
	Mustard Beet Parsley	*Brassica juncea* L., *'Red Lion'* *Beta vulgaris* L., *'Bulls Blood'* *Petroselinum crispum Mill., 'Plain Leaved or French'*	Microgreens are harvested at the first true leaf stage of growth and belong to the group of "functional foods," and have higher levels of bioactive compounds	Samuoliene et al., 2017
2017	Kale	*Brassica oleracea* L.	Kale was grown to five defined developmental stages, fully expanded cotyledon (microgreen 1 or MG1), seedlings with two true leaves (microgreen 2 or MG2), seedlings with four true leaves (baby green 1 or BL1), seedlings with six true leaves (baby green 2or BL2), and mature plants with more than eight true leaves (adult).	Waterland et al., 2017
	Alfalfa Swiss chard	*Medicago sativa* L. *Beta vulgaris* subsp. *vulgaris*	Microgreens are harvested just above the roots when the cotyledons are fully formed or the first true leaves have emerged. They can be grown in soil or soil substitutes or hydroponically and require high-light conditions for efficient growth. Microgreens are halfway in size between sprouts and their older counterparts, such as baby spinach, but deliver the most in terms of flavor and nutritional values compared to the other two types of crops.	Reed et al., 2018
2018	Molfetta Trocadero Mugnuli	*Cichorium intybus* L. *Lactuca sativa* L. *Brassica oleracea* L.	They are young and tender vegetables, obtained from the seeds of numerous species (vegetables, herbaceous plants, aromatic herbs and wild edible plants), harvested a few days or weeks after germination, when the cotyledons are fully developed and the first true leaves may be emerging	Paradiso et al., 2018
2019	Coriander Jute Swiss chard	*Coriandrum sativum* *Corchorus olitorius* *Beta vulgaris*	Microgreens constitute a novel specialty crop, defined as immature greens harvested 51 without roots from the tender seedlings of vegetables, herbs, grains and wild crop relatives	Kyriacou et al., 2019
2020	Amaranth Kale Kohlrabi	*Amaranthus cruentus* L. *Brassica oleracea* var. *sabellica* *Brassica oleracea* Gongylodes Group	Microgreens are newly sprouted, immature plants without roots that are harvested after the development of the cotyledon leaves, or seed leaves, usually between 10 and 14 days from seeding	Tan et al., 2020
2021	Fenugreek Green pea	*Trigonella foenum-graecum L.* *Pisum sativum* L.	Microgreens are tender immature greens produced from the seeds of vegetables, herbs, or grains, inclusive of the wild relatives	Kowitcharoen et al., 2021
2022	Chinese basil	*Perilla frutescens* var. *crispa*	Microgreens are young vegetable seedlings harvested generally after the complete development of the cotyledons and/or the formation of the first leaves; they are considered innovative and emerging foods.	Dimita et al., 2022
	Lutfibey Bilensoy Dadas Arda Sazak Amazon Arifiye	*Onobrychis sativa* *Medicago sativa* *Trifolium pratense* *Cicer arietinum* *Lens culinaris* *Vigna unguiculata* *Zea mays*	Microgreens with a stem and cotyledon leaves are harvested before the true leaves emerge, when they are 5–10 cm in height depending on the plant	Altuner et al., 2022

from consuming mature plants, the rising prevalence of land field chemigation presents a number of challenges. In this context, advancements in agriculture that mitigate the consequences of increased external stress are highly prized. As a result of their unique biological features, microgreens are experiencing explosive growth and could soon become a fascinating new food source for improving human health [7,8]. Microgreens are gaining significant attention due to their positive effects on human health and beauty, their impressive nutritional content being 40 times higher than that of mature vegetables, their versatility in food creation, and their favorable impact on both the environment and economic viability. Since microgreens can be produced in either soil or hydroponically (the latter being the most frequent indoor farming technique), they have become one of the most popular crops in controlled environment farming. Microgreens are young vegetable greens that have not yet developed their cotyledonary leaves. Microgreens' popularity has skyrocketed in recent years due to the increased public interest in eating healthfully. Microgreens, sometimes known as "baby greens," are very young greens that are in between the sprout and baby stages of development. Although similar to baby greens

Table 2
Plant families explored for microgreens production.

Family	Species	References
Amaranthaceae	*Amaranthus caudatus* (Foxtail amaranth)	Li et al., 2015
	Amaranthus cruentus (Red amaranth)	Paśko et al., 2009; Li et al., 2015
	Amaranthus hypochondriacus (Prince's feather)	Li et al., 2015
	Maranthus tricolor (Edible amaranth)	Ebert et al., 2014
	Atriplex hortensis (Red orach)	Xiao et al., 2012
	Chenopodium album (Pigweed)	Jan et al., 2016
	Chenopodium quinoa (Duinoa)	Li et al., 2015
Apiaceae	*Anethum graveolens* (Dill)	Harakotr et al., 2019
	Coriandrum sativum (Coriander)	Kyriacou et al., 2020
Araliaceae	*Panax ginseng* (Korean ginseng)	Hong and Gruda, 2020; Song et al., 2021
Asteraceae	*Artemisia dracunculus* (Tarragon	Enache and Livadariu, 2016
	Cichorium intybus (Chicory)	Paradiso et al., 2018
	Taraxacum officinale (Common dandelion)	Lenzi et al., 2019
Basellaceae	*Basella alba* (Malabar spinach)	Yadav et al., 2019
Boraginaceae	*Borago officinalis* (Borage)	Bantis, 2021
	Phacelia tanacetifolia (Phacelia)	Pająk et al., 2019
Brassicaceae	*Brassica oleracea* var. *italica* (Broccoli)	Di-Bella et al., 2020
	Brassica oleracea var. *acephala* (Kale)	Neugart et al., 2018
	Sinapis arvensis (Field mustard)	Lenzi et al., 2019
	Wasabi japonica (Wasabi)	Xiao et al., 2012
	Brassica oleracea L.var. *capitata f. rubra (*Red cabbage)	
Chenopodiaceae	*Beta vulgaris* (Swiss chard)	Kyriacou et al., 2019
Convolvulaceae	*Ipomoea aquatica* (Water spinach)	Paradiso et al., 2018; Yadav et al., 2019
	Ipomea reptans L. (Morning glory)	Kowitcharoen et al., 2021
	Raphanus sativus L. *var. longipinnatus* (Purple radish)	Kowitcharoen et al., 2021
Cucurbitaceae	*Cucumis sativus* (Cucumber)	Yadav et al., 2019
	Cucurbita moschata (Pumpkin)	Yadav et al., 2019
	Lagenaria siceraria (Bottle gourd)	Yadav et al., 2019
Fabaceae	*Glycine* max (Soybean)	Ebert et al., 2017
	Medicago intertexta (Hedgehog medick)	Zrig et al., 2021
	Medicago polymorpha (Bur clover)	Zrig et al., 2021
	Melilotus indicus (Annual yellow sweet clover)	Zrig et al., 2021
	Vigna radiata (Mungbean)	Ebert et al., 2017; Mishra et al., 2021; Kowitcharoen et al., 2021; Kaur et al., 2022; Sangwan et al., 2022
	Cicer arietinum (Chickpea)	Kaur et al., 2022
	Trigonella foenum-graecum L. (Fenugreek)	Kowitcharoen et al., 2021
	Pisum sativum L. (Green pea)	Kowitcharoen et al., 2021
	Lens culinaris Medicus (Lentil)	Kowitcharoen et al., 2021
	Mucuna pruriens (Kalonch)	Chandrashekharaiah, 2013
	Caeselpenia mimosoides (Mimosa thorn)	Lekha et al., 2019
Lamiaceae	*Ocimum basilicum* (Sweet basil)	Xiao et al., 2015
	Ocimum xafricanum (Lemon basil)	Harakotr et al., 2019
	Ocimum sanctum (Sacred basil)	Harakotr et al., 2019
	Salvia hispanica (Chia)	Pająk et al., 2014
Linaceae	*Linum flavum* (Golden flax)	Pająk et al., 2014
Malvaceae	*Corchorus olitorius* (Jute mallow)	Yadav et al., 2019
	Hibiscus subdariffa (Red roselle)	Ghoora et al., 2018,
Onagraceae	*Oenothera biennis* (Evening primrose)	Pająk et al., 2014
Pedaliaceae	*Sesamum indicum* L. (Black sesame)	Kowitcharoen et al., 2021
Plantaginaceae	*Plantago coronopus* (Buck's-horn plantain)	Puccinelli et al., 2021
Polygonaceae	*Rumex acetosa* (sorrel)	Puccinelli et al., 2021
	Fagopyrum esculentum Moench (Buckwheat)	Kowitcharoen et al., 2021
Portulacaceae	*Portulaca oleracea* (Purslane)	Puccinelli et al., 2021
Rosaceae	*Sanguisorba minor* (Salad burnet)	Lenzi et al., 2019

in size, these plants are harvested later than sprouts. Microgreens are grown from seeds of herbs, vegetables, and grains. Cotyledons are the first true leaves that develop on firmly rooted seedlings of food plants. Microgreens, like their full-grown counterparts, consist of a central stalk and two sets of recently expanded, immature true leaves [9,10]. Not all tender young plant greens are considered microgreens, as stated by Gioia et al. (2017) [11]. They can be picked anywhere from 1 to 3 inches tall (depending on the species) and their harvest time is anywhere from 7 to 21 days after sowing. When compared to sprouts, microgreens might be seen as an improvement due to their greater nutritional value and intense flavor and taste [12]. Microgreens may also contain more phytochemicals, minerals, and vitamins than their fully grown counterparts [13,14]. As a result, customers who incorporate microgreens into their diets may see improved dietary value and health benefits. Due to their extreme fragility and limited shelf life, microgreens provide a number of challenges for both growers and distributors [12]. Microgreens' nutritional value and storage life have been

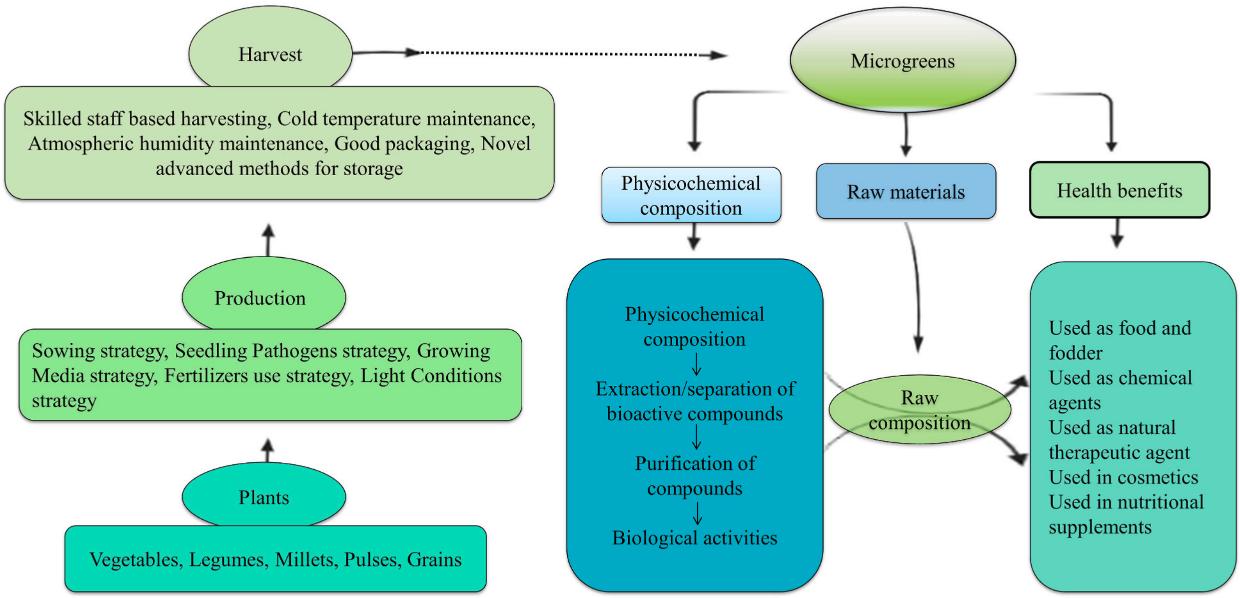

Fig. 1. Displays a variety of plant-specific production methods using an innovative research approach.

studied after a variety of pre- and post-interventions [15]. Since microgreens are a relatively new specialty food, there is not yet a large body of study on their nutritional content and health benefits.

The growing prevalence of chronic diseases underscores the urgency to explore innovative solutions in agriculture. The surge of interest in urban farming, particularly in controlled environments, aligns with the quest for a reliable, easily accessible, and nutritionally dense food supply. Amid this backdrop, microgreens emerge as a compelling subject, offering unique biological features and nutritional benefits that make them a potential catalyst for improved human health. However, challenges in production, distribution, and a limited understanding of their nutritional content and health benefits highlight the need for a comprehensive review. This paper aims to bridge existing gaps by synthesizing recent studies on the history, production, biochemical changes during germination, nutritional value, health advantages, and market trends of microgreens. Through this comprehensive exploration, we seek to contribute valuable insights that will inform future research, promote sustainable agricultural practices, and advance our understanding of the role microgreens play in enhancing human health and nutrition.

2. Origins of microgreens

In the 1980s, Americans first began regularly include unripe vegetables in their diets. A chef's garden in the United States is the most well-known provider of these vegetables because it grows and ships them while still young. Since then, trendy eateries have been increasingly serving such underdeveloped veggies because to their nutritious and novel qualities [16]. Microgreens is a term used to refer to these young veggies. However, numerous greenhouses throughout the world now cultivate microgreens. Since the year 2000, when the term "functional foods" was coined, microgreens have been widely recognized as a source of health and longevity [17]. They are currently utilized extensively in the agricultural system to produce a wide range of goods [18–20]. Microgreens have been around for decades, and different plant species from diverse plant families have been used to make them, but no universal definition has emerged in that time. Many different definitions of microgreens can be found across the scientific literature. For this reason, we have compiled a comprehensive summary of the definitions of microgreens from various plant research, which can be found in Table 1. Therefore, microgreens can be described as the germinations of seeds that have fully grown genuine leaves and non-senescent cotyledons, but are removed before the development of roots.

3. Methods for mass-producing microgreens

Microgreens can be grown everywhere there is a stable temperature and humidity level. Most of them come from controlled environments like greenhouses or farms. Three to four individuals can efficiently cultivate 90 kg of microgreens in an area of 400 square meters (m^2), yielding 300 g per square meter every week. However, depending on the growing conditions and species, harvests can occur in as little as 10–14 days [21]. Microgreens growth is greatly influenced by temperature. Growing microgreens successfully requires a production temperature of less than 20 °C. Allred and Mattson (2018) found that a rise in production temperature from 14 °C to 22 °C linearly reduces yield by 35%–40% [21]. Microgreens are planted at densities ranging from 1 seed/cm^2 for pea (*Pisum sativum*) and sunflower (*Helianthus annuus*) to 10 seeds/cm^2 for small-seeded plant species, depending on the species and their state of development at harvest. Fresh weight of mizuna, mustard, and arugula microgreens increases with seed density (3 seeds/cm^2), whereas plant weight at the individual level falls in a proportional manner [21].

The substrates utilized for germination also play a role in microgreens production. Greenhouse benches with overhead or sub-irrigation, or controlled germination chambers, are ideal for sowing the seeds. Allred and Mattson (2018) found that an increase in substrate depth from about 1.75 cm to 6 cm resulted in a greater rise in harvested fresh weight from the microgreens [21]. Microgreens are susceptible to several pests and parasites during the germination stage; however, the short production cycle (6–20 days) and the naturally occurring bioactive chemicals mitigate the aforementioned impacts [22–25]. The two most significant factors in the effective cultivation of microgreens are the absence of pests and the regulation of humidity. Skilled harvesters are essential for minimizing output losses when gathering microgreens. While harvesting is still primarily a manual process, appropriate machinery is now used to ensure the best possible results. Microgreens come in many varieties and have been examined for their economic viability from a wide range of plant groups (Table 2). Fig. 1 depicts a variety of manufacturing methods used in various facilities. Currently, *Amaranthaceae*, *Brassicaceae*, and *Fabaceae* species and cultivars account for the bulk of microgreen production [17,22].

3.1. Seed processing & planting methods

Priming seeds before sowing has been used for decades to improve germination rates and consistency across a wide range of crops. While germination rates were unaffected by matric priming with various soaks of sodium hypochlorite or hydrogen peroxide for table beet and chard [26], shoot dry weights were significantly increased. However, when using vermiculite for seed germination, the shoot dry weight was found to be higher than when using untreated seeds, and no further seed treatments significantly increased fresh weight when using this germination and planting method [26]. The outcomes were comparable for radish, kale, and amaranth. The study demonstrated that primed germinated seed treatments had significantly faster germination, which led to greater shoot dry weights, but had little effect on the germination percentage [27]. These findings were confirmed by the research of Murphy et al. (2010), who used a hydroponic nutrient film approach to grow microgreens for use on tables [28]. The microgreens had the highest shoot fresh weight when they were pre-germinated in vermiculite. In addition to enhancing germination after incubation in vermiculite, Trichoderma fungi also helped reduce Pythium in beet seed balls [29]. Seeding arugula microgreens in a peat-lite mixture yielded similar results, with pre-germination resulting in significantly greater yields than direct seeding [30]. Overall, the majority of seed treatments don't do much to affect germination rates or yields [30]. However, pre-germinating and priming seed can reduce cropping times and improve yields in a condensed time frame [26].

3.2. Combating pathogens in seedlings

Due to the high seed and plant densities, the seedling stage of growth, and the climatic parameters utilized in manufacturing, microgreens may be especially prone to a number of plant illnesses that thrive in these very specialized environments. Root rot, seed rot, and young plant rot are all symptoms of Pythium, one of several plant diseases [29]. Due to the short production cycles and edible nature of microgreens, the use of conventional fungicides is limited during their development. There has been investigation into non-traditional methods of disease management, such as the application of *Trichoderma* species [29]. Although these methods show promise, they are most effective when used routinely and in regions with low illness pressure [29]. However, they did determine that high *Trichoderma* application was effective.

Seed treatments with bacteria have also been shown to promote the growth of buckwheat microgreens. Endophytic bacteria of the genus *Herbaspirillum* have been found in buckwheat, according to research by Ref. [31]. After isolating and applying the endophytic bacteria as a seed and media therapy, the scientists demonstrated increased fresh and dry weight in microgreen production, leading them to hypothesize that the treatment would be a viable strategy to increase yields in buckwheat microgreen production [31]. Seed treatments to promote microgreen growth, as well as effective methods to avoid seedling and root rots, which can become a problem in the high wetness and dense planting associated with microgreen production, have not received a lot of attention from researchers. Microgreen farmers would benefit greatly from additional investigation into non-chemical or natural methods of pest control.

3.3. Expanding media tactics

Microgreens can be grown in many different types of media. There is a wide variety of materials used in greenhouses, with some growers favoring perlite, others favoring vermiculite [26], and still others opting for soil-free greenhouse mixes. Most farmers choose peat-based mixes or synthetic mats [11], but filter paper has been used in experiments to evaluate additives to the germination media, such as leftover brewer's yeast [32]. Sand and vermiculite composts, as well as composts made from sand, peat, coconut coir dust, sugarcane filter cake, and vermi compost, have all been examined [33]. Muchjijab et al. (2015) found that all of these methods were effective for cultivating microgreens [34].

Recycled textile fiber, jute-kenaf fiber, peat, and polyethylene terephthalate mats all yielded comparable fresh weights, with slightly lower yields recorded in polyethylene terephthalate mats and higher yields on peat substrate [11]. Nitrate, sulphate, and potassium concentrations in microgreens produced on these media are distinct from those found in those cultivated in others. Peat-based substrates showed higher quantities of nitrate, sulphate, and potassium, as well as higher populations of enterobacteriaceae and yeast mold. Aside from peat, no aerobic microbial population differences were discovered. None of the substrates tested contained *E. coli* [11]. A study comparing radish microgreens produced hydroponically on polyethylene terephthalate mats to those grown in a soil-less peat-based substrate found that *E. coli* was more likely to thrive in the hydroponic system. However, it is possible that differences in watering schedules were to blame for this rather than the substrates themselves [35]. It has also been shown that increasing

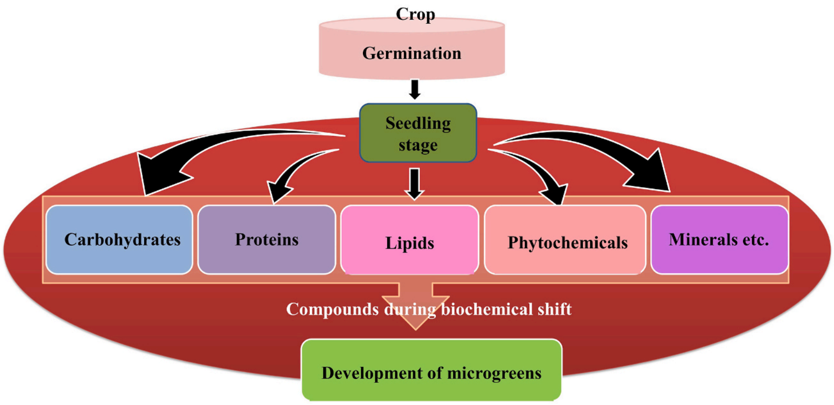

Fig. 2. Microgreens undergo a metabolic transition during germination, and this transition is accompanied by the expression of a variety of chemicals.

the germination substrate with ascorbic acid and spent brewer's yeast can boost rye microgreens' germination rates by at least 10%. It was found that [32]. Therefore, microgreens can be grown in a wide range of organic and inorganic media. Along with cost and convenience of procurement, the ability to prevent the spread of human and plant illnesses should be considered while choosing a suitable growing medium.

3.4. *Strategy for applying fertilizers*

Fertilization is used sparingly, with many farms instead relying on the nutritional density of commercially available peat lite soils. The short time it takes for microgreens to grow means that they don't need a lot of fertilizer. In order to supply nutrients, either conventional fertilizer or unconventional ones, such as spent brewer's yeast, can be used [36]. Both the biomass and hypocotyl length of rye microgreens were improved when treated with discarded brewer's yeast at a volumetric concentration of 50% [36]. Treatment with 100 mg L-1 of ascorbic acid resulted in higher fresh weights in the same trial. A more typical approach, including pre-plant calcium nitrate fertiliser application and post-plant liquid fertiliser treatment, boosted fresh weight by roughly 20% despite the very short 15-day cropping period. Studies using arugula microgreens confirmed the benefits of applying a pre-plant fertiliser, followed by 75–150 mg L^{-1} of nitrogen fertilization at various stages of production [28,30]. Microgreens of Chinese kale can be successfully cultivated in commercial settings using a Hoagland's solution at half strength. However, in that study, plant growth was allowed to continue beyond the customary (30-day) time frame for cultivating microgreens [37]. The researchers found that the Chinese kale responded to the light regimes in a very different way than the 21-day-old brassica microgreens had. Mizuna, arugula, and mustard microgreens did not have significantly greater fresh weights at higher fertiliser concentrations [21]. The effectiveness of fertilizers in the formation of microgreens is dose-dependent, and care must be taken to avoid wasting fertilizer during the germination process by applying too much.

3.5. *Strategy for low-light conditions*

Many types of microgreens are grown in artificial conditions that exclude all sunlight. One of the most studied aspects of microgreen production is, therefore, the effect of light quantity and quality on biomass accumulation, bioactive compound concentrations, and carotenoids and other pigment concentrations [37–42]. Although microgreens can be grown in artificially lit growth chambers, the vast bulk of the crop is still cultivated in greenhouses. High intensity discharge lighting, such as high pressure sodium (HPS) lamps or light-emitting diode (LED) arrays, is required if ambient light falls below 10–12 mol day^{-1} m^{-2} [37,43]. The effect of light quality on microgreen production is less clear because of the wide range of responses observed among species and varieties, which in turn depends on the parameters assessed and the light quality combinations analyzed. However, it appears that both development and antioxidant levels benefit from exposure to high amounts of blue light.

4. Taking advantage of the metabolic change that occurs when a seed germinates

Microgreens undergo biochemical changes during development that are affected by the environment under which they germinate and by any "seed invigoration" treatments applied to the grains to promote germination and subsequent seedling growth. Priming seeds involves hydrating them with a solution that promotes absorption and the first reversible stage of germination but inhibits radicle protrusion through the seed coat [44]. Seeds can be primed in a variety of ways, including by soaking them in osmotic solutions like polyethylene glycol (PEG), halopriming with salt solutions, or hydropriming with water [44]. In order to maximize the nutritional and medicinal benefits of microgreens, researchers have recently focused on finding the optimal temperature and time combination for pre-sowing and sprouting treatments. After 40 h of germination at 25 °C and 15.84 h of tap water soaking, foxtail millet reaches its highest total phenolic content, total flavonoid content, and antioxidant activity [45]. The optimal germination conditions for sorghum suitable for supplemental food formulations (i.e., low tannin and high protein contents) have been discovered to be steeping for 24 h at 31 °C followed by germination for 4.5 days at 30 °C [46]. The amount of phytochemicals in germinated grains is affected by the pH of the soaking solution, which in turn is regulated by the enzyme activities in the seeds. The optimum pH for brown rice was between 3.0 and 5.8 [47], with a lower cytosolic pH increasing GAD activity. When germinated barley grains were exposed to a buffer solution (pH 6.0), the GABA content was somewhat higher than that of water [48]. Under less-than-ideal conditions for germination, seedlings may accumulate phytochemicals due to the activation of secondary metabolism [49]. Rehydration results in high levels of oxidative stress, which can lead to an increase in the production of reactive oxygen species (ROS) and potentially harmful effects on the seed's DNA, proteins, lipids, and other macromolecule structures. Since induced environmental stress during germination can be classified as an abiotic elicitor, ROS scavenging is critical for successful seed germination under stress and consists of non-enzymatic components, primarily connected with an excess of antioxidants (such as phenolics) [50]. It is important to note that pre-sowing grain treatments and stressful conditions during germination can both reduce the germination rate and the amount of dry matter produced. Commercial use of those manipulations of environmental factors during germination should be properly set up for each species in order to generate microgreens with higher nutritional and health-promoting characteristics without severely compromising production levels.

Significant biochemical, nutritional, and sensory changes are suggested in the edible products after the once dormant dry seeds begin their metabolic activity, including remobilization, disintegration, and accumulation [51]. The primary and secondary metabolites produced by germinating seeds differ in their biological effects when compared to those of non-germinated seeds [52–54]. Fig. 2 depicts the levels of metabolite expression observed during germination of whole grains, and this section reports on those levels. However, most of the reported results only apply to young seedlings, and they are very dependent on the species, the stage of growth at which the seedlings were observed, the environmental conditions under which the germination took place, and the laboratory procedures used. Microgreens contain a wide variety of important substances during their development, including carbohydrates, proteins, lipids, phytochemicals, and minerals.

4.1. *Carbohydrates*

4.1.1. *Substantial carbohydrates*

Since the mobilization of complex polymers like starch is one of the processes involved in seedling development that has been the subject of the most research, the significant changes in grain carbohydrates in the majority of germinated grains have been thoroughly investigated. Increasing the grain's digestibility [55,56], amylases catalyze the hydrolysis of starch, which is stored in grains as amylose and amylopectin, to simple sugars, especially glucose, maltose, and, to a lesser extent, sucrose [57]. While buckwheat tends to store more glucose than maltose during germination, other cereals like rice, sorghum, and millet appear to store more glucose than maltose [58,59]. There was a correlation between the glucose to maltose ratio of 5-day-old buckwheat microgreens at a germination temperature of 20 °C and the amounts of α-amylase and β-amylase formed in grains during malting [59]. While early wheat germination is characterized by a preference for sucrose, later germination (3 days post-imbibition) is characterized by a preference for glucose and maltose [57]. Similar variations were seen with rice, where sugar predominated not long after consumption. Sucrose levels remained elevated in germinated rice seedlings for an extended time after imbibition [60], but glucose content increased more rapidly and maltose did not exist at a considerable level until much later (7 days post-imbibition). It has been observed in various species, including wheat [61], that hydrolysis of starch yields an adequate amylose content with little modification. This demonstrates the importance of store carbohydrates during germination, when microgreens are grown.

4.1.2. *Carbohydrate structures*

The fiber content of the whole grain is quite high. Cellulose, hemicellulose, and lignans are water insoluble fibers, while β-glucans and arabinoxylans (AXs) are water-soluble fibers that can be extracted with or without water [62]. Other grain species only contain lower amounts of β-glucans than sorghum and millet [63], barley (5–11%), and oats (3–7%). Germination has a variable effect on the dietary fiber content of microgreens, depending on genotype, germination time, and fiber fraction [52]. Dietary fibers in germinated wheat appeared to rise after 196 h of incubation [64,65], despite a decrease in concentration during the first 48 h of germination. There were no observable changes after 72 h of barley germination [66]. Increases in total dietary fiber are seen in rice after malting [67], which may be explained by the formation of new main cell walls. Germinated brown rice cultivars have exhibited an upward trend in total fiber content, as well as soluble and insoluble fiber fractions, however the ratio of soluble to insoluble fractions varies in response to genotype and processing conditions [68]. Similarly, the insoluble fraction of oats increases during germination [69]. Microgreens of barley and oats have significantly less β-glucans due to the hydrolytic activity of endogenous β-glucanases [62]. In species with a higher concentration of β-glucans, like wheat, the amount of soluble fraction remained constant for the first 96 h and then increased steadily for the next 168 h [64], while in species with a lower concentration of β-glucans, like oats, the amount of soluble fraction decreased gradually over time, up to 144 h.

4.2. *Proteins*

Albumins (water-soluble), globulins (salt-soluble), glutelins (alkali-soluble), and prolamins (alcohol-soluble) are the principal storage proteins in most cereals. Proteolytic enzymes hydrolyze the storage proteins into peptides and amino acids after two to three days of imbibition during grain germination, increasing nutritional bioavailability [70]. It has been observed that the amount of prolamins in triticale, barley, rye, oats, and wheat reduces as germination time increases [64]. However, many authors have found a rise in crude proteins in oats [71], brown rice [72], oats [73], and barley [73]. This occurs because, upon absorbing water, the cereal's proteins and amino acids are hydrolyzed to transportable amides and then transported to the growing portions of the seedlings [74]. Protein content, on the other hand, is dependent on the rate of protein synthesis relative to the rate of protein degradation during germination [75]. An increase in amino acid concentrations and notable shifts in free amino acid composition have been observed [59, 65]. In particular, the amino acids necessary for protein synthesis are more concentrated in germinated whole grains. Amino acid levels are most affected by the length of germination and the type of grain used. The quantities of the essential amino acids isoleucine, leucine, phenylalanine, valine, and threonine and methionine in waxy wheat peaked after 36 h of germination [65]. The rice and buckwheat malts produced higher quantities of amino acids after 5 and 4 days of germination, respectively, but asparagine and, methionine and histidine amino acids were characterized by lower amounts in both species [58]. Albumin concentration increases during oat germination, and this is good news because albumin is rich in the essential amino acids lysine and tryptophan, while globuline and prolamine quantity declines due to their lack of lysine [76].

4.2.1. The amino acid alpha-butyric

Glutamate decarboxylase (GAD) catalyzes the -decarboxylation of L-glutamic acid, resulting in the four-carbon non-protein amino acid γ-aminobutyric acid (GABA). It is the major inhibitory neurotransmitter in the mammalian cerebral cortex [77]. Although most studies on GABA production in cereals have focused on brown rice [48,65], some researchers have found differences in GABA levels during wheat and barley germination. Microgreens, regardless of species, show a significant increase in GABA levels during development. GABA content in brown rice seedlings increased 2- to 5-fold depending on the type [78], and up to 8- to 12-fold when germinated for 2–4 days at 27–35C [79–81]. The higher GAD activity and lower glutamate content seen during germination provide more evidence for this. However, the GABA content in cereal microgreens is significantly affected by temperature or abiotic stress and grain preparation prior to germination.

4.3. Lipids

Triacylglycerols (TAG) such as oil is found abundant in the embryo, scutellum, and aleurone of whole grains, even though endosperm starch is the predominant carbon storage in cereals. To release TAG from oil bodies, germination sets in motion a series of coordinated metabolic processes that ultimately result in a net conversion of oil to sugars [82]. At first, lipases break down TAG to free the esterified fatty acids (FAs). The glyoxylate and -oxidation cycles can then be used to convert free fatty acids (FFAs) to sugars [82]. The steps that transform triglyceride into sugars during seed germination are discussed in detail in the aforementioned literature. The increase of free fatty acids (FFAs) in the endosperm correlated with the slower onset of TAG mobilization [83]. Although oil reserves in the embryo degrade before those in the scutellum, oats are unusual among cereals because of their high oil content relative to carbohydrate and protein concentration. During the first 48 h of germination in waxy wheat, the level of essential FAs (linoleic and linolenic acids) was not considerably altered [65]. The microgreens development considerably altered the FA composition in 9-day-old wheat seedlings, especially the linolenic acid (18:3), as reported by Ozturk et al. (2012) [84]. Wheat microgreens, on the other hand, had higher concentrations of palmitic acid, linoleic acid, and oleic acid after 3 days of germination [85]. It is also important to remember that the pre-germination treatments and lipase activity in whole grain tissues play a significant influence in the metabolic dynamics of FAs, and that the levels of certain FAs either steadily increased or decreased as germination progressed. Oryzanol, together with tocopherols and tocotrienols, are responsible for the nutritional value and health-promoting properties of rice sprouts, and it is the primary component of the unsaponifiable lipid fraction [86]. After germination, the concentration of -oryzanol increased 1.13 and 1.20 times in rough rice and brown rice, respectively [87]. Strategies to improve the content of oryzanol from rice microgreens could be explored because its concentration is based on cultivar-specific content in kernels [88], water uptake rates during sprouting, and germination timing [86].

4.4. Minerals and phytate

Phytate is the major form of phosphorus storage in many plant-based diets, including mature grains and legumes [89]. The phytases catalyze the conversion of phytate into ortho- and myo-inositol phosphate as well as inorganic phosphate, and they are a subfamily of the high-molecular-weight histidine acid phosphatases. Sung et al. (2005) found that phytase activity in barley was exceedingly low at the beginning of germination but increased by a factor of eight within the first several days [90]. Although phytase concentration in whole grains varies greatly among cereal species, rye has the highest values and oats have the lowest values [62]. Therefore, phytate levels drop to varying degrees during germination [91]. Phytate was reduced by 60% when brown rice was germinated for 12–72 h [92], but by up to 87% when sorghum seedlings were cultivated for 4 days [93]. More study on phytate breakdown during germination processes has been described for brown rice [72], barley [69], pearl millet [91,94], corn [95], sorghum, and wheat [91]. As phytate levels drop, minerals like phosphorus become more bioavailable. Ca and Mg concentrations in wheat and barley changed during germination, with Ca decreasing and Mg increasing, respectively [96]. Tracer elements including copper, iron, zinc, manganese, and cobalt tend to rise during germination period, while the main macro-elements (Na, K, Mg, Ca, and P) in maize tend to dip after two days of germination before increasing up to six days later [95]. The HCl-extractability of both major and trace minerals increased after germination for these species [95], albeit this was highly impacted by cultivar. Finger millet's Ca, Fe, and Zn extractability improved from 76.9%, 18.1%, and 65.3% in the whole grain to 90.2%, 37.3%, and 85.8%, respectively, after 96 h of germination (Mbithi et al., 2000). Zn and Fe bio-accessibility in hydrothermally processed microgreens of wheat rose to 27% and 37%, respectively, from 15% to 14% in unprocessed germinated wheat.

Table 3
Nutrition profile of different types of microgreens.

S. No	Crop name	Scientific name	Nutritional value and uses	References
1	Amaranth	*Amaranthus vridis*	Have vibrant colors and used for garnishing, Rich in Calcium, Iron and β-Carotene	Nautiyal et al., 2022
2	Beetroot	*Beta vulgaris*	High antioxidant properties and rich in vitamin C	Nautiyal et al., 2022
3	Broccoli	*Brassica oleracea*	Rich in minerals, vitamins and regulates immune system	Nautiyal et al., 2022
4	Fenugreek	*Trigonella foenum-graecum*	Rich in protein, vitamins and minerals	Nautiyal et al., 2022
6	Chickpea	*Cicer arietinum*	Nutrient and phytochemicals rich, Antioxidant activity	Kaur et al., 2022
7	Tamarind	*Tamarindus indica*	Rich source of storage proteins and protease inibitors	Jafar et al., 2017
8	Mimosa thorn	*Caesalpinia mimosoides*	Rich source of storage proteins and protease inibitors, antimicrobial activity	Lekha et a., 2019
9	Castor bean	*Ricina communis*	Rich source of storage proteins and protease inibitors	Lone et al., 2017
10	Mungbean	*Vigna radiata*	Nutrient and phytochemicals rich, Antioxidant activity	Mishra et al., 2021 Kaur et al., 2022 Sangwan et al., 2022

Table 4
Advantages and applications of some of the most popular microgreen vegetables/crops.

S. No	Crop name	Scientific name	Nutritional value and uses	References
1	Amaranth	*Amaranthus vridis*	Have vibrant colors and used for garnishing, Rich in Calcium, Iron and β-Carotene	Nautiyal et al., 2022
2	Beetroot	*Beta vulgaris*	High antioxidant properties and rich in vitamin C	Nautiyal et al., 2022
3	Broccoli	*Brassica oleracea*	Rich in minerals, vitamins and regulates immune system	Nautiyal et al., 2022
4	Fenugreek	*Trigonella foenum-graecum*	Rich in protein, vitamins and minerals	Nautiyal et al., 2022
6	Chickpea	*Cicer arietinum*	Nutrient and phytochemicals rich, Antioxidant activity	Kaur et al., 2022
7	Tamarind	*Tamarindus indica*	Rich source of storage proteins and protease inibitors	Jafar et al., 2017
8	Mimosa thorn	*Caesalpinia mimosoides*	Rich source of storage proteins and protease inibitors, antimicrobial activity	Lekha et a., 2019
9	Castor bean	*Ricina communis*	Rich source of storage proteins and protease inibitors	Lone et al., 2017
10	Mungbean	*Vigna radiata*	Nutrient and phytochemicals rich, Antioxidant activity	Mishra et al., 2021 Kaur et al., 2022 Sangwan et al., 2022

5. Benefits of microgreens for your health

Flavonoids, carotenoids, and α-tocopherol were found in quite high amounts across a range of seedling types. Microgreens made from tartary buckwheat were shown to have more flavonoids than other types of microgreens. Tartary and common buckwheat microgreens may serve as a healthy alternative to other types of vegetables in the Czech Republic [97]. Microgreens, sprouts, and leafy greens all come from the buckwheat plant, and all three are excellent sources of the phenolics (rutin, quercetin, vitexin, isovitexin, orientin, isoorientin, and chlorogenic acids) that give buckwheat its powerful antioxidant capabilities. Microgreens have been demonstrated as suitable sources for bioactive chemicals in studies conducted on five different types of Brassica vegetables [98]. Ultrahigh-performance liquid chromatography and photodiode array multistage high-resolution mass spectrometry (29) were able to identify 164 polyphenols, including anthocyanins (30), flavonol glycosides (105), and derivatives of hydroxycinnamic and hydroxybenzoic acids. According to the USDA's National Nutrient Database, the microgreen cotyledon leaves have a higher nutrient density than the mature leaves. Light management, as reported by Kopsell et al., in 2012, can also boost the nutritional content of microgreens [41]. Pinto et al. (2015) compared the mineral profiles of microgreens and mature lettuce to demonstrate the former's superior nutritional profile [99]. The research has yielded useful results that can be applied in both theoretical and practical settings. Microgreens had larger concentrations of Ca, Mg, Fe, Mn, Zn, Se, and Mo than mature lettuces, which had higher concentrations of N, P, and K. The presence of different nutrients, vitamins and minerals in microgreens from different sources are shown in Table 3 [100].

Therefore, microgreens could be considered a rich source of minerals. They are recommended as safe in the human diet, especially for children, to meet their mineral demands because of the extremely low NO_3 content. The advantages of growing some of the most popular vegetables as microgreens are listed in Table 4.

6. The health benefits of microgreens

Microgreens have been the subject of extensive scientific inquiry because of their high concentrations of vitamins, minerals, and phytochemicals. Researchers have focused on vitamin C (VC), phytochemicals (such as carotenoids and phenolics), and a few minerals (copper, zinc, and selenium) for their ability to neutralize free radicals and limit the damage from oxidative stress (Se). Microgreens have been compared to their fully developed counterparts in terms of antioxidant capacity and content [3,99]. VC, also known as ascorbic acid, is an effective antioxidant because of its role in collagen synthesis, immune system regulation, and wound healing [101]. Since vegetables are rich in VC, many studies have looked at the VC content of various microgreens [14,102]. Microgreens of jute (*Corchoris olitorisu* L.) and cucumber (*Cucumis sativus* L.) were shown to have higher VC levels than their mature equivalents in a study [13]. The VC content of water spinach was similar in its microgreen and mature forms. Plants of other species, such as Amaranthus

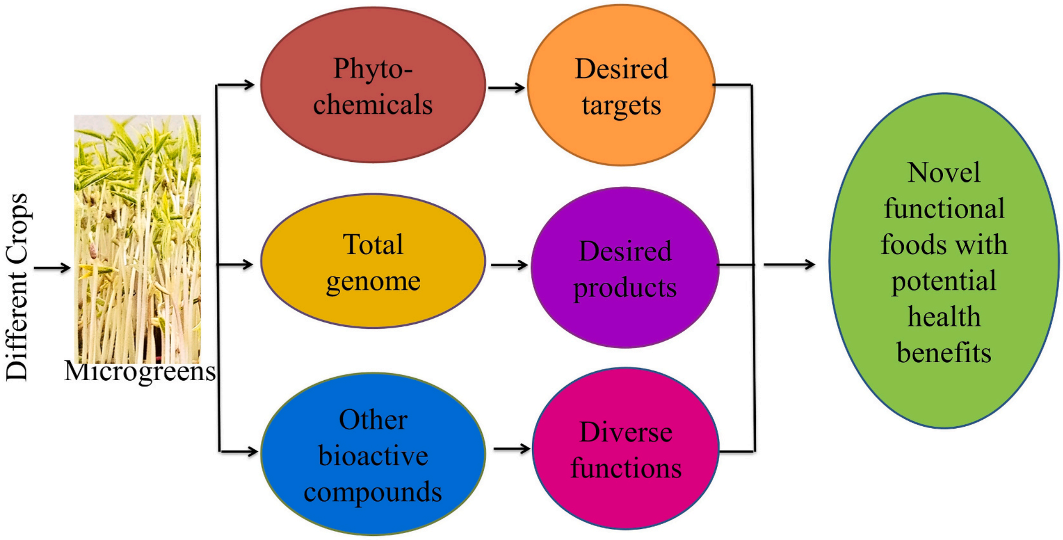

Fig. 3. Microgreens are functional foods with significant functional relevance.

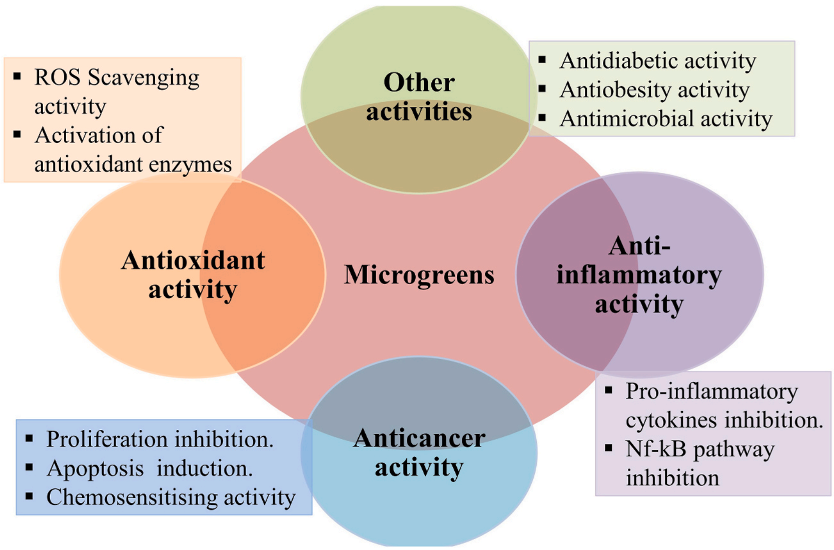

Fig. 4. The therapeutic potential of microgreens.

(*Amarnthus tricolor* L.), bottle gourd (*Lagenaria siceraria* Standl), palak (*Beta vulgaris* L. var. bengalensis Roxb), pumpik (*Cucurbita moschata Duchesne),* and radish (*Raphanus raphanistrum*), showed higher VCas in their mature stages compared to their microgreen counterparts. Microgreens (7.5 mg/g) of traditional Sicilian broccoli have a significantly higher VC content than baby greens (6.1 mg/g) [4]. Several trace elements, such as copper, zinc, and selenium, are essential cofactors or components of antioxidant enzymes (such as superoxide dismutase) in the human body [103]. Consuming insufficient levels of antioxidant components can reduce antioxidant enzyme activity [104]. Microgreen samples have been frequently analyzed for the presence of antioxidant minerals like those listed above in comparison to their full-grown counterparts [22,99,105]. Microgreens showed significantly higher Zn and Cu contents than their equivalent adult stages (P 0.05), as determined by Waterland et al. (2017) in their evaluation of the mineral content of kale cultivars (*Brassica oleracea*) during the microgreen, baby leaf, and adult stages [106]. Butkute et al. (2018) looked at the *Medicago lupulina*, *Onobrychis viciifolia*, *Astragalus glycyphyllos*, and *Astragalus cicer* legumes at the seed, sprouted seed, and microgreen phases [107]. Microgreens significantly improved the nutritional profiles in terms of mineral composition compared to raw or sprouted seeds of these tiny legumes [107].

Phytochemicals, such as phenolics and carotenoids, are abundant in microgreens. Carotenoids include the lipophilic plant pigments xanthophylls (including lutein and zeaxanthin) and carotenes (including -carotene and lycopene) as well as other bioactive chemicals [108]. The presence and characteristics of various bioactive chemicals in microgreens are depicted schematically in Fig. 3, indicating that microgreens are a very high-quality functional food.

Carotenoids have been shown to have antioxidant activity and play important physiological roles in humans [109]. Carotenoids are abundant in vegetables, especially those with deep hues [110]. Microgreen wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) were found to have a higher carotenoid concentration than the seed phase when analyzed for their carotenoid profiles [111]. Phenolic compounds, including everything from small molecules like phenolic acids to highly polymerized compounds like tannins, are the most common type of secondary metabolite in plants [112]. Microgreens are superior to mature Brassica plants as a source of antioxidants due to their higher polyphenol levels and more varied polyphenol profiles [113]. Antioxidants found in plants, called phenolics, aid in plant recovery from free radical damage and have many beneficial benefits on human health. All of this puts microgreens in a strong position for use as healthful functional meals.

7. Consumption of microgreens and its effects on health

Microgreens' rising popularity can be attributed to a number of nutritional and chemical reasons, as well as the fact that they are increasingly recognized as a fresh source of physiologically active chemicals. Current research has been continuously progressing while the pilot trial showed promise in decreasing blood glucose, controlling weight, and preventing cardiovascular disease. Phytochemicals in microgreens are highly digestible, suggesting that they may have antibacterial, anti-inflammatory, antioxidant, and anti-diabetic effects [114,115]. Ascorbic acid, carotenoids, and isothiocyanates are all abundant above, and they have a significant anti-proliferative influence. Modulation of plasma and liver lipid metabolism and inhibition of cholesterol and triglyceride production are also discussed by Huang et al. (2016) [116]. The biological promise of microgreens to the medical field is most clearly depicted in Fig. 4.

7.1. Microgreens' cancer-fighting potential

Predictions for the future indicate an increase in the prevalence of malignant tumors, the second leading cause of death worldwide. There is, therefore, a critical need for accessible cancer prevention strategies, such as boosting intake of phytochemicals found in plants [117]. Inhibiting specific metabolic processes and mechanisms within cancer cells, microgreens are viewed as potential in cancer prevention due to their wide variety of polyphenols, vitamins, carotenoids, and minerals [114]. Researchers found that microgreens from four species of the Brassicaceae family (broccoli, radish, etc.) inhibited the growth of human colorectal cancer cells. Cells committed apoptosis, produced reactive oxygen species instantly, and entered a G2/M cell cycle halt. Hormone-mediated route encourages malignant growth, which is why breast and prostate cancer are so common today. Microgreens are rich in phytochemicals including indoles and flavonoids, which have been shown to protect against prostate and breast cancer in the early stages of the disease. Indinol-3-carbinol significantly inhibited oestrogen receptor alpha (ER-) signaling in MCF-7 breast cancer cells. In addition, it was found that down-regulating estrogen-responsive genes such trefoil factor 1 and cathepsin-D led to up-regulation of the tumour suppressor gene [118,119].

7.2. Microgreens have anti-inflammatory properties

Inflammation has a significant role in the onset of numerous diseases, including diabetes, heart disease, and cancer. Higher levels of phytochemicals in microgreens are associated with their ability to regulate the immune system and protect against the aforementioned diseases and health issues. The NF-kB pathway has been shown to be critically important in a wide variety of inflammatory stimuli. Pro-inflammatory cytokines, such as tumor necrosis factor alpha (TNF-α), interleukin 1 beta (IL-1), and interleukin 6 or 8 (IL-6, IL-8), are all the product of NF-induction kB's of transcription of pro-inflammatory genes. A significant concentration of polyphenols and glucosinolates is found in microgreens, and these compounds may block kinases from being phosphorylated or ubiquitinated, two steps essential to the NF-kB signaling pathway. The aforementioned data suggests that glucosinolates may inhibit NF-kB by blocking the degradation of inhibitor alpha of the nuclear factor kappa light polypeptide gene enhancer in B cells [120,121]. The inflammatory enzyme cyclooxygenase-2 (COX-2) is essential. An increase in prostaglandin production may destabilize an inflammatory process. Microgreens include a variety of polyphenols, some of which may decrease COX-2 activity [121]. Previous studies have shown that AhR plays a significant role in immunological regulation. The transcription of interleukin-17 (IL-17) has been shown to be affected. Interleukin-27 (IL-27) stimulates the formation of FoxP3-IL-10 (IL-10) producing type 1 regulatory T cells, and AhR plays a role in this process. Microgreens have a high concentration of AhR ligands in their phytochemical makeup. These findings suggest that indole-3-carbinol, along with other polyphenols and glucosinolates may have an effect on AhR-mediated immunological responses and T-cell regulation [121,122]. Also, excessive liver lipid levels are linked to inflammatory responses, and Huang et al. (2016) discovered that eating red cabbage microgreens can reduce these levels [116]. Marotti et al. (2021) report that licorice, or *Glycyrrhize glabra* L., possesses anti-inflammatory actions that are mediated through decrease of the proinflammatory cascade [123]. Microgreens from broccoli, as reported by Subedi et al. (2019), have been shown to have an effect on the immune system. Broccoli sulforaphane-enriched (PGE2) inhibited inflammatory proteins such as tumor necrosis factor-α (TNF-α), interleukin-1 (IL-1), and prostaglandin E2. Microgreens have several health benefits, including those indicated in Fig. 1, including their ability to fight cancer and inflammation [121].

7.3. Microgreens' antimicrobial properties

Inhibition of many diseases is enhanced when seeds germinate all the way to the microgreen stage. A study found that broccoli microgreens rich in gallic acid, esculetin, ferulic acid, and myricetin inhibited the growth of a variety of bacteria, including Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Bacillus subtilis*), food-borne pathogens. The MICs for these bacteria ranged from 390 to 1560 _g/mL. Another in vitro study indicated that the principal anti-Helicobacter active chemical, sulforaphane, had potent bactericidal action against *Helicobacter pylori*, with exceptionally active inhibitory zones (>5 cm) [124]. Microgreens have been linked to the presence of numerous healthful compounds, including flavonoids, glucosinolates, and phenols [125].

7.4. Activity inhibiting diabetes

Several studies have shown that microgreens are beneficial for people with diabetes. A new approach was employed to investigate the effects of broccoli microgreens powder on insulin resistance in people with type-2 diabetes. The results showed that powdered broccoli microgreens with a high sulforaphane concentration may significantly reduce serum insulin levels and lessen diabetic complications [126]. Another study has shown that sulforaphane, which can be found in early broccoli microgreens, may be effective as an adjunct treatment for type 2 diabetes. Hyperglycemia and oxidative conditions can be kept under control with the help of some PPRs that this may activate [127].

7.5. Combating obesity

As a leading cause of serious metabolic diseases like type 2 diabetes and cardiovascular disease, obesity has quickly become a pressing problem on a global scale. Microgreens from broccoli have been demonstrated to lower obesity by influencing lipid metabolism. Microgreens powder may improve lipid profiles and the OX-LDL/LDL ratio in people with type-2 diabetes as an additional therapy, lowering obesity and cardiovascular disease risk factors [128]. It has been suggested that the mechanism that regulates the lipid metabolism of broccoli microgreens is related to sulforaphane's ability to activate the Nrf2 pathway [127]. A recent study found that the glucoraphanin in broccoli microgreens can decrease lipid accumulation and increase Nrf2 activation. It worsens diabetes and obesity by suppressing the expression of numerous genes involved in lipogenesis and gluconeogenesis [129].

8. Market tendencies for microgreens

Microgreens are becoming increasingly common in high-end dining establishments, and supermarkets are stocking more and more varieties of them. They are actively growing on their media after purchase, and can be harvested at any time to be used as fresh as possible in home-cooked meals. In addition to human nutrition, the cosmetics industry is a growing niche market for microgreens [130]. Consumers concerned with their health have shown interest in microgreens because of their potential as oils and components in cosmetics.

People's desire to boost their immune systems by eating foods rich in antioxidants and other health-promoting elements has prompted a shift toward microscale vegetables, which has been fueled by the recent COVID-19 epidemic. In the face of a global disruption of supply networks and significant changes in purchasing patterns brought on by the ongoing COVID-19 pandemic, homemade microgreens provides a fascinating and sustainable alternative. Sprouting seeds and cultivating little plants for salads is an easy hobby to try at home. Fresh, nutrient-dense vegetables can be obtained on demand, eliminating the need for long-distance transportation and reducing the quantity of fossil fuels consumed in product distribution [131]. The microgreens' retail price was found to be anywhere from five- to eleven-times higher than their cost to cultivate [132]. As a result, growing microgreens is a profitable enterprise that can help keep the economics of underprivileged communities in both rural and urban areas afloat. Due to rising consumer interest and demand, the global microgreens market is expected to expand at a compound annual growth rate of anywhere from 7.5% from 2021 to 2026 [130] to 13.1% from 2020 to 2028 [133]. In 2020, the North American market for microgreens was the largest in the world, while the Asia-Pacific area saw the fastest increase [130]. More flavor, color, and textural options are available when many crop varieties are grown together [134]. Super mixes of these crops are subsequently sold for anywhere from $66 to $110 per kilogram in the United States [135]. Across all types of infrastructure, microgreens generated the highest average return (40%) followed by flowers (30%) and tomatoes (10%) [136]. In 2020, the percentage of land devoted to growing microgreens was 25% in the Midwest, 59% in the Northeast, and 71% in the South [130]. In 2019, retail outlets (hypermarkets, supermarkets, and grocery stores) represented for 46.8% of the market for fresh microgreens [137]. The retail sector is predicted to grow at a compound annual rate of 11.4% between 2021 and 2028. Allied Market Research predicts an annual growth rate of 11.1% for the global microgreen market between 2021 and 2028. From an anticipated $1,417,641,000 in 2020, the microgreens industry stands to earn $3, 795,471,000 by 2028. Some key trends in the microgreen industry include the increasing use of cutting-edge production technology, the expansion of indoor, vertical, and greenhouse farming, and the increased demand for nutritious, high-quality food products [133, 138,139].

9. Challenges inherent with microgreens farming

Advances in our understanding of preharvest factors affecting production and quality and postharvest factors controlling shelf life are the primary source of microgreens damage and future issues. Chemicals used for seed sterilization, antibacterial activity, pre-sowing treatments, and the usage of pesticides and other harmful chemicals are the primary causes of the problems associated with microgreens.

Short shelf life, which reduces nutritional value during storage, and the possibility of illness and public health contamination are the two main downsides of microgreen cultivation. Microgreens have limitations on their commercialization and mass manufacturing because of their short shelf life and rapid quality decrease. Numerous pre- and post-harvest practices are used to increase microgreens' storage life.

Another potential downside is the high cost of generating microgreens, which can include the price of substrate material, seeds, and labor. Moreover, in some locations, prices have recently dropped since larger producers have entered the market and more efficient production and harvesting techniques have been developed.

Foodborne diseases, commonly known as food poisoning or foodborne illnesses, result from the consumption of contaminated food or beverages containing bacteria, viruses, parasites, or chemicals. According to the Centers for Disease Control and Prevention (CDC) estimates in 2018, approximately 48 million cases of foodborne diseases occur annually. These illnesses are typically acute and manifest through symptoms such as diarrhea, nausea, stomach cramps, and vomiting. In a study conducted by Santos et al., in 2018, the antimicrobial properties of cold-pressed virgin almond oil (VAO) were investigated against various types of bacteria [140]. Their results revealed inhibitory activity against Gram-negative bacteria only, suggesting the hydrophobic nature of VAO may allow it to penetrate the lipopolysaccharide layer in the cell walls of Gram-negative bacteria. These findings contribute to the awareness that microgreens could be susceptible to the risk of pathogenic and microbial attacks, potentially resulting in foodborne diseases [141]. Hence, it is essential for individuals cultivating microgreens to prioritize hygienic conditions and refrain from using contaminated water or other items.

10. Tactics for solving difficulties

Microgreens have the potential to significantly reduce the resources needed to cultivate greens, improve the human diet's nutritional value, and even shape culinary fashions. Research is needed on crop-specific data on the relationship between sowing rate or growing medium and yield and quality, as well as on efficient and environmentally friendly non-chemical methods for seed surface sterilization and antimicrobial action. Since most shoppers like their food to have a more subtle flavor, it's important to draw inspiration from regional resources including landraces, underutilized crops, and wild edible plants. Phytonutrient density and gustatory appeal require equal consideration. Increasing the microgreens' bioactive functional chemical and vital mineral content can assist fill nutritional gaps in the human diet. In addition to enhancing their flavor, this process can reduce the amount of harmful compounds and increase the amount of healthy ones found in the food.

Kou et al. (2013) and Kou et al. (2014) found that a storage atmosphere with comparatively high O2 (14.0–16.5 kPa) and fairly low CO2 (1.0–1.5 kPa) is optimum for a product's shelf life [142,143]. Researchers also worked to enhance the atmospheric composition of packaging in order to extend the shelf life of microgreens. Certain harvesting and preparation practices can extend the microgreens' storage life. The impact of preharvest calcium treatment on broccoli microgreen quality was investigated. Microgreens that were treated had a 21-day longer shelf life and better quality after harvest [142]. Buckwheat microgreens have been the subject of related study into how to extend their freshness [131]. Microgreens' superoxide dismutase and peroxidase activities were raised, and their biomass production was increased by more than 50 percent after being treated with calcium chloride at a concentration of 10 mM. Due to the treatment, the microgreens now have a longer shelf life and a higher calcium content [144].

Post-harvest methods, which are associated with storage conditions, require precise regulation of temperature and air composition. Therefore, the length of time microgreens can be preserved depends on a number of elements such as temperature, relative humidity, the packaging material used, and the microbial load. There has been a lot of study dedicated to figuring out how to keep products from going bad in storage after they've been harvested. In order to prevent the growth of microbes in the post-harvest stage, chlorinated water is used to wash microgreens in proportions that do not alter the flavor or aroma of the crop. The researchers used chlorine, citric acid, ascorbic acid, and ethanol spray, in varying concentrations and configurations, as disinfectants. Their results showed that a spray of citric acid and ethanol can be used instead of chlorine for washing microgreens [144].

There is a need for more research on the impact of harvest timing, growth stage, and pre-harvest spray applications on the quality and bioactive content of microgreens. The purpose of this study is to determine the optimal photoperiod, intensity, and spectrum for growing microgreens in order to maximize the benefits of the dietary supplement L-carnitine. The mechanism regulating the induction of secondary metabolites production and light signal transduction pathways must be elucidated, and the molecular, physiological, and biochemical responses associated with these alterations must be identified in future studies. Mechanical damage during washing, spinning, and drying reduces the longevity of microgreens. To overcome these limitations, suitable strategies need to be created. Increases in both industrial microgreens production and the development of ready-to-eat packaged microgreens are significantly reliant on improvements in sanitation. Further research is needed to explore the efficacy of various sanitation solutions and the impact of drying methods on quality and shelf-life, but there is an urgent need for effective sanitizers that are alternatives to sodium hypochlorite. Important data for optimizing postharvest handling and developing high-quality ready-to-eat foods is provided by the genetic variation in chilling sensitivity and its interactions with growth stage, storage time, and atmospheric composition. Microgreens' postharvest temperature-light-OTR interactions need to be evaluated so that an O_2/CO_2 balance is achieved that inhibits respiration but avoids the development of off-odor.

Although customers may initially save money by purchasing microgreens from large farms, they may subsequently come to regret this decision due to a drop in quality and a shorter shelf life [145]. Furthermore, rather than preplanning and stocking a larger inventory, it is more practicable for restaurants or brokers to take a call and order fresh microgreens on the spot. If gas costs continue to climb, farmers that are located close to their customers will benefit even more. If you want the freshest, highest-quality microgreens, growing them in your own homes, be it in a room, on a balcony, or on a roof is the best option. Using this method, it's simple to provide your loved ones the health benefits of microgreens. Keeping track of your regular household expenses in this way is simple and

Chickpea Mungbean

Fig. 5. Chickpea and Mungbean microgreens cultivated in lab conditions.

inexpensive. Some of the microgreens cultivated in the laboratory within a week are depicted in Fig. 5.

11. Conclusion and way forward

Microgreens stand out as a notable functional food with the potential to enhance both health and lifespan. Their ease of cultivation at home, coupled with financial benefits, makes them an appealing dietary addition. Visually, texturally, and sensorially diverse, microgreens offer a unique and enriching culinary experience. Their short growth cycles allow for efficient, pesticide-free production, promoting environmental sustainability and garnering acceptance among health-conscious consumers. The ongoing extraction, isolation, and characterization efforts of microgreens in recent scholarly studies indicate a burgeoning field of study, particularly in biomedicine and related industries.

The identified health-promoting components within microgreens, such as glucosinolates, phenolics, flavonoids, vitamins, minerals, and pigments, highlight their potential as a nutritional powerhouse. Overcoming nutritional bottlenecks in conventional breeding, microgreens demonstrate a robust profile, suggesting a higher potential for preventing chronic diseases. Their antioxidant, antimicrobial, anti-inflammatory, anti-diabetic, and anti-cancer properties underscore their versatility in medicinal applications. However, further research is imperative to understand their in vitro and in vivo physiological roles, including cardioprotective, hepatoprotective, neuroprotective, and enzyme inhibitory potentials.

In moving forward, well-designed clinical trials are essential to comprehensively elucidate the impact of microgreens on human health, providing concrete evidence for their health-improving effects. As the exploration of microgreens continues, their promising attributes position them as a valuable subject of study, offering a potential avenue for future advancements in preventive and therapeutic medicine.

Data availability statement

All the data is presented in the article.

CRediT authorship contribution statement

Jafar K. Lone: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Renu Pandey:** Writing – review & editing. **Gayacharan:** Writing – review & editing, Visualization, Validation, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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