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Vertical farming with an emphasis in microgreens: A review

Saeed Nooryan[1*], **Hamid Reza Roosta**[2]

[1, 2] *Department of Horticultural Sciences, Faculty of Agriculture and Natural Resources, Arak University, 38156-8-8349 Arak, Iran.*

Review Article

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ABSTRACT

With the world's population increasing and a large percentage of this population living in urban areas, the need for efficient and low-consumption agricultural methods is becoming more and more necessary. Vertical farming as a solution to the challenges of food security and environmental change, using vertical spaces and controlled environments, by reducing the consumption of various resources, reducing greenhouse gas emissions and environmental pollution of traditional agriculture, while helping the environment, enables the production of agricultural products. Microgreens, which have high amounts of vitamins, minerals and antioxidant compounds, can be used as a new generation of healthy foods and an ideal option for cultivation in vertical systems. Several factors, including the selection of appropriate species, control of the light spectrum (especially blue and red spectra), temperature, humidity, seed density and type of growing medium, affect the growth and quality of microgreens. Along with its advantages, vertical farming faces challenges such as high initial cost, high energy consumption, limited crop yield, gaining consumer trust, and competition with traditional crops. However, technological advancements and further research will help reduce these challenges and expand vertical farming. This article examines the vertical farming system, especially its potential for producing microgreens.

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* Corresponding author: S. Nooryan
E-mail address: saeednooriyan70@gmail.com

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1. Introduction

It is predicted that by 2050, the world population will reach about 10 billion people, of which about 70% will live in urban areas (Naikoo *et al*., 2022; Chowdhury *et al*., 2023; Righini *et al*., 2023). This population growth, especially in cities, will increase the demand for agricultural products to meet food needs. Traditional agricultural methods will not be able to meet this demand. On the other hand, with the expansion of the area under agricultural crops, we will witness adverse environmental consequences in the future (Jowell *et al*., 2017; United Nations, 2017). In this context, the development of sustainable agriculture by providing solutions that ensure food security with minimal damage to the environment is essential (Lada *et al*., 2018).

In recent years, vertical farming systems, which involve growing crops in vertical layers in controlled environments, have been introduced as a promising and more environmentally friendly solution to address food security challenges, with advantages such as optimal use of resources, reduced water consumption, no soil, minimal land use, reduced carbon emissions, and low vulnerability to climate fluctuations (due to controlled environments) (Martin *et al*., 2019; Romeo *et al*., 2018; Kozai *et al*., 2019, van Delden *et al*., 2021). Vertical farming is expanding and is predicted to have an annual growth rate of 25% by 2030 (Jowell *et al*., 2017). The global market value of this system was estimated at $4 billion in 2022 and is predicted to exceed $27 billion by 2030 (Ebert, 2022). This system, in addition to its advantages (superior production in terms of quantity and quality), also allows for the production of fresh food in the vicinity of or even within large cities (Besthorn., 2013). In addition to these, it should be noted that vertical farming is successful when the crops selected for cultivation are pleasing to consumers' tastes, market demand, and economically justified. In particular, plants that require less water reduce production costs and improve profitability. Also, the increasing desire to consume nutrient-rich vegetables has created new opportunities for producers. In the past few decades, microgreens have been considered as a special product with high demand and cost-effective production, which is usually grown commercially in vertical racks and controlled greenhouse conditions. In addition to their high nutritional value, these plants can solve global food security issues. In some cases, their convenient and inexpensive production system justifies their cultivation on large-scale commercial farms, especially to cope with situations such as food shortages or unfavorable weather conditions for production (Rajan *et al*., 2019). Also, after the COVID-19 pandemic, the development of vertical farming of microgreens has accelerated due to the increased interest of consumers in fresh and healthy foods (Ebert, 2022). Although it is possible to grow a wide range of plants in vertical farming systems, issues such as plant height, length of the growing season, and costs have made crops such as leafy greens and microgreens more suitable options than other plants. It has been suggested that plants suitable for this system usually have a short growth period (less than 60 days), limited height, and moderate light requirements (100–300 μmol m^{-2} s^{-1}), which microgreens have (Kalantari *et al*., 2017. Kozai *et al*., 2016).

Several countries have commercially implemented vertical farming, which has been accompanied by positive consumer feedback. A study showed that consumer attitudes in four countries, the United States, the United Kingdom, Singapore, and China, were positive towards vertical farming, especially since the various benefits of this method are aligned with the United Nations Sustainable Development Goals (Ares *et al*., 2021). Vertical cultivation of microgreens has also been carried out commercially in controlled environment farms in places such as Milan, Italy, Riyadh, Saudi Arabia, Maldives in Asia, and Latvia in Europe by various companies, which indicates an increase in the area under cultivation of this system in different climates (www.hydroponicsfactory.com and www.ifarm.fi). Vertical farming has been growing in Europe. The Netherlands (Amsterdam, Eindhoven), Germany (Berlin), Sweden (Stockholm), France (Paris), Italy (Milan), and Belgium (Brussels) are among the pioneers in the exploitation of this system, and other countries such as Switzerland, Norway, Spain, and the United

Kingdom are developing this method (Butturini and Marcells., 2020). Despite the studies conducted, due to the dispersion and lack of case studies of microgreen production in vertical farming, this review was conducted to investigate the potential of vertical farming in the production of microgreens. The main sections of this paper include examining the factors affecting cultivation, economic and social challenges, market acceptance, and related issues in vertical farming systems. This research, while introducing and stating the advantages and challenges of vertical farming, examines whether vertical farming of microgreens can be used as a new method in sustainable agriculture?

2. General understanding of a vertical farming system

The general function of a vertical farming system can be seen schematically in image number one. This image shows the equipment and conditions necessary for success in a controlled cultivation environment (such as a greenhouse or plant factory). Insulated walls (energy conservation), air circulation system, dehumidification system (for recycling and reusing water), cultivation trays on the floor of each floor, artificial lighting from above the products and on each floor (one of the most important necessary equipment), climate control system (temperature and humidity control), carbon dioxide supply tank and nutrient solution tank are the main components of these systems (Vatistas and *et al.*, 2022).

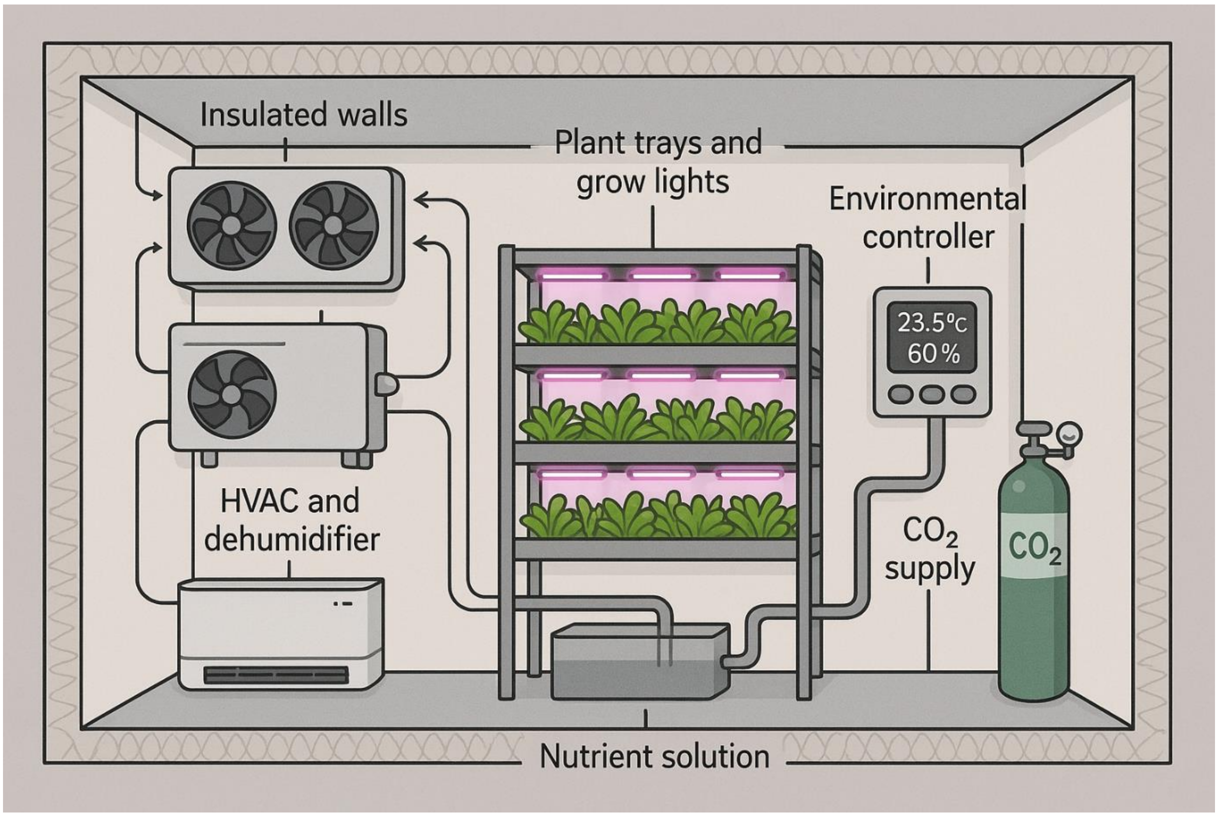


Figure 1. General view of a vertical farming system and its components

3. Benefits of Vertical Farming

3.1. Reducing water consumption

Vertical farming improves water efficiency by using advanced technologies such as hydroponics, aeroponics and aquaponics, which save up to 95% of water (Johnson, 2023). For example, hydroponic systems can reduce water consumption by up to 90% compared to soil farming (Graamans *et al.*, 2018). These systems also allow for precise control over water consumption (Pattison *et al.*, 2018). In addition, closed-loop systems in vertical farming recycle water and nutrients, increasing resource efficiency (Gertphol *et al*., 2018). Vertical farming is a highly efficient solution for growing crops, especially in areas with scarce water or poor-quality water resources (Casey *et al*., 2022).

3.2. Land Use Reduction

Vertical farming reduces land use for crop production in confined urban spaces and areas with scarce arable land (Chen *et al*., 2020). Compared to traditional farming methods, this method achieves higher yields per unit area and reduces the need for extensive agricultural land. This method is particularly useful in urban areas, where the need for large agricultural land is minimized (Barbosa *et al*., 2015; Kulak *et al*., 2013). It also supports crop production in urban environments, independent of climatic conditions or soil use (Van Gerrewey *et al*., 2022). Overall, vertical farming offers a sustainable solution to land scarcity, especially in densely populated urban areas (Carotti *et al*., 2023).

3.3. Contributing to environmental sustainability

To address pervasive challenges such as water scarcity, limited access to energy resources, and environmental pollution caused by traditional agriculture, vertical farming can be considered as a suitable solution. By using closed hydroponic systems in vertical greenhouse cultivation, water consumption is reduced to a great extent compared to traditional cultivation of the same crop, which reduces excessive water withdrawal from underground sources (Wildeman, 2020). In closed systems, this method greatly reduces the negative effects of groundwater pollution by preventing the outflow and waste of fertilizer runoff (Gruda, 2019; Bol *et al*., 2018). In this method, by using and operating intensive and controlled systems, the water and energy consumption pattern is optimized and pollution caused by polluted water runoff and pesticides, which is more common in traditional agricultural systems, is prevented (The United Nations., 2017). Another benefit of this system is the reduction of the distance between farms and local markets, which in turn reduces greenhouse gas emissions from vehicles (Astee and Kishnani., 2010). In fact, by reducing the need to send products to places of consumption and reducing transportation, carbon emissions to the environment are greatly reduced (Kalantari *et al*., 2017; Chaudhry *et al*., 2019). Vertical farming also helps to preserve and sustain the environment by using less land for cultivation, which restores ecosystems and reduces pressure on more agricultural land (Corvalan *et al*., 2005. Despommier., 2010. Muller and *et al*., 2017). Also, by reducing the need for agricultural land, the destruction of pastures and forest lands is reduced, the pressure on natural ecosystems is reduced, and these areas are given more opportunity to recover (Hallikainen, 2018). If properly designed to use renewable energy in these systems, greenhouse gas emissions and their negative impacts on the environment can be significantly reduced and environmental sustainability can be improved (Tuomisto, 2019; Kikuchi *et al*., 2018). In addition, the use of renewable energy sources such as solar and wind energy also reduces greenhouse gas emissions from fossil fuels (Xydis *et al*., 2021; Asgari *et al*., 2024).

3.4. Possibility of using new technologies

Vertical farming maximizes crop yields by using advanced systems such as soilless farming, artificial lighting, use of plant growth-promoting rhizobacteria (PGPRs), controlling climate conditions, increasing plant resistance to biotic and abiotic stresses, and reducing the need for chemical fertilizers (Azizoglu *et al*., 2021). It is possible to cultivate modified crops with characteristics such as low height and fast growth (short growing period) in vertical farming. Finally, the integration of other smart technologies such as the use of artificial intelligence and automation of greenhouses in the cultivation area has made the management of vertical farms much more efficient, which has made and increased its potential for the future of agriculture brighter (Kusuma *et al*., 2020).

3.5. Ensuring Food Security

Vertical farming is a promising solution to increase food security by producing fresh produce year-round in controlled environments such as greenhouses, reducing dependence on seasonal crops and imports (Smith, 2017; Goodman and Miner, 2019). This method is particularly efficient and provides food security in urban areas where agricultural land is limited and transporting food over long distances is more expensive. Using advanced technologies such as agricultural tunnels, vertical farming provides ideal conditions for agricultural production. In these controlled systems, environmental factors such as light and temperature are carefully regulated, allowing the cultivation of high-quality crops all year round, as well as reducing dependence on weather and food imports (Lee *et al*., 2023; Tolentino *et al*., 2021). In this system, by increasing access to fresh, pollution-free and healthy products in urban areas, consumer confidence in purchasing and consuming these products increases, which also improves food security (Liu *et al*., 2016; Kim *et al*., 2015).

3.6. Economic

Vertical farming will not only be defined as a sustainable and innovative way of producing food, because it can help both improve the economy of local areas and provide new jobs in urban areas (Mukherji and Morales., 2010). When a new industry such as vertical farming is formed and developed, it will also help economic development by creating new jobs in the fields of agriculture, technology, marketing and sales and new opportunities will be formed (Al-Kodmany, 2018; Allegaert, 2020). Vertical farming, with its high yield per unit area, can increase the production of some crops by several times compared to traditional farming and conventional greenhouses (Benke and Tomkins, 2017). Since this system is not very dependent on climatic conditions, it is possible to continue crop production continuously throughout the year, and in this case, the reduction in yield due to climate change is minimized. Also, these farms are usually established near their target consumption centers, which can reduce transportation and storage costs and provide fresher products to the consumer (Beacham *et al*., 2019). Also, due to the fact that production is active all year round and is not dependent on climatic conditions in this system, we will see higher production efficiency, which will result in a more stable income for farmers (Katz and Bradley., 2013). Another advantage of this vertical farming system is that it can be cultivated in areas with dense populations or limited resources or adverse climatic conditions (such as urban areas suffering from water shortages or extreme heat), which can be considered as a sustainable economic solution (Pinstrup-Andersen, 2018;). In addition, by increasing access to healthy food in food production systems in controlled environments, price fluctuations caused by resource shortages or climate change are reduced, which ensures greater financial security for production (Healy and Rosenberg., 2013). Overall, and regardless of specific and detailed cases, vertical farming can generally be seen as a cost-effective solution to future food crises by reducing production or transportation costs and increasing productivity (Touliatos and *et al*., 2016).

4. Vertical Farming and Related Techniques

Vertical farming systems, with their efficient use of resources such as water, fertilizers, and occupied space, enable the high-yield production of various crops. These systems operate in a controlled environment (temperature, light, humidity, and CO_2), making more effective use of both horizontal and vertical space while achieving higher productivity, thereby reducing the need for large land areas. Modern technologies such as hydroponics, aeroponics, and aquaponics can enhance production efficiency through precise management of fertilizers and other growth parameters like pH, EC, water quality, etc. Additionally, in enclosed vertical farming environments, artificial lighting (energy-efficient and optimized LEDs) provides adequate light, creating an ideal growth environment for plants. (Specht *et al*., 2019).

Table 1. introduces these technologies along with their advantages and disadvantages.

	Definition	Benefits	Disadvantages	Reference
Hydroponics	The cultivation of plants in a nutrient solution without soil, where minerals are supplied through irrigation water and the solution is recycled.	Preventing material wastage Eliminating soil-borne diseases Improving crop health and quality	High initial cost and capital investment Requires specialized expertise for optimal system management	Savvas, 2003
Aeroponics	Growing plants in the air, where the roots are nourished by a nutrient mist.	Extremely low water consumption Enhanced oxygen absorption by roots	stem vulnerability to technical ures (e.g., interrupted mist w = halted growth) quires precise and continuous nitoring/management	
Aquaponics	The combination of a hydroponic system and fish farming simultaneously.	The natural utilization of fish waste as organic fertilizer for plants.	High capital investment Technical complexities in system design	

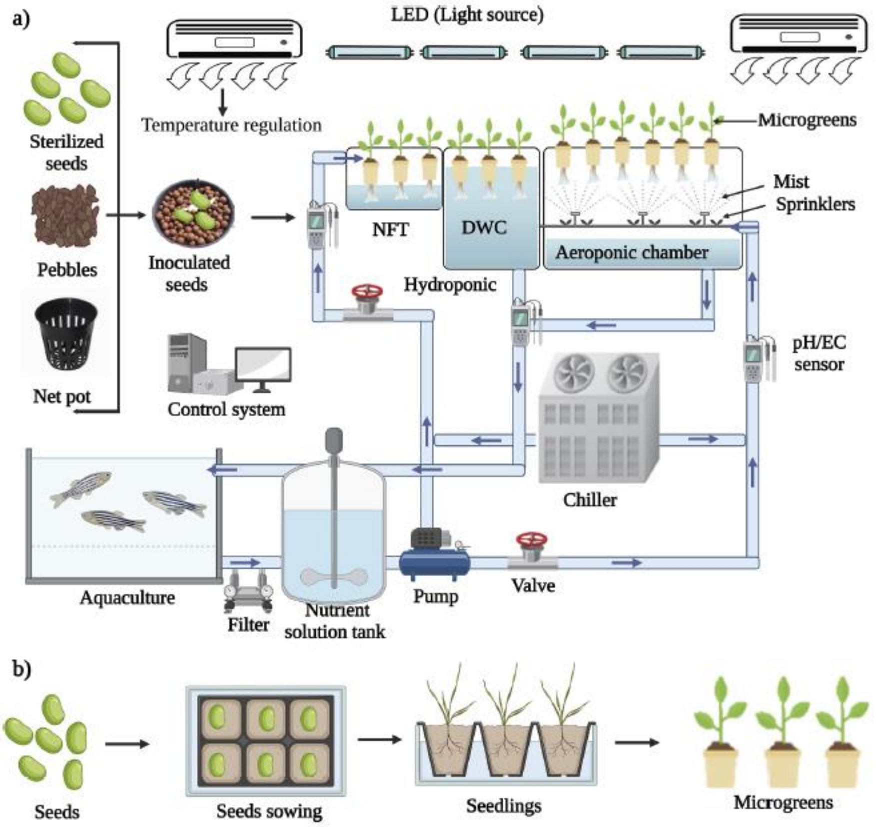


Figure 2. A schematic and general overview of various soilless and soil-based methods that used for cultivating microgreens in greenhouses. a) aquaponic, hydroponic (NFT and DWC), and aeroponic cultivation system. b) soil-based cultivation (Partap *et al*., 2023)

5. Determinants and Efficacy Factors in Vertical Farming of microgreens

5.1. Importance of Microgreens Consumption and Definition

A significant portion of the world's population suffers from malnutrition, with both micronutrient and macronutrient deficiencies evident in their diets (Norman *et al*., 2021; Wells *et al.,* 2019). Adequate intake of diverse nutrients can help combat hidden hunger (Bailey, 2015). Studies show that daily consumption of fruits and vegetables as part of a healthy diet reduces the risk of many diseases. However, only a small portion of the world's population meets the recommended daily intake (LeeKwan *et al*., 2017). On the other hand, excessive consumption of conventionally grown fruits and vegetables, which are produced using chemical fertilizers and pesticides, may pose serious health risks rather than preventing disease. This is due to the heavy dependence on hazardous agricultural chemicals, which gradually endangers the entire food chain (Szpyrka *et al*., 2015; SandovalInsausti *et al*., 2021). Microgreens are considered the next generation of "superfoods" or "functional foods" due to their content of antioxidants, vitamins, minerals and phenolic compounds, which are increasingly in demand for dietary enrichment (Kyriacou *et al*., 2016; Sun *et al*., 2013; Le *et al*., 2020). These nutritious products, which are fresh sprouts of various vegetables, grains, and medicinal plants, are harvested at the early stages of growth (usually 7–21 days after germination) when the sprouted stem and cotyledon leaves are present (Galieni *et al*., 2020) and are recognized as an excellent option for increasing food quality (Treadwell *et al*., 2020). Microgreens have also been introduced as a suitable option for vertical farming due to their high nutritional value, unique and attractive taste, aroma, texture, appearance, and colors for consumers, short growth period, and low space requirement for producers (Xiao *et al*., 2012; Savvas, 2003; Samuolienė *et al*., 2019; FerrónCarrillo *et al*., 2023). These nutrient-rich sprouts contain a higher percentage of phytonutrients (including ascorbic acid, beta-carotene, alpha-tocopherol, and phylloquinone) and minerals (such as calcium, magnesium, iron, manganese, zinc, selenium, and molybdenum) than mature leaves. At the same time, their nitrate content is significantly lower, making them an excellent source of essential minerals for all age groups (Pinto *et al*., 2015).

5.2. Factors Affecting Microgreen Cultivation

5.2.1. Soilless Cultivation

Studies have shown that hydroponic systems such as NFT (Nutrient Thin Film Technique) and DWC (Deep Water Cultivation) are suitable for the production of some microgreens. Microgreens produced in this system also had a higher nutrient content, although some other varieties performed better in soil cultivation (Tan *et al*., 2020). In a study that compared two vertical cultivation methods (multi-level hydroponics) and horizontal (ebb *and* flow) methods for cultivating microgreens, the results showed that the vertical system performs better due to the optimal use of vertical space and better control of environmental conditions such as light and temperature. It has been reported that in the vertical system, the increase in production per unit area was even up to ten times compared to the horizontal system, which makes it possible to cultivate microgreens in urban environments (Al-Chalabi, 2015;). However, there are also problems such as bacterial contamination in these systems that require more careful management (Xiao *et al*., 2014a).

5.2.2. Choosing the right plant for cultivation

Different varieties of microgreens have different growth requirements, and these differences indicate that choosing the right species for commercial cultivation is very important. In one study, four different plants, red basil, red radish, chickpea, and sunflower, were investigated for microgreen cultivation, and the results showed that the growth period and nutritional requirements of these plants differed. For example, red basil required 27-31 days to grow, while red radish was ready for harvest after 7 days from sowing. It was also observed that in sunflower, the seed coat needed to be removed manually to prevent uneven growth of microgreens. (Xiao *et al*., 2012).

5.2.3. Light

Light plays a very important role in the growth, photosynthesis, color, flavor, and secondary metabolites of microgreens, such that different light spectra can increase the content of compounds such as anthocyanins, phenols, and vitamins. A study showed that blue and red light increased anthocyanin and phenolic compound content in amaranth microgreens, respectively (Alrifai *et al*., 2021). Today, LED lighting systems are considered an efficient solution in controlled cultivations such as greenhouses. A very practical advantage of this technology is the ability to precisely adjust the parameters of intensity, quality, and duration of light radiation, which is of particular importance. Due to advantages such as appropriate energy efficiency, small size, long lifespan, and reduced heat emission to the environment, LEDs can be said to be a more environmentally friendly option for greenhouse plant cultivation by reducing energy consumption (Azizi *et al*., 2024). In controlled environment vertical farming systems, artificial light replaces sunlight. Traditional lamps such as high pressure sodium (HPS) and metal halide (MH), although functional, have disadvantages such as excessive heat generation, low energy efficiency, and high maintenance costs. These advantages of LED technology, as previously stated, make it a superior option in vertical farming. Research has shown that LED lighting can greatly increase the concentration of compounds such as vitamins C and E and phenolic compounds in microgreen crops. Blue and red light primarily affect vegetative growth, while far-red and infrared light affect germination and flowering (Singh *et al*., 2015; Nishio *et al*., 2000).

Various studies have shown that the combination of blue and red light in the PAR range (400-700 nm) provides the highest photosynthetic efficiency. However, in the experiment, it was found that light intensities (330-440 μmol m^{-2} s^{-1}) increased antioxidant compounds in Brassica microgreens. The optimal light intensity for microgreens is between 200 and 500 μmol m^{-2} s^{-1}, and the blue and red light spectrum can affect the accumulation of bioactive compounds (Brazaityte *et al*., 2015). The effect of light intensity on the growth and biochemical compounds of microgreens has been investigated in various studies. In a study, it was shown that the use of an LED system with blue, red and infrared spectra can increase antioxidant compounds, phenols and carotenoids in soybean microgreens. Also, a light intensity of 100-400 μmol μmol m^{-2} s^{-1} was suggested for optimal growth and nitrate reduction (Zhang *et al*., 2020). In another experiment, by examining three levels of light intensity (120, 160 and 210 μmol μmol m^{-2} s^{-1}), it was observed that high light intensity (210 μmol μmol m^{-2} s^{-1}) increased dry weight and dry matter percentage, and low light intensity (120 μmol μmol m^{-2} s^{-1}) led to an increase in hypocotyl length and cotyledon area in Brassica species. The pigment content in microgreens is also affected by light intensity. Medium light intensity (160 μmol μmol m^{-2} s^{-1}) increased the green color in green cabbage and kale cultivars, and low light intensity enhanced the purple color in red mizuna microgreens. On the other hand, high light intensity (210 μmol μmol m^{-2} s^{-1}) increased the total phenolic content and antioxidant capacity in most Brassica species.

Morphological studies showed that low light intensity increased hypocotyl length in all species, while high light intensity decreased this parameter (Flores *et al*., 2024). In green cabbage, high light intensity resulted in an increase in total phenolic content compared to low light intensity. This increase may be due to the stimulation of secondary metabolite biosynthesis pathways under light stress. Also, in some species, such as red mustard, moderate light intensity had the greatest effect on increasing antioxidant capacity (Zhang *et al*., 2019). In red cabbage, low light intensity increased fresh weight yield, while high light intensity improved dry weight and dry matter. Low light intensity also resulted in an increase in chlorophyll a and b content in most species, while high light intensity decreased these pigments, which is consistent with previous findings that chlorophyll is degraded under intense light (Jones-Baumgardt *et al*., 2019). Different species have shown different responses to light intensity; in green cabbage, high light intensity increased total phenolic content, probably due to stimulation of secondary metabolite biosynthesis pathways under light stress, while in red mustard, moderate light intensity had the greatest effect on antioxidant capacity (Zhang *et al*., 2019).

In an experiment to investigate the effect of light combinations on chrysanthemum flowers, the highest photosynthesis rate was recorded under combined red (650 nm) and blue (440 nm) light, and the lowest photosynthesis rate was recorded under blue-far-red (720 nm) and blue light alone. It was noted that although the combination of red and far-red light may increase stem length, it can also reduce stem strength and thickness (Kim *et al*., 2004). In another study on lettuce, combined blue-red light increased the synthesis of anthocyanin compounds, increased protein content, and increased phenylalanine ammonia lyase (PAL) activity (Heo *et al*., 2012). Research on basil microgreens also showed that blue light increased cotyledon area, fresh weight, chlorophyll, and anthocyanin content. It is interesting to note that the synthesis of phenolic compounds and antioxidant activity in green basil was maximized under red light and in red basil under blue light (Lobiuc *et al*., 2017). In lettuce, the use of blue LED light with an intensity of 238 μmol m^{-2} s^{-1} increased biomass and photosynthetic parameters compared to a light intensity of 80 μmol/m2/s. This increase is likely due to the regulation of chloroplast proteins under the influence of blue light (Muneer *et al*., 2014). Also, in radish microgreens, carotenoid accumulation was maximized in the range of 330–440 μmol m^{-2} s^{-1}, while mustard microgreens showed the best growth in the range of 110–220 μmol m^{-2} s^{-1} (Brazaitytė *et al*., 2015). Boletus microgreens produced optimal antioxidant levels and reduced nitrate content under moderate light intensities (330–440 μmol m^{-2} s^{-1}) (Viršilė *et al*., 2013). In terms of energy consumption, lettuce grown under red-blue LED light (95% red, 5% blue) showed a 50% reduction in energy consumption per unit dry biomass compared to traditional lighting methods (Poulet *et al*., 2014). In another study, the effect of four types of LED light (white, red-blue hybrid, monochromatic red, and monochromatic blue) on lettuce growth in a greenhouse was investigated. The results showed that white light and the red-blue hybrid had the greatest effect on lettuce growth and photosynthetic characteristics (Soufi *et al*., 2024). Studies on basil and strawberries have also confirmed that LED technology not only increases biomass yield and antioxidant content, but also produces lower nitrate levels in plants compared to fluorescent lamps. In these studies, a red-to-blue light ratio of 0.7 was identified as the optimal conditions for balanced growth and optimal nutritional properties (Piovene *et al*., 2015). Although the red-blue light combination has been shown in most studies to improve photosynthesis and growth of microgreens, the ideal spectral ratio and intensity for maximum efficiency have not yet been fully determined and more research is needed in this area (Poulet *et al*., 2014; Piovene *et al*., 2015).

5.2.4. Temperature and Humidity

The need for adequate research on the effects of temperature, carbon dioxide, and humidity on growth has been emphasized in order to achieve the best growth performance and production of microgreens (Hatfield *and* Prueger, 2015). In a study on the growth of broccoli microgreens, the appropriate temperature was recommended between 18 and 24 ° C and a relative humidity of 60%. It should be noted that humidity below 40% may cause wilting, and humidity above 80% increases the risk of mold and bacterial growth (Kou *et al*., 2013). In another experiment, the appropriate temperatures for germination and growth of basil microgreens were reported to be between 20 and 24 ° C and a relative humidity of about 65% (Rusu *et al*., 2021). In one study, environmental conditions including 20°C, 60-70% relative humidity, pH of irrigation water 5.8-6, and EC 1.0-1.2 dS/m were adjusted to improve germination, uniform plant growth, and high-quality microgreen production. This suggests that precise control of environmental factors in indoor cultivation systems allows for high-quality crop production throughout the year (Nicola *et al*., 2020). It was also stated that environmental conditions including 95-98% relative humidity and 18-20°C resulted in uniform germination and rapid growth of lettuce seedlings (Oh *et al*., 2010).

5.2.5. Seed Density and Cultivation

Seed density is a key factor in optimizing resource utilization, including space, water, and nutrients. Studies show that the optimal seed density for different microgreen species is different. For example, a density of 100–120 g/m2 is recommended for sunflower, chickpea, and corn, 60–70 g/m2 for mustard, broccoli, and red cabbage, and 50–60 g/m2 for dill, basil (equivalent to approximately 21,700 plants/m2 for basil), and areola (Huang *et al*., 2016). High seed density can lead to competition for resources and reduced crop quality, while low density may reduce yield. It has been shown that seed density and seed treatment methods such as priming (soaking seeds in chemicals or water) can affect germination and growth of microgreens. Studies have shown that matrix priming (using vermiculite) can increase germination and shoot weight by up to 2.79 times. Also, appropriate seed density (such as 109 g of seeds per cell for radish) can improve fresh yield of microgreens (Hoang *and* Thuong, 2020). Although increasing seed density can reduce the weight of each plant, it can also increase overall yield (Palmitessa *et al*., 2020). In a study of onion, high planting density in a floating hydroponic system was associated with improved leaf area index, fresh weight of stem and root, and increased fresh and dry biomass per square meter, suggesting it as an ideal option for vertical cultivation. This method could be beneficial for onion growers due to the possibility of early harvest for better marketability (Mousavi *et al*., 2025).

5.2.6. Nutrition and nutrient solutions

Changing the composition of nutrient solutions can affect the mineral and phytochemical content of microgreens for optimal growth. For example, reducing or eliminating potassium from the nutrient solution allows the production of low-potassium microgreens, which is suitable for the diet of kidney patients (Renna *et al*., 2018; Pannico *et al*., 2020). The use of balanced nutrient solutions, such as half-strength Hoagland solution, plays a key role in providing essential elements and improving product quality. Research shows that growing microgreens in coconut fiber media is associated with a significant reduction in nitrate, indicating a positive effect of this media on optimal nutrient uptake (Di Gioia *et al*., 2016). The nutrient solution should contain balanced amounts of macro and micro elements. The recommended N-P-K ratio is usually considered to be 2-3-3%, and its periodic replacement prevents nutrient deficiencies (Rusu *et al*., 2021). Adjusting the electrical conductivity (EC) in the range of 1.2 to 1.8 mS/cm prevents osmotic stress and maintaining the dissolved oxygen concentration in water above 6.5 mg/L helps in optimal root development and reduces the growth of pathogens (Yang *and* Kim, 2020). The nutritional requirements of plants depend on the species, growth stage and environmental conditions. In soilless culture, Hoagland solution (1938) is known as a balanced source of nutrients, and insufficient concentrations can lead to deficiency or toxicity (Savvas *et al*., 2003). Microgreens use seed reserves in the early stages of growth, but quickly become dependent on external nutrition. Studies have shown that the use of 25% Hoagland solution from the fifth day of cultivation is sufficient for Brassica species, in the case of kale and lettuce, the commercial solution of 0.4% FloraGro from the seventh day gives good results (Gerovac *et al*., 2016; Weber, 2016). Also, maintaining the pH of the solution in the range of 6 to 6.8 is essential for optimal nutrient uptake.

5.2.7. Type of growing medium

Growing mediums, as the place where plants are established, play a fundamental role in their growth, and choosing the right medium depends on the needs of the plant. Organic media can reduce the need for fertilization by retaining moisture and providing nutrients, while mineral media such as perlite or sand help improve ventilation and drainage. A balanced combination of these media can yield favorable results (Roosta *et al*., 2024). As mentioned, the growing medium plays an important role in the germination and growth of microgreens. In a study comparing peat and perlite media (70/30) with cellulose, it was shown that the combination of peat and perlite improved the germination and growth of plants. For example, the germination of red basil in this medium reached 90%, while in cellulose it was only 80%. This difference may be due to the better ability of peat and perlite media to retain moisture and exchange air (Murphy *and* Pill, 2010). For successful plant cultivation, the use of porous and non-toxic growing media such as rock wool, perlite, pumice, expanded clay, polyurethane foam and coconut fibers has been recommended (Savvas, 2003). In tropical regions such as Thailand, cost-effective alternatives such as coconut fiber dust, sugarcane filter cake and vermicompost have been introduced as growing media, which in addition to being low in cost, have low levels of microbial contamination (Muchjajib *et al*., 2015). In addition, new substrates such as biostrata (a combination of biopolymers and natural fibers) have been developed as a lightweight and recyclable option for hydroponic cultivation of microgreens, although further research is needed to evaluate their performance. The use of fiber mats in special trays, especially in the Nutrient-Filled Technique (NFT) system, is also common (Treadwell *et al*., 2010). Studies emphasize that the growing medium has a significant impact on the quality of microgreens and can affect yield, dry matter percentage and nitrate concentration (Di Gioia *et al*., 2017).

5.2.8. Cultivation containers

Microgreens are usually grown in open plastic trays, which exposes them to environmental pollutants and requires repackaging after harvest, increasing costs. Vertical farming in closed containers overcomes this problem by ensuring gas exchange, light penetration, light transport and market-ready packaging. Studies have used a variety of containers, including 0.5-liter peat-filled pots for brassicas (Brazaitytė *et al*., 2015), grooved trays (28 × 54.5 cm) with soilless mix for red cabbage and arugula (Berba and Uchanski, 2012), clear boxes (14 × 14 × 8 cm) with peat soil (2:1) for basil (Lobiuc *et al*., 2017), and 5-inch hydroponic pads for lettuce and kale (Weber *et al*., 2016). Challenges such as moisture accumulation in closed systems can be reduced by UV sterilization (15 min) and the creation of micro-holes for gas exchange, which leads to reduced repackaging costs.

5.2.9. Biological factors

Elicitors are molecules that activate plant defense responses and increase the production of secondary metabolites. The use of abiotic elicitors such as methyl jasmonate and jasmonic acid can increase the content of phenolics and glucosinolates in microgreens. Also, physical factors such as UV light and nanoparticles can also affect the production of antioxidant compounds and these methods are promising for improving the nutritional quality and medicinal value of microgreens (Baenas *et al*., 2016).

5.2.10. Harvesting time

The harvesting time of microgreens is usually 7 to 21 days after cultivation and germination, depending on the variety, and the height of the plants is approximately 5 to 6 cm. The optimal harvesting time preserves the nutritional composition and flavor of the product. Harvesting in the morning and storing at -20 ° C can improve the quality and shelf life of microgreens (Noichinda *et al*., 2007). Freeze-drying of samples is recommended to preserve bioactive compounds such as carotenoids. Also, timely harvesting prevents excessive nitrate accumulation (Saini *and* Keum, 2018).

5.2.11. Post-harvest conditions

Microgreens are susceptible to various microbial contaminations due to their short growth period (7-21 days). Indicative bacteria such as E. coli and pathogenic fungi such as Pythium, which are mainly transmitted through contaminated seeds, irrigation systems or inappropriate moisture conditions, pose problems (Riggio *et al*., 2018; McGehee *et al*., 2019). The use of biological control agents such as Trichoderma biofungicides, along with adherence to hygiene principles in the cultivation environment, can be effective in controlling these contaminations. Also, disinfecting seeds with 80% ethanol and deionized water before cultivation greatly reduces the risk of contamination transmission (Tavan *et al*., 2021). Research shows that storage at 4°C with low-oxygen packaging can increase the shelf life of microgreens. Also, washing the product with compounds such as chlorine or organic acids (such as ascorbic acid) is effective in reducing the microbial load, although safety and health considerations for consumption should be examined and studied (Yan *et al*., 2022). The use of UV light and blue light systems in hydroponic environments have also been suggested as complementary methods for controlling microbial contamination. Given the possibility of transmission of contamination from seeds to edible parts of the plant, sanitary management at all stages of production from cultivation to harvest seems essential. (Kim *et al*., 2016).

In Figure 3, images of sample microgreen products are shown. Also, table 2 shows images of various microgreen samples at different growth stages.

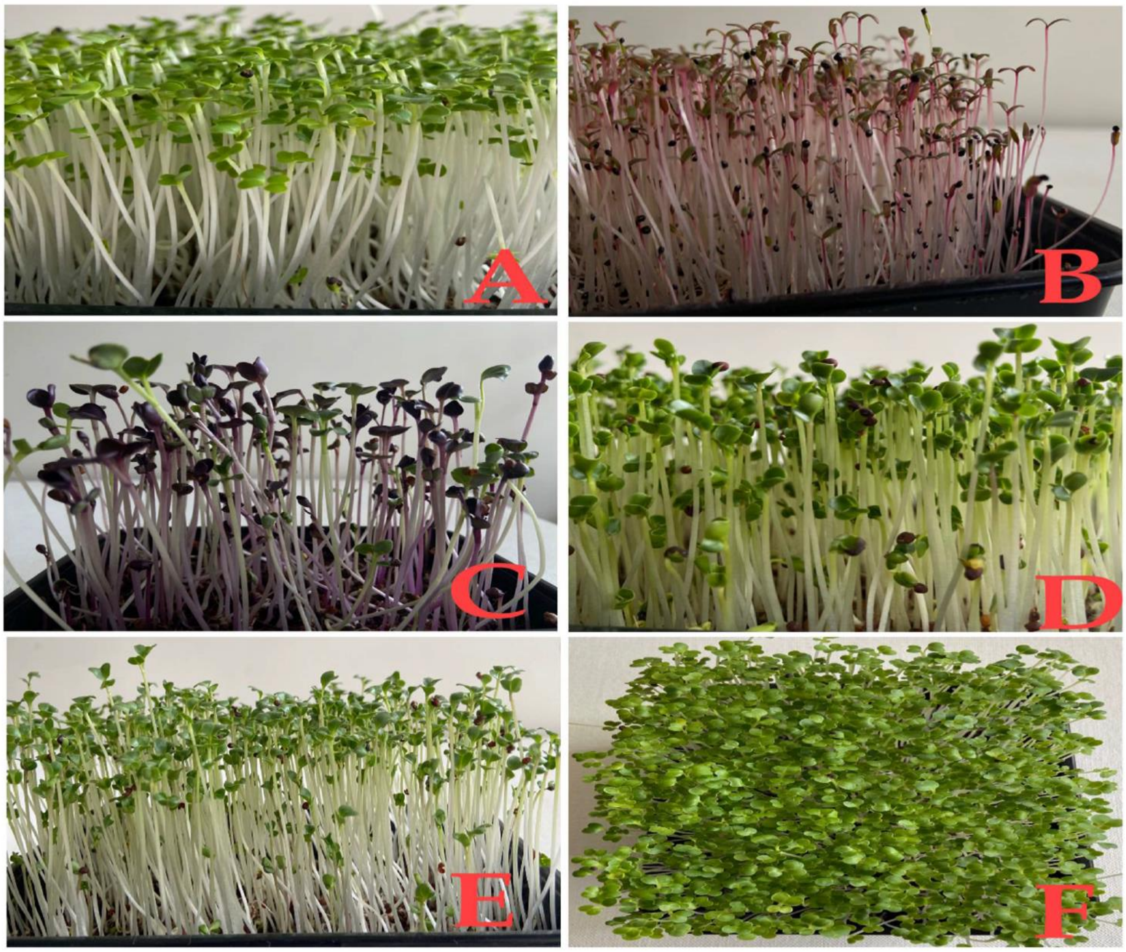
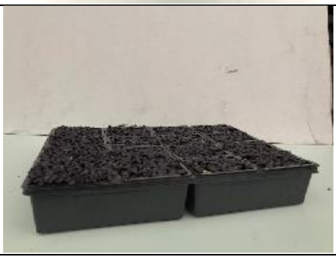


Figure 3. (A) Bokchoy, (B) Red amaranth, (C) Purple radish,(D) Kale, (E) Broccoli, and (F) Bokchoy (Bhaswant *et al*., 2023)

Table 2. Images of various microgreens (Ciuta *et al*., 2020)

scientific name of the plant	**Newly germinated**	**4 days after germination**	**7 days after germination**
Raphanus sativus			
Ocimum basilicum			

Pisum sativum			
Helianthus annuus			

5. Challenges in vertical agriculture

Vertical farming faces several challenges, including high energy consumption, the need for high initial financial investment, limitations in the variety of crops that can be cultivated, and the high cost of products. These factors have limited the expansion of this agricultural method (Pinto *et al*., 2015; Avgoustaki and Xydis, 2020).

One of the main challenges facing the vertical farming industry is the financial aspect of these systems. The initial cost of setting up a vertical farm can be several times higher than that of a state-of-the-art greenhouse. In addition, the ongoing costs are also very high, and it is estimated that in some cases they may cost two to five times more to operate than commercial greenhouses (Rabobank, 2018). For example, this has led to high production costs for crops such as lettuce, which are about twice the price of the same crop in traditional greenhouses. These high costs have made it difficult to justify the economic feasibility of producing crops in these systems (Benis and Ferrao, 2018). There have been reports of financial failures of start-ups in the vertical farming industry, for example in the Netherlands and Sweden, which have led to the closure of these centers (Sijmonsma, 2018, 2019). This financial challenge has arisen even for relatively successful companies, indicating that business models in this industry may not yet be fully realized and require more sustainable planning and investments (Nils, 2018).

Energy consumption in vertical farming systems, especially in the areas of lighting (providing sufficient light for growth by electric lights) and climate control, is high and sometimes very high. Meanwhile, larger facilities can be more cost-effective than small units due to the reduced relative energy footprint and the spread of production costs. Of course, these systems require a skilled workforce due to their advanced information technologies and automation, which should also be considered (SharathKumar *et al*., 2020; Delorme *et al*., 2022). High energy consumption is one of the biggest challenges of vertical farming. This is especially evident in the provision of artificial light. Studies show that European greenhouses are currently comparatively more energy efficient than vertical farms (Graamans *et al*., 2018). This is largely due to the high and critical use of artificial lighting systems in vertical farms, which accounts for a significant portion of the costs and energy consumption. Also, the environmental sustainability of these systems, depending on where and how the required energy supply is sourced, is still a matter of debate and requires further study (Stanghellini *et al*., 2019).

In terms of obtaining organic certification in the European Union in recent years, products produced by vertical farms have not been able to qualify. This can reduce the attractiveness of consuming vertical crops for some consumers in some countries (European Commission, 2008). On the other hand, high competition in marketing between vertical crops and advanced greenhouses in Europe (especially in countries such as the Netherlands), which have been able to market their products at a lower price due to their strong relationship with distribution networks and high production efficiency, has been another factor limiting supply. This makes vertical farms look specifically at producing high-value-added products or niche markets in order to survive in their target market. Most vertical farms in Europe are still engaged in producing specific and limited products, and for example, growing products with high financial value and demand such as tomatoes or strawberries that require more space, light and a longer period of time for production is not yet fully justified from an economic perspective (Den Besten, 2019).

In fact, the development of this technology has faced the previously mentioned obstacles such as high initial costs, high urban land prices, labor costs, and competition with the cost of traditional products, which are generally cheaper. For vertical farming to become a common and widespread method in agriculture, increasing its economic profitability will be essential (Gan *et al*., 2023; Wang *et al*., 2023).

Since this vertical farming system uses different equipment and methods, it also requires more management. For example, managing hydroponic systems and maintaining the balance of nutrients in nutrient solutions are very important because an imbalance of nutrients leads to a decrease in the quantity and quality of products. It is also important to control the root part. The accumulation of toxic compounds produced by the roots and the rapid spread of destructive infectious diseases in closed systems are other technical problems. This suggests that selecting an appropriate growing medium and engineering the root microbiome that can significantly improve plant performance requires more attention and knowledge (Sambo *et al*., 2019; Grunert *et al*., 2016). However, even if energy issues are managed and prices reach competitive levels for market entry, a fundamental question remains: how will consumers react to producing a significant portion of their food in closed, controlled environments? (Willet *et al*., 2019). Other issues such as the use of robots, cybersecurity risks, reduced employment opportunities in rural areas, and lack of transparency in labeling are also relevant, although they seem to be less important than previously expressed concerns (such as energy consumption and high costs of vertical farming products) (Jager *et al*., 2023).

Conclusion

Vertical farming is a new, scientific and practical solution that addresses structural challenges and barriers such as water scarcity, land use reduction and environmental sustainability for sustainable agricultural production, as well as microgreen production. This review shows that vertical farming systems have a very acceptable performance with the ability to optimize resource use, improve product quality and allow for continuous production throughout the year, especially for the cultivation of microgreens, which are desirable and healthy in terms of edible properties. Factors such as soilless cultivation, the use of optimal light spectra using LED technology and controlled environmental conditions have had a great impact on increasing production efficiency and nutritional value of products. These benefits are in line with the increasing consumer demand for fresh and healthy products in societies and have strengthened the potential of vertical farming in ensuring food security in urban areas.

It should be noted that the development of vertical farming for the cultivation and exploitation of microgreens faces further obstacles such as high initial investment costs, high energy consumption, and limited crop diversity. Of course, despite these obstacles and challenges, the efficiency of this system in producing valuable products in controlled environments has made it a viable method in line with sustainable agricultural policies. The need for further research and case studies to improve technologies, reduce costs, and increase market acceptance is certainly emphasized. From all the studies, it can be concluded that the development of vertical farming of microgreens, if these challenges are well investigated and resolved, can be proposed as a transformative approach in sustainable agriculture.

Conflict of interest

The authors have no conflicts of interest.

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