Review

Some Emerging Opportunities of Nanotechnology Development for Soilless and Microgreen Farming

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Abstract: Global food demand has increased in tandem with the world’s growing population, prompting calls for a new sustainable agricultural method. The scarcity of fertile soil and the world’s agricultural land have also become major concerns. Soilless and microgreen farming combined with nanotechnology may provide a revolutionary solution as well as a more sustainable and productive alternative to conventional farming. In this review, we look at the potential of nanotechnology in soilless and microgreen farming. The available but limited nanotechnology approaches in soilless farming include: (1) Nutrients nanoparticles to minimize nutrient losses and improve nutrient uptake and bioavailability in crops; (2) nano-sensing to provide real-time detection of pH, temperature, as well as quantifying the amount of the nutrient, allowing desired conditions control; and (3) incorporation of nanoparticles to improve the quality of substrate culture as crop cultivation growing medium. Meanwhile, potential nanotechnology applications in soilless and microgreen farming include: (1) Plant trait improvement against environmental disease and stress through nanomaterial application; (2) plant nanobionics to alter or improve the function of the plant tissue or organelle; and (3) extending the shelf life of microgreens by impregnating nanoparticles on the packaging or other preservation method.

Keywords: agricultural nanotechnology; sustainable agriculture; soilless farming; microgreen farming; nutrient solution; substrate culture

1. Introduction

According to the United Nation (UN) Food and Agriculture Organization (FAO), as of 2018, the world’s agricultural land area covered approximately 36% (4.80 billion ha) of the world’s land surface (13.4 billion ha) [1]. Over a decade, the area was reported to have decreased by 0.4% (4.82 billion ha). The top five countries with the most agricultural land area are the USSR, China, Australia, the United States of America, and Brazil, with 0.55 billion ha (11%), 0.47 billion ha (10%), 0.45 billion ha (9%), 0.42 billion ha (9%), and 0.21 billion ha (4%), respectively [2]. Furthermore, although Malaysia has only 0.86 million hectares of agricultural land, it contributed significantly to world economical crops; oil palm and rubber [3]. The United Nations, on the other hand, predicts that the world’s population will reach 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100 [4]. The increased demand for food caused by the world’s growing population has resulted in a decrease in global agricultural land area per capita over time. Another issue to consider is soil health and fertility, which is the foundation of conventional crop cultivation. Climate change,
unsustainable agricultural practices, and overgrazing have all had a negative impact on soil health and fertility [5]. The most concerning aspect is that according to the FAO’s representative at the 2014 World Soil Day forum, the world’s top soil could be depleted within 60 years, and roughly one-third of the world’s soil has already been degraded [6]. It was also reported that producing just 3 cm of topsoil could take a whopping 1000 years. As a result, we are urging for a new sustainable approach to meeting an increasing population’s food demand, ensuring global food security, and addressing the soil degradation problem.

Moreover, the report of the EAT-Lancet Commission, published in early 2019, reignited debate about the sustainability of the global food system [7]. According to the report, “the existing global food system necessitates a new agricultural revolution focused on sustainable intensification and powered by sustainability and system innovation”. Rapid advances in knowledge about the use of nanotechnology in agriculture will be required to provide the necessary innovation for a significant leap forward in the efficiency of agricultural crop fertilization techniques.

2. Soilless Farming
2.1. Definition and Types of Soilless Farming

The literal definition of soilless farming is crop cultivation without the use of soil. The soil is used as a medium in conventional farming to provide an essential nutrient to the crops via the root. In soilless farming, the same essential nutrients are pre-mixed in the water reservoir (also known as the aerated nutrient solution (Figure 1)) and efficiently delivered to the root, along with other controlled conditions (i.e., high levels of oxygen, suitable temperature, and pH, etc.). Hydroponic, aquaponic, and aeroponic are the three most common types of soilless farming of aerated nutrient solutions. The cultivation of crops using porous substrate culture as a growing medium instead of natural soil is also another type of soilless farming (Figure 1).

![Figure 1. A basic illustration of types of soilless farming and its advantages.](image-url)
2.1.1. Aerated Nutrient Solution

Hydroponics is a type of horticulture method that uses an aqueous solvent to grow plants, typically crops, without soil by utilizing mineral nutrient solutions and high oxygen supplies. Among the most common hydroponically grown crops are tomatoes (*Solanum lycopersicum* L.), lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L.), strawberries (*Fragaria ananassa* L.), cucumbers (*Cucumis sativus* L.), melons (*Cucumis melo* L.), eggplant (*Solanum melongena* L.), peppers (*Capsicum annuum* L.), and herbs (e.g., basil (*Ocimum basilicum* L.), cilantro (*Coriandrum sativum* L.), rosemary (*Rosmarinus officinalis* L.), etc.) [8]. Several hydroponic techniques have been introduced for optimal growing conditions, such as:

- **Deep water culture (DWC):** the most basic hydroponic method, which involves floating a plant on a recirculating solution of well-oxygenated nutrients via a floating platform (i.e., styrofoam).
- **Wick system:** the simplest hydroponic system in which a wick (bundle of fiber) connects and transports nutrients from the water reservoir to the crop’s growth pot/tray.
- **Nutrient film technique (NFT):** A pump continuously delivers an oxygenated nutrient solution to the root of the crop’s growth pot/tray. Suitable for crops with a small root mass (i.e., herbs, strawberries, and lettuce).
- **Drip system:** A pump continuously delivers an oxygenated nutrient solution to the stems of crops in an individual growth tray/pot. Appropriate for large root masses i.e., squash (*Cucurbita maxima* Duchesne), melon, and tomato.
- **Ebb and flow systems:** an oxygenated nutrient solution is flooded into a tray containing a single crop growth pot. Ideally suited for fruiting crops.

Aeroponics is a method of growing plants in an atmosphere of air or mist without the use of soil or an aggregate medium. In this system, a fine mist of nutrient solution from the reservoir nutrient solution is sprayed every few minutes into the sealed root chambers that hang in the air.

Aquaponics is a hybrid of aquaculture, which produces fish and other aquatic creatures, and hydroponics, which produces plants without the use of soil. Aquaponics combines the two in a symbiotic relationship in which the discharge or waste of marine animals is fed to plants.

2.1.2. Soilless Substrate Culture

Another method of soilless farming is to replace the soil with other substrate cultures as a growing medium in crop cultivation. Organic substrate culture (pine (*pinus* spp.) bark, rice (*Oryza sativa* L.) husk, sawdust, wood chips, coconut (*Cocos nucifera* L.) coir, fleece, grape (*Vitis* spp.) marc, sugar cane (*Saccharum officinarum* L.) fiber, peat, etc.,) and inorganic substrate culture (perlite, glass wool, clay, gravel, sand, rock wool, zeolite, vermiculite, hydrogel, etc.,) can be used for this purposes [9]. Some of the substrates are biowaste from agricultural industries; thus, using these substrates as a substitute for soil could be one method of utilizing the abundance of agricultural residue or biowaste. For example, Atif Riaz et al. reported the use of four agricultural wastes for daisy (*Gerbera jamesonii* Adlam) cultivation, including coconut coir dust, farm yard manure, leaf compost, and local compost (Lahore) [10]. The four substrates medium in combination with silt outperforms the conventional medium in terms of plant growth and flower quality, indicating its high potential for use in daisy production. In another study, a mixture of 50% spent mushroom waste and 50% peat moss with NPK fertilizer supplementation increased Kailaan (*Brassica oleracea* var. *Alboglabra*) productivity [11]. At a dose of 4 kg m$^{-2}$, a mixture of two types of spent mushroom waste from *Agaricus subrufescens* and *Pleurotus ostreatus* showed promising results for arugula (*Eruca vesicaria* L.) and lettuce cultivation [12]. Substrates of vermicompost, compost, and anaerobic digestion in sage cultivation show no significant difference in terms of chemical composition, yield, and essential oil composition when compared to peat cultivation [13]. The oyster mushroom was grown in four different
substrates: baobab (*Adansonia digitata* L.) fruit shell, wheat (*Triticum aestivum* L.) straw, sawdust, and maize (*Zea mays* L.) cobs, with the following yields: sawdust (682 g) > wheat straw (594 g) > maize cobs (518 g) > baobab fruit shell (482 g) [14].

### 2.2. Soilless Farming versus Conventional Farming

Conventional farming is well-known for requiring a large amount of water, a large amount of land, and a high nutrient intake. Crops are also more likely to be infected by soil-borne diseases as a result of cultivation, which also degrades the soil [15]. Due to the use of nutrient-rich water instead of soil for crop nourishment, aerated soilless farming allows for the conservation and efficient use of water and nutrients. Several studies have been published on the water use efficiency (WUE) of crops grown in soilless cultivation versus soil cultivation [16]. For example, crop water requirements for hydroponically grown peppers, strawberries, tomatoes, lettuce, and spinach are 58, 136, 35, 1.6, and 8.3 L kg\(^{-1}\), respectively, whereas crop water requirements for soil cultivation are 110, 544, 78, 76, and 106 L kg\(^{-1}\) [17–20]. Water conservation in crops grown in aerated soilless cultivation ranges from 2 to 48 times that of soil cultivation. El-Sayed et al. reported in another study that the water consumption of sweet pepper cultivates in substrate culture of straw and perlite required less water, at 207 and 230 L/m\(^3\), respectively, compared to soil cultivation at 315 L/m\(^3\) [21]. Van Ginkel et al. reported a comprehensive comparison of conventional vs. hydroponically vs. aquaponically grown leafy greens (i.e., lettuce, cabbage (*Brassica oleracea* L.), arugula, sunflower (*Helianthus annuus* L.), etc.), where hydroponic and aquaponic cultivation required 66 and 8 times less water consumption, respectively than conventional cultivation [19]. The authors also reported that conventional cultivation requires double the nitrogen, which could be due to nitrogen loss in the runoff, resulting in eutrophication downstream.

Crops grown in aerated soilless farming are known to produce higher yields and quality than conventional farming. This is due to the controlled environment provided by soilless farming, which includes nutrients, pH, temperature, light, carbon dioxide, oxygen, and other factors [22]. Nutrients can be adjusted as effectively as possible to maximize efficiency while minimizing the environmental impact. Hydroponically grown lettuce yielded 11 times more (41.0 kg/m\(^2\)) than soil cultivation (3.9 kg/m\(^2\)) [17]. In another study, hydroponically grown strawberries produced a 10% higher yield than conventionally grown strawberries [23]. It has also been reported that the amount of beneficial bioactive compounds in hydroponically grown fruits and vegetables has increased. Basil grown hydroponically has higher levels of total phenols, lipoic acid, rosmarinic acid, vitamin C, vitamin E, and antioxidant activity [24]. Hydroponically grown lettuce has higher alphatocopherol levels than conventionally grown lettuce [25]. The levels of the carotenoids capsanthin and capsorubin in hydroponically grown red paprika (*Capsicum annuum* L.) (46.74 and 4.50 mg, respectively) are significantly higher than in conventionally grown red paprika (29.57 and 2.81 mg, respectively) [26].

As previously stated, soilless farming requires less space and allows for vertical farming, which increases yield per area unit. According to Van Ginkel et al., hydroponically and aquaponically grown fruits and vegetables have 29 and 10 times higher areal productivities than conventional cultivation methods, respectively [19]. Therefore, this practice can address issues in confined spaces, such as urban areas. Moreover, the plants are less vulnerable to pests and weed growth because they thrive in a controlled nutrient solution. As a result, the use of herbicides is not needed. Pesticides are used at a much lower rate than in soil cultivation, owing to the plants being much stronger and less vulnerable to environmental influences [27].

However, the main disadvantage of aerated soilless farming is the high-energy consumption. According to Barbosa et al., hydroponically grown lettuce required 82 kJ more energy per 1 kg of the product than soil cultivation of lettuce in Yuma, Arizona [17]. The high-energy consumption in hydroponics is due to cooling and heating loads, artificial lighting supplementation, and circulating pump consumption, which are 74,000, 15,000,
and 640 kJ/kg, respectively. The cooling and heating loads are used to maintain the ideal temperature for lettuce cultivation, which is 23.9 °C. While artificial lighting is used to maximize the crop yield and ensure consistent production all year. According to Van Ginkel et al., hydroponically grown vegetables consume 30 times more energy than conventionally grown vegetables. While both aquaponically grown and conventionally grown vegetables consume roughly the same amount of energy [19]. As a result, more research into efficient consumption and cost-effective energy, or even switching to renewable energy, is needed (i.e., water, wind power, solar, or geothermal).

2.3. Research Focus and Issues in Soilless Farming

Macronutrients (nitrogen [N], phosphorus [P], potassium [K], sulfur [S], magnesium [Mg], and calcium [Ca]) and micronutrients (iron [Fe], copper [Cu], nickel [Ni], zinc [Zn], manganese [Mn], boron [B], and chlorine [Cl]) are the two forms of nutrients that plants need. The aim of aerated soilless farming research is to optimize nutrient solutions to increase crop yield and quality, reducing nutrition waste, and maintaining crop health while minimizing nitrate content in crops [16].

When optimizing a hydroponic nutrient solution, four conditions must be considered; (1) pH (2) electrical conductivity (EC), (3) nutrient composition, and (4) temperature. The alkalinity of a solution is used to determine the amount of bicarbonate ions (HCO₃⁻) in the solution that readily reacts with dissolved nutrients. It has been reported that alkalinity levels greater than 2 mM can significantly impede crop growth [28]. An alkaline pH also causes the formation of insoluble forms of nutrients, particularly iron (Fe) and zinc (Zn), rendering them unavailable for plant uptake. pH is used to maintain optimal crop growth conditions, which are typically in the range of pH 5.5 to 6.5 for hydroponic systems and pH 6.5 to 8.5 for aquaponic systems [29,30]. Table 1 shows the specifically recommended electrical conductivity (EC) and pH of common hydroponically grown crops [30,31] and Table 2 summarizes the effect of pH on nutrient availability in the cultivation of hydroponically grown crops [16,32]. Therefore, carefully balancing the pH of the nutrient solutions is critical to avoiding loss of nutrients from solution, such as physico-chemical nutrient phenomena that may cause precipitation, cophosphation, and complexation, thereby altering nutrient availability in crops; and interaction (i.e., antagonism or competition) among different nutrients, which eventually affects the chemical forms and uptake processes of the nutrients [16].

Table 1. The optimum range of electrical conductivity (EC) and pH of common hydroponically grown crops.

| Crops                        | pH          | EC (d/Sm⁻¹) |
|------------------------------|-------------|-------------|
| African Violet (Saintpaulia ionantha H. Wendl.) | 6.0–6.8     | 1.4–1.8     |
| Asparagus (Asparagus officinalis L.) | 6.0–7.0     | 6.0–6.8     |
| Banana (Musa acuminata Colla)   | 5.5–6.5     | 1.8–2.2     |
| Basil (Ocimum basilicum L.)     | 5.5–6.0     | 1.0–1.6     |
| Bean (Phaseolus vulgaris L.)    | 6.0         | 2.0 to 4.0  |
| Broccoli (Brassica oleracea L. var. italica) | 6.0 to 6.8 | 2.8 to 3.5  |
| Cabbage (Brassica oleracea L.)  | 6.5 to 7.0  | 2.5 to 3.0  |
| Carnation (Dianthus caryophyllus L.) | 6.0         | 2.0 to 3.5  |
| Celery (Apium graveolens L.)    | 6.5         | 1.8 to 2.4  |
| Cucumber (Cucumis sativus L.)   | 5.0 to 5.5  | 1.7 to 2.0  |
| Eggplant (Solanum melongena L.) | 6.0         | 2.5 to 3.5  |
| Fig (Ficus benjamina L.)        | 5.5 to 6.0  | 1.6 to 2.4  |
| Leek (Allium porrum L.)         | 6.5 to 7.0  | 1.4 to 1.8  |
| Lettuce (Lactuca sativa L.)     | 6.0 to 7.0  | 1.2 to 1.8  |
| Marrow (Cucurbita pepo L.)      | 6.0         | 1.8 to 2.4  |
| Okra (Abelmoschus esculentus L.)| 6.5         | 2.0 to 2.4  |
| Pak Choi (Brassica rapa L.)     | 7.0         | 1.5 to 2.0  |
| Peppers (Capsicum annuum L.)    | 5.5 to 6.0  | 0.8 to 1.8  |
Table 1. Cont.

| Crops                      | pH      | EC (d/Sm⁻¹) |
|----------------------------|---------|-------------|
| Parsley (Petroselinum crispum (Mill.) Fuss) | 6.0 to 6.5 | 1.8 to 2.2  |
| Rhubarb (Rheum × rhabarbarum L.)         | 5.5 to 6.0 | 1.6 to 2.0  |
| Rose (Rosa abietina Gren.)               | 5.5 to 6.0 | 1.5 to 2.5  |
| Spinach (Spinacia oleracea L.)           | 6.0 to 7.0 | 1.8 to 2.3  |
| Strawberry (Fragaria ananassa L.)       | 6.0      | 1.8 to 2.2  |
| Sage (Salvia officinalis L.)             | 5.5 to 6.5 | 1.0 to 1.6  |
| Tomato (Solanum lycopersicum L.)        | 6.0 to 6.5 | 2.0 to 4.0  |
| Zucchini (Cucurbita pepo L.)             | 6.0      | 1.8 to 2.4  |

Table 2. The effect of pH on nutrient availability in the cultivation of hydroponically grown crops.

| Nutrients                | Plant-Absorbable Ionic Forms of Nutrients | The Influence of pH on Its Availability |
|--------------------------|-----------------------------------------|-----------------------------------------|
| Nitrogen                 | NH₄⁺                                    | Available to form at pH 2 to 7, while above pH 7 will decrease its concentration |
|                          | NO₃⁻                                    | pH 6.5 is ideal; pH 8.5 increases unionized ammonia levels, which are harmful to fish, and reduces plant nutrient uptake from micronutrient precipitation. |
| Phosphorus               | PO₄³⁻                                   | The dominant orthophosphate ions are H₂PO₄⁻ and HPO₄²⁻, with the latter being the dominant species at pH levels of 5 and 10, respectively. |
|                          | HPO₄²⁻                                  |                                        |
|                          | H₂PO₄⁻                                  |                                        |
| Potassium                | K⁺                                      | Available to form at pH 2 to 9 with a minimal amount of it can form a soluble complex with SO₄²⁻ or bind with Cl⁻. |
| Calcium and magnesium    | Ca²⁺                                    | Available to form at pH 2 to 9, but may complex with other nutrient ions. At pH greater than 8.3, Ca⁺ and Mg⁺ can easily react with CO₃²⁻ (present in water) to form carbonate precipitate. Ca⁺ (if more than 2.2 mol m⁻³) can react with HPO₄²⁻ when the pH rises above 7.3. The formation of soluble complexes with SO₄²⁻ increases as the pH rises from 2 to 9. |
|                          | Mg²⁺                                    |                                        |
| Copper, manganese, zinc,boron, and iron | Cu²⁺, Mn²⁺, Zn²⁺, B³⁺, Fe²⁺, Fe³⁺         | When the pH rises above 6.5, it reacts with OH⁻ and precipitates. |

Plant growth, development, and production are influenced by the total ionic concentration of a nutrient solution, and the EC of a nutrient solution is a reliable measure of the quantity of available plant-absorbable ions in the root zone [31]. The EC values primarily measure the concentrations of K⁺, H⁺, Na⁺, Ca²⁺, Mg²⁺, HCO₃⁻, SO₄²⁻, OH⁻, and Cl⁻, so increasing EC means increasing the total concentration of nutrient salt [32]. The ideal EC values for hydroponic cultivation are usually between 1.5 and 2.5 d/Sm⁻¹, and Table 1 shows the specific recommended EC ranges of common hydroponically grown crops [30,31]. Higher EC values have been shown to reduce nutrient uptake by increasing osmotic pressure, whereas lower EC values have been shown to harm plant health and yield [33].

As shown in Table 2, some nutrients can form complex ions and precipitate with other nutrients, affecting the nutrient availability. The presence of H₂PO₄⁻ and SO₄²⁻ in the nutrient solution, for example, can easily convert free ions of K⁺, Ca²⁺, and Mg²⁺ into K-phosphate/Ca-phosphate/Mg-phosphate minerals and K-sulfate/Ca-sulfate/Mg-sulfate minerals, rendering them unavailable for root uptake [34]. The concentration of free ions in the nutrient solution decreases as a result of complexation reactions, impacting elemental bioavailability. As a consequence, it is important to analyze the nutrient solution’s composition thoroughly.

Temperatures in growth media can have an impact on the chemical reaction rates of nutrients in solution, nutrient transport in the medium, physiological aspects of ion uptake.
rate, and the functioning of soil microbial communities. Temperatures below or above optimal levels can have a positive or negative impact on plant metabolic activities. This can include the accumulation of phenolic compounds, reactive oxygen species (ROS), nutrient uptake, chlorophyll pigment formation, photosynthesis, and finally the plant’s growth and development [35]. The optimal growth medium temperature can aid in the improvement and optimization of the aforementioned plant physiological processes [35]. It has been reported that high temperatures increase the production of ROS, which then have a negative impact on plant metabolism, limiting growth and yield [36]. Calatayud et al. discovered that nutrient uptake by roots decreased in most plant species at low temperatures [37]. The solubility of oxygen changes as a function of temperature, and as the temperature rises, the availability of oxygen to plant roots decreases. However, as temperature rises, the rate of chemical reactions in plant roots accelerates, resulting in an increase in respiration rates. As a result, the ideal temperature is always a compromise between the decrease in oxygen availability and the increase in metabolic rate provided by higher temperatures. Optimal solution temperatures for almost all commercially grown plant species will be in the 15–30 °C range. For example, the optimum temperature for nutrient solution for potatoes (Solanum tuberosum L.) is in the 20–25 °C range [38], whereas the optimum temperature for plants such as cucumbers is higher, at 28 °C [39]. Some plants, such as onions (Allium cepa L.), require a slightly higher solution temperature, even in the 26–30 °C range. Others, such as lettuce and baby leaf crops, prefer much lower temperatures, with best results around 20 °C [40]. Moreover, elevated temperatures and long photoperiod exposure have been shown in studies to increase the quality and quantity of root exudates from cucumber plants. Exudation of organic acids from root cucumber plants was higher in plants grown at 30 °C/25 °C and photoperiod exposure day/night cycles at 14/10 h than in plants grown at 25 °C/20 °C and photoperiod exposure day/night cycles at 10/14 h [41]. As a result, studies should be carried out to determine the optimal temperatures for meeting the nutrient uptake demands of specific crop plants. Low temperatures are known to cause deficiency and leaf damage in crop plants. At low temperatures, crop mobility and volatilization were most likely to blame [35]. Soilless substrate farming research focus on optimizing the substrate in terms of coarseness index/particle size and composition, which has been shown to affect the plant physiology, yield, and fruit quality [42]. To allow root penetration and thus increasing nutrient availability to crops, the ideal soilless substrate should have a low bulk density, high total porosity, a proper aeration system, and a high water-holding capacity. The air porosity, total pore space, and plant-available water-keeping ability of the media are all known to be influenced by the particle size of the substrate [43,44]. According to various studies, the optimum substrate culture conditions are as listed in Table 3 [45–47]. Increased coarseness index or particle size of the substrate has been reported to increase total porosity, air capacity, and total organic matter while decreasing bulk density and moisture level (water content) [46,47]. A fine particle substrate (less than 1 mm) has been reported to have less aeration and a higher water-holding capacity than a coarse substrate [48]. In another study, carrot (Daucus carota L.) hydroponically grown in 0.6 mm perlite was determined to be the optimal size due to the higher root yield obtained when compared to larger perlite (1.2, 2.5, and 5.0 mm). Carrot grown in ultra-fine perlite (0.3 mm) produced shorter and whitish roots due to excessive water content, which caused a lack of oxygen in the substrate’s air zone [45]. Aside from that, substrate composition factors such as stability, cation-exchange capacity, pH, and air-water balance all play a role in selecting the best culture substrate [43,44]. Beneficial microorganisms (e.g., Arbuscular mycorrhizal fungi) found in the organic substrate can be considered an added advantage over the inorganic substrate. Strawberries grown in coconut fiber, for example, yielded more strawberries than grown in perlite medium [49].
Table 3. Optimum range conditions of the substrate culture.

| Properties                        | Suggested Optimum Range |
|-----------------------------------|-------------------------|
| Particle size/coarseness index    | 0.5–2.0 mm              |
| Total pore space                  | >85% vol                |
| Bulk density                      | <0.4 g/cm³              |
| Air capacity                      | 20–30% vol              |
| Total water-holding capacity      | 600–1000 mL/L           |
| pH                                | 5.3–6.5                 |
| Electrical conductivity           | <0.5 dS/m               |
| Total organic matter              | >80%                    |

3. Microgreen Farming

3.1. Definition, Nutritional Value, and Benefits of Microgreen Farming

Microgreens are edible seedlings that grow to a height of about 13 inches and are harvested when they have two fully formed cotyledon leaves, which happens about 7–14 days after germination (Figure 2) [50]. Microgreens include a variety of vegetables (e.g., radish (Raphanus sativus L.), broccoli (Brassica oleracea L. var. italica), mesclun (Lactuca sativa L.), etc.), herbs (e.g., basil, cilantro, etc.), and flowers (e.g., sunflowers, etc.). Microgreens are typically more aromatic than mature counterparts, with vivid colors and tender textures, considering their limited scale. Microgreens are often said to be nutritionally beneficial, and their growing methods (hydroponic, compost, or soil) can have an effect on their nutritional value [51]. Hence, microgreens are referred to as superfood and functional food, which means that they can provide essential nutrients in a practical manner. According to Xiao et al., the 25 commercially available microgreens varieties (i.e., arugula, bull’s blood beet (Beta vulgaris L.), celery (Apium graveolens L.), cilantro, China rose radish, garnet amaranth (Amaranthus cruentus L.), golden pea tendrils (Thermopsis montana Nutt.), green basil, green daikon radish, magenta spinach, mizuna (Brassica rapa L.), opal basil, opal radish, pea tendrils (Pisum sativum var. macrocarpon), pepper cress (Lepidium bonariense L.), popcorn shoots (Zea mays var. everta), purple kohlrabi (Brassica oleracea L.), purple mustard (Chorispora tenella (Pall.) DC.), red beet (Beta vulgaris L. subsp. vulgaris), red cabbage (Brassica oleracea var. capitata L.), red mustard (Brassica juncea L. Czern.), red orach (Atriplex hortensis L.), red sorrel (Rumex acetosa L.), sorrel (Rumex acetosa L.), and wasabi (Eutrema japonicum (Miq.) Koidz.) produced 4–40 times the carotenoid concentrations and essential vitamins as a mature plant would [52]. In another study, hydroponically grown broccoli microgreens produced more nutrients (Cu, Zn, Mg, and Mn) than vegetables. While compost-grown broccoli produced more nutrients (i.e., P, K, Ca, Cu, Na, Mg, Zn, Mn, and Fe) than the vegetables [51]. Microgreens of green curly kale (Brassica oleracea var. sabellica), red mustard, broccoli, and radish have been shown to have sufficient vitamin C, minerals, and antioxidant bioactive compound contents, as well as higher total carotenoid levels than adult plants [53]. When compared to NQS 11.1 (Nutrient Quality Score, based on 11 desirable nutrients and 1 nutrient (sodium) to be limited), microgreens of cauliflower (Brassica oleracea L. var. botrytis), broccoli, and broccoli raab (Brassica rapa L. subsp. oleifera var. ruvo) scored higher than mature plants, highlighting their high levels of vitamin A and E, as well as Ca and Mn [54]. In contrast to previous claims, Khoja et al. reported that hydroponically grown fenugreek (Trigonella foenum-graecum L.), rocket (Eruc avesicaria subsp. sativa), and broccoli microgreens had lower mineral contents than mature plants. When compared to mature fenugreek, only fenugreek microgreens showed a significant increase in iron uptake in Caco-2 cells [55].
Furthermore, growing microgreens conserves space, time, and resources. Microgreens, as previously said, are nutrient-rich, containing up to 40 times as many nutrients as their mature counterparts. This means that any harvested microgreens harvest is equivalent to 40 times their mature counterparts, or, in another way, they require 40 times less energy to produce the same nutritional content. Producing 10,635 lbs of broccoli microgreens offers the same amount of nutrition as growing one-acre mature broccoli area, according to Weber et al. [51]. Microgreens cultivation decreases crop processing time dramatically, as harvesting microgreens takes just 7–14 days versus several months for mature plants. Traditional mature broccoli, for example, takes 100–150 days to harvest, while broccoli microgreens take just 7–9 days from seed to harvest [51,56]. This translates to a 93–95% reduction in processing time, which is particularly intriguing given the need to boost food production efficiency to feed an increasing population. Because one cycle cultivation of microgreens takes less time, fewer resources are required. Growing broccoli microgreens, according to Weber et al., reduced water consumption by 158–236 times when compared to the nutritionally equivalent amount of mature broccoli [51]. Microgreens also allow for vertically aerated soilless farming, which more effectively utilizes both horizontal and vertical spaces, resulting in a higher yield per unit volume under controlled temperature, light, carbon dioxide, and humidity conditions [57]. Microgreens are currently in high demand in the market due to their high nutritional content and ease of cultivation, and more people are integrating them into their daily diet for nutrition.

3.2. Issues and Research Focus in Microgreen Farming

The rapid degradation of postharvest product quality and the poor shelf life of microgreens are their main drawbacks. Since microgreens have a short shelf life of three to five days even when refrigerated and are consumed in small quantities, it is critical to determining whether there is a connection between produce spoilage and human pathogen contamination, in which plant tissue damage allows pathogens to attach or enter [58]. Microgreens, including lettuce, spinach, parsley (*Petroselinum crispum* var. *crispum*), basil, strawberries, green onions (*Allium fistulosum* L.), melons, sprouts, and tomatoes, are prone to pathogen infection from seed to harvest [59]. Growing conditions that encourage the growth or transfer of microorganisms, processing practices that expose the commodity to contaminants from animals or humans, and physiological characteristics of the plant that allow contact and binding with microorganisms all make these crops high-risk. Micro-
greens are commonly grown in greenhouses and climate-controlled buildings where birds, insects, and wildlife have little contact. Furthermore, since the commodity is harvested in one to three weeks, fertilizers, whether manure or otherwise, are rarely used in indoor and greenhouse operations. For sprouts and microgreens grown hydroponically, on the other hand, water for irrigation is a major problem. Norovirus can touch and attach to vegetables and fruits directly from experimentally infected irrigation water, according to field studies [60,61]. In the sprouting industry, seed contamination is a well-known problem [62]. If seeds are infected, pathogens may become internalized early in the growing process and are difficult to remove once established. As a result, there is a significant body of literature devoted to evaluating effective seed disinfection procedures. The normal type of chemical disinfection, according to the US Food and Drug Administration (FDA), is 20,000 ppm calcium hypochlorite [58]. Furthermore, as previously mentioned, environmental factors such as water use and nutrient demand, as well as microgreen cultivation methods, can affect nutritional value, which must be taken into account when determining how to grow microgreens and whether they are a nutrient-rich crop that can be grown sustainably.

As a result, microgreen farming research is primarily focused on three areas: improving quality, yield, and nutritional value, ensuring food protection, and extending shelf life. The ideal conditions for rising microgreens are a constant supply of neutral to slightly acidic water with an optimum water-holding capacity (55–70% v/v), aeration (20–30% v/v), and low electrical conductivity (0.5–1.0 mS cm⁻¹) [46,63]. Some varieties of seeds are subjected to seed treatments such as overnight soaking and physiological treatments to improve germination (e.g., pre-germination, osmopriming, and matrix priming). During germination, flats can be covered or put in a low-light environment. The plants are exposed to light after about 3 days and are watered on a regular basis before the first true leaves appear. Matrix priming table beet and chard (Beta vulgaris L.) seeds in fine vermiculite for 6 days at −1 MPa and 12 °C increased the final germination percentage with a 50% shorter period needed when compared to untreated seedlings [64]. Pre-germination treatment of table beet and arugula seed balls with fine-grade exfoliated vermiculite imbued with 150% water for 5 days at 20 °C resulted in a 26% increase in shoot fresh weight m⁻² at 15 days after planting compared to sowing untreated seed balls [65].

Microgreen yield and quality can be influenced by growing media, pre-sowing fertilization, post-emergence fertigation, or their combination. A 1000 mg/L calcium nitrate pre-sowing application, as well as fertigation on a regular basis of 6 at 75 and 150 mg/L of N L⁻¹, increased the fresh yield of arugula microgreens grown on peat-lite [66]. Hu et al. discovered that when compared to sole nitrate (0:100 NH₄⁺:NO₃⁻⁻), moderate ammonium concentrations (15:85 NH₄⁺:NO₃⁻⁻) improved plant growth, photosynthetic response, chloroplast ultrastructure, and root structure of mini Chinese cabbage (Brassica rapa subsp. pekinensis Lour. Hanelt) [67]. In another study, Kou et al. looked at the effects of pre-harvest foliar applications of calcium chloride (CaCl₂) at 0, 1, 10, and 20 mM on broccoli microgreens for ten days and discovered that microgreens sprayed with 10 mM CaCl₂ had 50% more biomass and triple the calcium content of the untreated control [68].

Furthermore, due to the importance of light in driving photosynthetic biosynthesis, microgreen growth, morpho-physiology, biosynthesis, and phytochemical accumulation can be affected by photoperiod exposure and light condition (quality and intensity) [63]. Metal halide, fluorescent, incandescent, and high-pressure sodium (HPS) lamps are common supplemental light sources in vegetable production. Due to its high spectral quality (wavelength) and photon flux (intensity) which induce selective photoreceptor activation and an increase in phytochemical content in vegetables, including microgreens, advanced light-emitting diode (LED) technology has become increasingly feasible in the last decade for providing optimal light management [69]. By varying LED spectral efficiency, Brazaityt et al. showed species-dependent enhancement of various oxygenated (lutein, zeaxanthin, neoxanthin and violaxanthin) and hydrocarbon (α- and β-carotene) carotenoids in cabbage microgreens [70]. Supplemental blue/red/far red LED illumination (447/638 and 665/731 nm) increased carotenoids in tatsoi (Brassica rapa subsp. narinosas) and red pak
choi (*Brassica rapa* L.), while green light (520 nm) increased the lutein/zeaxanthin ratio and β-carotene content in mustard microgreens [71]. The nutritional quality of brassica microgreens (kohlrabi, mustard, red pak choi, and tatsoi were studied using five different LED irradiation levels (110, 220, 330, 440, and 550 mol m$^{-2}$ s$^{-1}$) [72,73]. It was discovered that applications of 330-440 mol m$^{-2}$ s$^{-1}$ resulted in a significant but species-specific increase in antioxidant activity, carotenoids, and total phenols.

Variables influencing the shelf-life of fresh-cut microgreens include pre-harvest and post-harvest procedures, as well as various packaging materials and changed atmosphere packaging (MAP) [74]. It has been reported that applying calcium chloride to microgreens broccoli before harvest (pre-harvest) increased yield and quality while reducing tissue damage and microbial growth during storage, thereby improving quality and shelf life [68]. Combining washing in citric acid solution with ethanol spray provided the best microbial output on Tah Tasai Chinese cabbage (*Brassica rapa* subsp. *pekinesis* Lour.) microgreens [75]. The oxygen transmission rate of the film affected the equilibrium concentrations of carbon dioxide and oxygen but had no significant impact on the product’s shelf life. Kou et al. investigated the effects of storage temperature, MAP, and wash conditions on the quality and shelf life of buckwheat (*Fagopyrum esculentum* Moench) microgreens [76]. Microgreens stored at 1, 5, and 10 °C had smaller microbial communities and less tissue electrolyte leakage than those stored at 15 and 20 °C, indicating that temperature has a direct impact on package atmospheres and product consistency. The oxygen transmission rate (OTR) of package films had a significant impact on package atmospheres due to differences in consistency and shelf life of microgreens packed in different OTR films, with buckwheat microgreens packaged in 16.6 pmol/(m$^2$ s Pa) oxygen transmission rate package films having the freshest appearance with the lowest tissue electrolyte leakage on day 21. While chlorine (100 mg/L) wash initially reduced microbial populations, however, after 7 days of storage, all washed microgreens had accelerated microbial populations.

4. Nanotechnology Advancements in Agriculture

Nanotechnology has limitless applications in agriculture, including agrochemical delivery systems that allow for the controlled release of pesticides, fertilizers, and herbicides; plant trait improvement against environmental disease and stress; field-sensing systems that monitor crop conditions and environmental stresses; increased production rate and crop yield; increased resource efficiency; and waste reduction [77]. Nanotechnology has enabled agrochemicals to be encapsulated or incorporated into a matrix of polymers, metals, carbon-based materials, micelles, liposomes, and other substances, which are known as agronanochemicals. Nanotechnology also enabled for controlled release of active ingredients and site-specific delivery, demonstrating its potential to be a game-changer in the development of integrated pest and disease management [78]. Three chitosan-based agronanofungicides systems were synthesized in order to develop potent antifungal agents: chitosan-hexaconazole nanoparticles (CHEN), chitosan-dazomet nanoparticles (CDEN), and chitosan-hexaconazole-dazomet nanoparticles (CHDEN) [79–81]. All systems demonstrated a controlled release with a release time of up to 130 h, whereas pure fungicides were fully released in 4 h. Accordingly, both in vitro and in vivo studies have shown that incorporating fungicides into the chitosan matrix has significantly reduced and suppressed the basal stem rot disease in oil palm (*Elaeis guineensis* Jacq.), with four times lower half-maximal effective concentration (EC$_{50}$) and disease reduction up to 75% [82]. Furthermore, chitosan-based agronanofungicides phytotoxicity, cytotoxicity, and genotoxicity studies revealed the superiority of the chitosan nanoparticles, in which they act as a defensive wall to shield the fungicide’s toxic effect on oil palm seedlings, cells, and DNA [83,84]. Long half-lives ($t_{1/2}$) of fungicide in stem tissue and leaf tissue were also discovered at 383 and 515 days, respectively, indicating high uptake and retention time, indicating the ideal desired properties for chitosan-based agronanofungicides for improved management of oil palm basal stem rot disease [85].
Abiotic stresses that reduce crop growth and productivity are due to drought, salinity, alkalinity, submergence, and mineral toxicity/deficiency [86]. Because plants are subjected to a wide range of environmental stresses throughout their lives, they develop defensive mechanisms at various levels by modulating genetic, biochemical, and physiological pathways. Plants adapt molecular pathways to cope with these stresses by changing gene expression. Several studies have found that the effect of nanoparticles on plant growth and development varies with concentration. Nanoparticles are involved in upregulating the activities of antioxidant enzymes like superoxide dismutase, catalase, and peroxidase [87]. The application of SiO$_2$ and ZnO nanoparticles, for example, increases the accumulation of amino acids and free proline. They also have the ability to improve nutrient and water absorption. The use of these nanoparticles increases the activity of antioxidant enzymes such as superoxide oxidase, catalase and peroxidase, and nitrate reductase, resulting in plant tolerance to abiotic stress [88,89]. Nanoparticles may also be able to regulate stress gene expression. Ag nanoparticles, for example, have been shown to regulate several gene expressions in *Arabidopsis* using microarray analysis. In this regard, a significant portion of gene expression is related to the response to pathogens, metals, oxidative stress (e.g., cytochrome P450-dependent oxidase, superoxide oxidase, and peroxidase), and hormonal stimuli (e.g., signaling of ethylene). As a result, the genetic responses induced by nanoparticles are directly related to plant stress resistance [90].

Various types of nanosensor have been tested for various plants including carbon-based electrochemical, plasmonic, nanowire, fluorescence resonance energy transfer (FRET), and antibody nanosensors [91]. Nanoparticle-based sensors have been adopted as tools for in-field environmental monitoring and food processing, including online and real-time detection of pesticides, pathogens, toxic materials, bacteria, microbes, and other contaminants that may exist in food, plant, soil, air, and water. For example, to detect *Xanthomonas axonopodis pv. vesicatoria*, which causes bacterial spot disease in *Solanaceae* plants, fluorescent silica nanoparticles in combination with antibodies were developed [92]. In a separate study, Lau et al. proposed using differential pulse voltammetry (DPV) on disposable screen-printed carbon electrodes to detect plant pathogen *Pseudomonas syringae* in mouse-ear cress (*Arabidopsis thaliana* L.) [93]. Magnetic nanoparticles have been investigated for use in food safety applications, where contaminants such as food allergens, mycotoxins, and pesticide residue have been analyzed using magnetic nanoparticles integrated immunoassays [94]. Various enzyme-based biosensors have been used in pesticide detection in conjunction with various nanomaterials. Biosensors with nanomaterials boost analyte response, sensitivity, and selectivity. Acetylcholinesterase, organophosphate hydrolase, and laccase are some of the most widely used enzymes in pesticide detection biosensors. The fundamental mechanism underlying pesticide detection using enzyme-based biosensors is decreased catalytic activity of these enzymes in the presence of pesticides, which function as enzyme inhibitors [95].

Plant nanobionics is a new branch of bioengineering in which nanoparticles are inserted into living plant cells and chloroplasts to alter or improve the function of the plant tissue or organelle [96]. The ultimate goal is to develop a diverse range of plants capable of imaging objects in their environment and acting as independent light sources. Because of their ability to generate energy through photosynthesis and sunlight, plants are well suited for such functions. Nanobiotechnology researchers hope to develop bionic plants with improved photosynthesis efficiency and biochemical sensing, which will increase productivity and crop yield. Giraldo et al., for example, created highly charged single-walled carbon nanotubes that spontaneously penetrated chloroplasts after being coated with DNA and chitosan [97]. By capturing visible and near-infrared light wavelength spectra and converting them into excitons, which then transfer electrons to photosynthetic machinery, the embedded single-walled carbon nanotubes in chloroplasts have the potential to improve photosynthesis light reactions, resulting in a 49% increase in photosynthetic activity when compared to the control. Moreover, plant nanobionics has also made it possible for plants to act as detectors for the existence of various chemicals in the soil, water, and even the
air. Wong et al., for example, developed a nanobionic plant that can detect nitroaromatics in groundwater by injecting carbon nanotubes (CNTs)-based IR-fluorescent sensors into spinach plant leaves [98].

5. Nanotechnology Approaches in the Soilless Farming

The main aim of using nanoparticles in soilless farming is to minimize nutrient losses while also increasing yields through better nutrient and water management. Due to their high specific surface and related reactivity (particle size less than 100 nm), nanoparticles can provide the plant with more soluble and usable forms of nutrients, restricting precipitation and insolubilization processes that are widely established for many conventional fertilizers (e.g., phosphate fertilizers). Nanoparticle’s unique properties, such as tunable physico-chemical properties and the ability to cross the plant cell wall, can increase nutrient uptake in the plant root. As a result, nanoparticles are more effective nutrient carriers for plants than conventional fertilizers, proving that nanoparticles are a promising tool in general, particularly for soilless growing systems.

5.1. R&D and Innovation on Nanotechnology Approaches in Aerated Soilless Farming

As previously stated, the R&D focus in aerated soilless farming is on optimizing nutrient solutions to increase nutrient uptake and minimize nutrient wastage, as well as the growing system method. The role of nanotechnology in this particular aspect is to resolve several issues involved in the mixture of nutrient solutions, as previously explained, and to maximize nutrient uptake, thereby increasing crop productivity and quality. Plant trait improvement against environmental disease and stress has also been studied. The recent R&D on nanotechnology approaches to improving soilless nutrient solutions is tabulated in Table 4. Positive effects of high uptake of Fe$_2$O$_3$ nanoparticles on hydroponically grown spinach were observed; increased stem and root lengths, biomass production, and magnetic properties [99]. The high magnetic properties indicate a high iron content, which is known to be beneficial to human health. Another study examined the effects of ZnO nanoparticles (25 nm) and bulk or natural form (1000 nm, bulk ZnO) on tobacco (Nicotiana tabacum L.) seedlings for 21 days in a nutrient solution supplemented with either ZnO nanoparticles, bulk ZnO, or ZnSO$_4$ (as a control) [100]. ZnO nanoparticles outperformed bulk-ZnO in terms of growth (root and shoot length/dry weight), leaf surface area and its metabolites, leaf enzymatic activities, and anatomical properties (root, stem, cortex, and central cylinder diameters). Haghghi et al. successfully alleviate the negative effects of heat stress in hydroponically grown tomatoes by incorporating bulk Se and Se nanoparticles in abiotic stress management, specifically with exposure to high and low-temperature stress [101]. When compared to bulk Se and the control, Se nanoparticles significantly increased chlorophyll content. SiO$_2$ nanoparticles have been shown to promote seed coat resistance and improve nutritional availability in maize plants [102]. Direct uptake of nano-sized silica by seeds is improved in a hydroponic incubation, which creates a potential barrier for plants such as maize. Zein nanoparticles derived from the maize enzyme have been proposed as effective delivery systems for agrochemicals to sugar cane plants, with a significant amount successfully translocated to the leaves using the fluorescence tracking method [103]. Therefore, all of these studies demonstrated that nutrient nanoparticles outperformed their bulk counterparts, proving our previous claim that nanoparticles are more efficient nutrient carriers for plants than conventional fertilizers.

Aside from that, contaminated water is a major issue in the soilless farming industry because water is a key component in the nutrient solution. Water contaminants include nitrates, phosphates, fertilizers, pesticides, bacteria, viruses, and toxic metals. As a result, eliminating these contaminants is critical to avoid unnecessary residue in food, as well as crop growth and productivity disruption. In this regard, research has shown that nanomaterials can be tailored to curtail this contaminant found in water that occurs naturally or as a result of industrial activity. For example, in hydroponically cultured garlic, Se nanoparticles were found to be less phytotoxic and to have a greater capacity for Hg sequestration than
SeO$_3^{2-}$ and SeO$_4^{2-}$ [104]. The study also discovered that Se nanoparticles captured a large amount of Hg$^{2+}$ by forming HgSe and HgSe nanoparticles, preventing Hg$^{2+}$ from entering the root stele and thus inhibiting Hg translocation and accumulation in the aerial parts. In addition to immobilizing Hg, Se nanoparticles promoted the conversion of Hg$^{2+}$ in plants to less toxic binding forms. Another study looked at the effect of ZnO nanoparticles on heavy metal uptake and accumulation in hydroponically grown romaine lettuce [105]. Cd and Pb accumulation in roots was reduced by 49% and 81%, respectively, according to the findings. Huang et al. discovered that adding nanomaterials such as graphene oxide, hydroxyapatite nanoparticles (20 and 40 nm), Fe$_3$O$_4$ nanoparticles, and nano-zerovalent Fe to hydroponically grown rice reduced arsenic uptake [106]. As the arsenic concentration increased, the weight of the aboveground parts of the seedlings decreased with the addition of nanomaterials. When compared to the control, the addition of various nanomaterials could boost seedling growth without the use of arsenic. Fe$_3$O$_4$ nanoparticles and nano-zerovalent Fe outperformed other nanomaterials in preventing arsenic from reaching the aboveground parts of rice seedlings. The addition of Ag nanoparticles has been reported to have potential in reducing antimony uptake and translocation in hydroponically grown soybean, opening up new avenues for food safety in antimony-contaminated areas [107].

Some nanomaterials have been shown in early nano-ecotoxicological studies to be toxic not only to plants, but also to a variety of soil microorganisms such as bacteria, fungi, and yeast [108,109]. In this regard, achieving sustainable agriculture intersects with the need to balance the benefits of nano-products in addressing environmental issues with the identification and management of potential environmental, health, and safety threats posed by nanoscale materials [110]. Because nanomaterials or nano-products are not intended to harm human health or the environment over the course of their life cycle, they should be included in the design and safety evaluation of engineered nanomaterials (ENMs) [111]. The method would promote nanomaterials that are safer by nature by taking into account both applications and consequences. This means that before the preparation of nanomaterials, their actions should be thoroughly investigated. ZnO nanoparticles, for example, were discovered to be capable of concentrating in the rhizosphere, entering root cells, and inhibiting ryegrass (Lolium perenne L.) seedling growth [112]. According to Zhao et al., Y$_2$O$_3$ nanoparticles and released Y$^{3+}$ did not affect rice germination rate. Low concentrations of Y$_2$O$_3$ nanoparticles (1, 5, and 10 mg/L) improved rice root elongation [113]. Notably, when the concentration of Y$_2$O$_3$ nanoparticles reached 20 mg/L or higher, root elongation was significantly inhibited. According to physiological and biochemical characteristics, Y$_2$O$_3$ nanoparticles at concentrations ranging from 20 to 100 mg/L significantly reduced chlorophyll contents and root activity in rice seedlings. ICP-MS and TEM analyses revealed that Y$_2$O$_3$ nanoparticles and Y$^{3+}$ were primarily absorbed and accumulated in the roots. ZnO nanoparticles treatments at all tested concentrations (10, 50, and 250 mg/L) decreased growth, total chlorophyll content, and soluble proteins while increasing carotenoids, lipid peroxidation, hydrogen peroxide, and electrolyte leakage in leaf when compared to the control [114]. These modifications, along with increased proline content and activities of superoxide dismutase, catalase, and guaiacol peroxidase in the treated plants, suggest that ZnO nanoparticles induced oxidative stress. The phytotoxicity effect of ZnO nanoparticles is indicated by a reduction in nettle-leaved goosefoot (Chenopodiastrum murale L.) growth.

In terms of sensing applications in soilless farming systems, nano-sensing R&D focuses on detecting and quantifying the amount of supplemental nutrients to ensure the availability of the interested nutrient throughout the cultivation process. Xu et al. developed a disposable phosphate sensor using a screen-printed electrode (SPE) modified with cobalt nanoparticles [115]. The results showed that cobalt nanoparticles improve the sensor’s detection limit in the initial state. Meanwhile, the corrosion of cobalt nanoparticles causes significant time drift and electrode instability. The disposable phosphate detection chip, on the other hand, has a linear range of 10$^{-1}$–10$^{-5}$ mol/L, a coefficient of variation of 0.5%, and a sensitivity of 33 mV/decade.

Other soilless farming techniques, such as aquaponics and aeroponics, are advancing at a rapid but limited rate in nanotechnology research. Luo et al. investigated the effects of
nano-Se supplementation on Koi carp growth, ornamental features, and health status, as well as lettuce yield and water quality, in aquaponic conditions [116]. Nano-Se, Premix, spirulina, bentonite, Ca(H₂PO₄)₂, soybean meal, wheat flour, rice bran, fish meal, and water make up the dietary supplement. When compared to the control group, the addition of nano-Se increased the weight gain rate of Koi carp in the 0.6 and 1.2 mg/kg nano-Se groups. Nano-Se supplementation was found to improve koi growth performance, health status, and ornamental quality while not reducing lettuce yield. In another study, the foliar spray of nano-fertilizer containing 60% of humic acid on aquaponically grown mint plants (Mentha × piperita L.) increased the fresh and dry weight of the shoot and root as compared to the control [117]. Nano-fertilizer increased chlorophyll content, soluble sugars, photochemical quantum yield, and photosynthesis efficiency index when compared to the control plants. In an aeroponic method, the effect of iron chelate and nano iron chelate fertilizer supplementation on chicory (Cichorium intybus L.) was investigated. The plant treated with nano-Se had the highest plant height, root length, root and shoot dry weight, leaf area, chlorophyll content, and carotenoid content.

Invention on aerated soilless farming is primarily concerned with improving the culture method and developing novel nutrient solutions as shown in Table 5. A patent has been filed, for example, to introduce the utility model of an indoor micro-bubble hydroponic device [114]. The utility model effectively incorporates micro-nano bubbler techniques and a controllable planting environment, makes full use of the family’s indoor environment, improves plantation efficiency, is simple to manage, saves energy, and has a variety of cultivation functions. A hydroponic seeding method of producing strong seedlings in a short period of time by using a hydroponic culture medium containing micro-nano bubbles has also been patented [114]. This method can reduce seedling damage and fall, thereby improving seedling quality and yield.

Hiking University of Science and Technology, Taiwan, patented a modified aquaponics system or fish-and-food symbiosis system in 2017 to reduce the cost and efficiency of the aquaponic system [114]. They use a photocatalytic catalyst reduction reaction filtration mode so that the water in the aquaculture tank containing fish excrement passes through a composite filter material of activated carbon nano-silver photocatalyst that has been irradiated with ultraviolet light. Following filtering, the water flows to the planting tube for plant cultivation, effectively overcoming the shortcomings of the traditional fish and vegetable symbiosis method, which involved complicated filtering devices, and achieving the breeding habit of changing fish and vegetable symbiosis, as well as a low-cost advantage. Seed germination and subsequent plant cultivation on agar nutrient medium containing nanoparticles such as Fe nanoparticles, Zn nanoparticles, and Cu nanoparticles of copper were patented as part of the proposed method for plant cultivation [118]. The invention aims to develop a method for cultivating plants on a nutrient medium containing nanoparticles of essential elements that improve seed germination as well as morphometric and/or physiological parameters of plants, resulting in higher-quality planting content.

An invention on a nano concentrate, a nano-lipid stable emulsion, a method of preparing a nano lipid concentrate, and a lipid delivery device for use as a carrier for the industrial, medical as well as animal, horticultural and agricultural chemistries were also patented [119]. Moreover, a process for delivering a liquid nano lipid particle system to a target that includes a plant, water for hydroponics, water for aeroponics, soil, manure, potting soil, an insect, an animal, a human being, machinery, pest surface areas, and plant surface areas has also been introduced [120]. The aquaponic system’s fish culture water body was treated with a nano catalyst composed of TiO₂ nanoparticles, magnesia nanoparticles, medical stone, purple clay, tourmaline, and zeolite. These nanocatalysts are intended to accelerate the decomposition and fermentation of fish excrement, resulting in a small molecular nutrient that can be consumed by vegetables as soon as possible. The nano-catalysis aquaponics method has the advantages of a fast catalysis rate, rapid decomposition of fish excrement, and the ability to reduce aquaponics startup time, save energy, and increase aquaponics production performance.
Table 4. Some of the most recent R&D on nanotechnology approaches to improving hydroponic nutrient solutions.

| The Incorporation of Nanoparticles into Nutrient Solutions | Type of Crops | Method of Soilless Cultivation | Finding | Ref. |
|----------------------------------------------------------|--------------|-------------------------------|---------|-----|
| Fe$_2$O$_3$ nanoparticles (30–40 nm) at concentrations of 100, 150, and 200 mg are mixed with Hoagland nutrient solution | Spinach *Spinacia oleracea* L.) | Hydroponic | According to the findings, adding nano Fe$_2$O$_3$ to spinach boost its growth rate in a dose- and time-dependent manner. After 45 days, the stems and roots of spinach grown in various Fe$_2$O$_3$ concentrations at 100, 150, and 200 mg, are approximately 1.45, 1.91, respectively, and 2.27 and 1.25, 1.38, and 1.75, respectively, times longer than the control spinach. | [99] |
| ZnO nanoparticles (25 nm) at concentrations of 0.2, 1, 5 and 25 µg are mixed with Johnson nutrient solution | Tobacco *Nicotiana tabacum* L.) | Hydroponic | When compared to the control, Nano-ZnO increased biomass indices such as root and shoot main and lateral lengths, as well as root and shoot weight. Low or middle levels of ZnO nanoparticles increased amino acids, phenolic compounds, proline, reducing sugars, and flavonoids whereas 25 µM ZnO nanoparticles did not increase proline or flavonoids. Nano-ZnO application increased the activity of superoxide dismutase, peroxidase, glutathione peroxidase, and polyphenol oxidase more than bulk-ZnO application. | [100] |
| Se nanoparticles (8–15 nm) at concentrations of 1, 4, 8 and 12 µM are mixed with a nutrient solution mixture of N (116 mg L$^{-1}$), P (21 mg L$^{-1}$), K (82 mg L$^{-1}$), Ca (125 mg L$^{-1}$), Mg (21 mg L$^{-1}$), S (28 mg L$^{-1}$), Fe (6.8 mg L$^{-1}$), Mn (1.97 mg L$^{-1}$), Zn (0.25 mg L$^{-1}$), B (0.70 mg L$^{-1}$), Cu (0.07 mg L$^{-1}$), and Mo (0.05 mg L$^{-1}$) | *Solanum lycopersicum* L.) | Hydroponic | The study discovered that both bulk Se (at concentrations of 2.5, 5, and 8 µM) and Se nanoparticles (at concentrations of 4, 8, and 12 µM) had positive effects on tomato growth parameters by increasing the fresh and dry weight and diameter of the shoots, as well as the fresh and dry weight and volume of the roots. In terms of chlorophyll content of tomato leaves grown under low-temperature stress (10 °C for 24 h), Se nanoparticles (27.5%) outperformed bulk Se (19.2%). | [101] |
| SiO$_2$ nanoparticles (20–40 nm) at a concentration of 1% w/v is mixed with Hoagland nutrient solution | Maize *Zea mays* L.) | Hydroponic | Hydroponically grown maize absorbed SiO$_2$ nanoparticles at a rate of 18.2%, resulting in a 95.5% increase in germination, a 6.5% increase in dry weight, and better nutrient alleviation in seeds exposed to SiO$_2$ nanoparticles than in seeds exposed to bulk silicon of SiO$_2$, Na$_2$SiO$_3$ and H$_4$SiO$_4$ and control. | [102] |
| Zein nanoparticles (135 nm) at concentrations of 0.88 and 1.75 mg/mL are mixed with Hoagland nutrient solution | Sugar cane *Saccharum officinarum* L.) | Hydroponic | After 12 h of exposure to zein nanoparticles, the concentration of nanoparticles adhering to sugar cane roots varied with dosage, with 110.2 µg NPs/mg dry weight of root in a low dose nanoparticle suspension (0.88 mg/mL) and 342.5 µg NPs/mg dry weight of root in a high dose nanoparticle suspension (1.75 mg/mL). The translocated nanoparticles were then observed in leaves with 4.8 µg NPs/mg dry weight of leaves in a low dose nanoparticle suspension (0.88 mg/mL) and 12.9 µg NPs/mg dry weight of leaves in a high dose nanoparticle suspension (1.75 mg/mL). | [103] |
Table 4. Cont.

| The Incorporation of Nanoparticles into Nutrient Solutions | Type of Crops | Method of Soilless Cultivation | Finding | Ref. |
|----------------------------------------------------------|---------------|-------------------------------|---------|-----|
| Hoagland nutrient solution was used in the early phase, and after the third leaf had fully expanded, hydroxyapatite nanoparticles (94–163 nm) at concentrations of 2, 20, 200, 500, 1000, and 2000 mg L\(^{-1}\) were mixed with 1% w/v carboxymethylcellulose | Tomato (\(Solanum lycopersicum\) L.) | Hydroponic | There were no phytotoxic effects on tomato plants grown in hydroponics with hydroxyapatite nanoparticles and increasing the concentration of the nano-mixture induces root elongation. For 200 and 500 mg L\(^{-1}\), the increase in root length was +64% and +97%, respectively, when compared to the control. | [108] |
| Fe\(_3\)O\(_4\) nanoparticles or TiO\(_2\) nanoparticles (10–30 nm) at concentrations of 50 and 500 mg/L are mixed with nutrient solution mixture of N (11.0 mM), P (1.2 mM), Ca (4.0 mM), K (7.0 mM), S (2.41 µM), Fe (17.8 µM), Zn (5.0 µM), Mn (10.0 µM) and Cu (2.7 µM) | Tomato (\(Solanum lycopersicum\) L.) | Hydroponic | When compared to the control and seedlings exposed to Fe\(_3\)O\(_4\) nanoparticles, seedlings grown with high concentrations of TiO\(_2\) nanoparticles displayed an irregular proliferation of root hairs one week after the start of the nanoparticle treatment. Tomato seedlings grown under different conditions had similar shoot morphology, and plants treated with nanoparticles showed no signs of toxicity. | [121] |
| Cu-Fe\(_2\)O\(_4\) nanoparticles at concentrations of 0.0, 0.04, 0.2, 1, and 5ppm are mixed with Hoagland nutrient solution | Cucumber (\(Cucumis sativus\) L.) | Hydroponic | After being exposed to Cu-Fe\(_2\)O\(_4\) nanoparticles, cucumber plants’ fresh weight and protein content increased. The activities of superoxide dismutase and peroxidase were also substantially higher in cucumber shoots and roots. The use of Cu-Fe\(_2\)O\(_4\) nanoparticles improved the absorption of Fe and Cu by cucumber tissues significantly. | [122] |
| Chitosan nanoparticles (149 nm) or chitosan-indole-3-acetic acid nanoparticles (183 nm) at various ratio are mixed with La Molina nutrient solution | Lettuce (\(Latuca sativa\) L.) | Hydroponic | Hydroponically grown lettuce treated with chitosan nanoparticles and chitosan-indole-3-acetic acid nanoparticles exhibits significant increases of 42.6% and 30.9%, respectively, compared to the control. In terms of the effect on leaf size, chitosan nanoparticles outperformed other treatments with the largest leaves. | [123] |
Table 5. Some of the recent patent on nanotechnology approaches in aerated soilless farming.

| Patent No./Year/Title | Method of Soilless Cultivation | Invention | Ref. |
|-----------------------|-------------------------------|-----------|------|
| N102701844B/2012/Rich-selenium-germanium trace element nanometer nutrition fertilizer for vegetable and fruit soilless culture | Hydroponic | The invention describes the preparation and manufacture of nutritional fertilizer rich in selenium and germanium trace elements for vegetable and fruit cultivation in courtyards or balconies using soilless cultivation. | [124] |
| CN206354136U/2017/A kind of indoor micro-nano bubble hydroponic device | Hydroponic | The current utility model's cultivation cabinet is a semi-hermetic layer stereo system, with the bottom opening passage effectively carrying out indoor and cultivation cabinet air exchange with reference to the ventilation ventilating fan. Aeration will be used by the micro-nano bubble generator to generate the other micro/nano level water vapor bubbles. The amount of dissolved oxygen increases the nutrient solution essentially. | [125] |
| JP2015097515A/2013/Hydroponic raising seedling method, and hydroponic culture method | Hydroponic | The invention is to provide a hydroponic seedling system capable of raising a strong seedling and shortening the seedling raising period by adding a hydroponic solution containing micro-nano bubbles during the plant seedling period. | [126] |
| KR20130086099A/2012/The method manufacture silver nano antimicrobial & lacquer tree a composite in uses functionality crop | Hydroponic | The current innovation is a method of growing functional crops using a silver nano antibacterial agent and a lacquer composition through hydroponic cultivation. | [127] |
| CN105417674A/2015/Preparation method and application of micro-nano sparkling water | Hydroponic | The invention reveals a method for preparing micro-nano sparkling water, which benefits the field of scientific and technological agriculture in areas such as soilless production, fruit and vegetable washing, biological repair, dirty water processing, and so on. | [128] |
| WO2017101691A1/2015/The method for cultivation of plants using metal nanoparticles and the nutrient medium for its implementation | Hydroponic | Seed germination and subsequent plant cultivation on an aseptic agar nutrient medium containing a variety of organic and inorganic components important for plant growth, such as iron, zinc, and copper in the form of electro-neutral metal nanoparticles. Chitosan can also be added to the nutrient medium. This process improves seed germination as well as plant physiological and morphological indices such as root length and root behavior, chlorophyll content in leaves, sprout length, and green mass yield. | [118] |
| KR20060055895A/2004/Silver nano-containing bean sprouts manufacturing equipment | Hydroponic | The present invention relates to the production of bean sprouts for cultivation with silver-containing water when the bean sprouts are cultivated. | [129] |
| CN203482710U/2013/Oxygenation and disinfection device for soilless cultivation nutrient solution | Hydroponic | A filter, an oxygen generator, an ozone generator, a rapid micro-nano bubble generator, and an ultraviolet disinfector are all part of the soil-free nutrient solution oxygenation and disinfection system. | [130] |
| Patent No./Year/Title | Method of Soilless Cultivation | Invention | Ref. |
|-----------------------|-------------------------------|-----------|------|
| AU2015370052B2/2014/Nano particulate delivery system | Hydroponic and aeroponic | The invention describes a system for delivering nano lipids, more specifically a nano concentrate, a nano lipid stable emulsion, a method for preparing nano lipid concentrates, and a system for delivering lipids for use as a carrier in manufacturing, medical, animal, horticultural, and agricultural chemistry. | [119] |
| AU2016202162B2/2012/Plant nutrient coated nanoparticles and methods for their preparation and use | Hydroponic and aeroponic | The invention describes a nanofertilizer with at least one plant nutrient coated on a metal nanoparticle that is made by combining a metal salt and a plant nutrient in an aqueous medium and then adding a reducing agent to the solution to form a coated metal nanoparticle. | [131] |
| TW201902343A/2017/Fish and vegetable symbiosis system including a support, at least one planting unit, a filtering unit, and a breeding unit | Aquaponic | The invention discloses a fish and vegetable symbiosis system comprising a support, at least one planting unit, one filtering unit, and one breeding unit. The fish and vegetable symbiosis device is outfitted with an artificial closed form of composite filter material-activated carbon nano silver photocatalyst. | [132] |
| CN104719233A/2015/Nano-catalysis aquaponics method | Aquaponic | The invention includes nano-catalyst aquaponics preparation steps involving the use of purple grit dust, tourmaline, nano-titanium, nano-magnesia, medical stone, and zeolite. | [120] |
5.2. Recent R&D and Innovation on Nanotechnology Approaches in Soilless Substrate Culture

The incorporation of nanoparticles into soilless substrate culture is a promising area that needs to be explored further due to nanoparticles’ unique physicochemical properties and high rate of absorption and penetration. However, only limited research has been reported in this area. Nanoparticles have the potential to improve the quality of substrate culture as a growing medium for crop cultivation. Imalia et al. created a growing media substrate made of hydrogel polymer derived from diaper waste and straw nanofiber [133]. This study is a good approach to utilizing a large amount of single-use diaper waste. It is reported that the higher the concentration of straw nanofibers (0%, 1%, 5%, 10%, 15%, and 20%) added to the hydrogel of diaper waste, the higher the constant rate of nanofiber release. This is due to the greater concentration difference which subsequently results in a greater diffusion driving force. As a result, the durability of the hydrogel structure is reduced at higher concentrations of straw nanofibers, as nanofibers indicated more easily leave the tissues. Besides, the preliminary study on the use of this mixture as a growing medium revealed great potential, as the green beans (*Phaseolus vulgaris* L. var. *vulgaris*) remained perfectly healthy and alive for four days. As a result, the growing media has met the needs of plants for adequate nutrient and mineral elements. In another study, garbage compost was modified with nanocarbon (1–5% w/w of garbage compost weight) for the cultivation of tall fescue (*Festuca Arundinacea* Schreb.) [134]. Each root pipe sows 0.2 g tall fescue seed after 7 days of passivation, and the temperature ranges from 19 to 27 °C, with a relative humidity of 60% to 72% maintained between experiment periods. The invention also reveals that modified nano-sized carbon, when interpolated at 5%, can regulate and monitor lawn soil nematode in a variety of ways, as well as minimize the amount of insecticide used in the soil. Greening soilless culture substrate with the following raw material volume ratios has been introduced: perlite 70–80, zeolite 8–10, vermiculite 5–10, ash modification (including nano-calcium carbonate, emulsifier, sodium lauryl sulfate, acetyl triethyl citrate, superphosphate, sepiolite powder, glutinous rice flour, and wintergreen) 10–15, China tea (*Camellia oleosa* L.) seeds shell 20–30, tobacco leftovers 8–15, and fertile 5–10 of the slow-release nutrient is applied to the cultivation matrix every m³ [135]. The cultivation base has been reported to have a high graininess, light quality, soil air capacity, and moisture content. The modified ash granulation improves ash dustability and decreases ash windage loss. Therefore, providing a cost-effective growing medium with low disease and insect risk.

6. Nanotechnology Approaches in the Microgreen Farming

Fruits and vegetables, including microgreens, retain living tissues that continue biological processes such as water transpiration, dormancy, and respiration after harvesting. As a result, quality deterioration occurs after cropping, such as softening, browning, wilting, off-flavor, and nutritional loss. These phenomena are significant contributors to the shortening of the shelf life of fruits and vegetables and rendering the produce unfit for consumption. The tainted and deteriorated fruits and vegetables are the results of a lack of shelf-life extension methods. As a result, extending the shelf life of fruits and vegetables has emerged as a critical issue in the food industry [136]. To prolong the shelf life of fruits and vegetables, freshness-keeping strategies work by preventing microbial contamination, slowing the ripening period, and controlling respiration (control the senescence process), and controlling transpiration (control the environment’s water humidity) [137].

Researchers have created a variety of shelf-life extension strategies so far, including cold storage, irradiation preservation, chemical-based preservations, modified atmosphere packaging, and bio-preservation. Nanotechnology’s application in the field of extending the shelf life of fruits and vegetables may be able to overcome the limitations of conventional preservation methods due to the beneficial specific attributes of nanomaterials, such as a higher surface-to-volume ratio, high-efficiency barrier properties, and broad-spectrum antibacterial properties [138]. Li et al., for example, developed nano-packaging by coating ZnO nanoparticle powder into polyvinyl chloride (PVC) film [139]. Nano-packaging
substantially reduced the rate of fruit decay and decreased the accumulation of malondialdehyde from 74.9 nmol/g in the control to 53.9 nmol/g in the nano-packaging, as opposed to the control (PVC film). Luo et al. developed low-density polyethylene (LDPE) coated with CaCO$_3$ nanoparticles in another study [140]. The nano-packaging reduced the total bacterial count as well as the yeast and mold count significantly. Furthermore, when compared to control yam samples, nano packaged fresh-cut Chinese yam (*Dioscorea polystachya* Turcz.) had significantly lower peroxidase, phenylalanine ammonia-lyase, and polyphenol oxidase activities. Nano-packaging, on the other hand, substantially decreased browning index, total phenolic and malondialdehyde content while maintaining overall visual appearance, titratable acid, and ascorbic acid. Application of edible coatings as a thin layer of edible film on the fruits and vegetables is another method of preservation that has been shown to improve the fruit and vegetable quality and shelf life by reducing gas exchange, deterioration, moisture loss, gas permeability (O$_2$, CO$_2$), as well as preserving the flavor, color, and appearance of the fruits and vegetables [141]. Zhu et al., for example, introduced a silicon oxides nanoparticles-chitosan complex (NSSC) film for tomato preservation [142]. The NSSC film substantially increased the shelf life of green tomatoes by slowing weight loss and softening, as well as delaying the loss of complete soluble solids and titratable acids. Tomatoes coated with NSCC film had higher antimicrobial activity than those coated with only chitosan films or the control.

Furthermore, combining nanomaterials with other preservation treatments has been shown to have a synergistic impact in extending the shelf life of harvested foods and vegetables [143]. Xu et al. studied the effect of 1-methylcyclopropene in combination with Ag nanoparticles on the preservation of king oyster mushroom (*Pleurotus eryngii*) [144]. They discovered that the combined preservation method could delay ripening and extend the shelf life of king oyster mushroom by inhibiting polyphenol oxidase activity while increasing superoxide dismutase and catalase activity. Additionally, the authors discovered that the combined technology outperformed the individual treatments of 1-methylcyclopropene and silver nanoparticles coating. In another study, Liu et al. used ZnO nanoparticles in conjunction with microwave heating to reduce the total bacterial count and improve the product quality of vacuum-packed Caixin (*Brassica chinensis* L.) [145]. The vacuum-packaged Caixin produced an acceptable product quality with the lowest bacterial colony number of 2.45 log CFU/g when treated with 0.02 g/kg ZnO nanoparticles and microwave heating at 400 W/150 s (microwave power/heating time).

Therefore, nanotechnology could be exploited to preserve microgreens, thereby extending their shelf life. However, despite their enormous potential, no previous research on this topic has been published to the best of the authors’ knowledge.

### 7. Future Research Directions

In the agricultural industry, developing sustainable cropping methods and ensuring food security have emerged as one of the major concerns. In comparison to field-based cropping methods, greenhouse-based hydroponic growing methods are advantageous as they require less machinery and pesticide use, allow farming on non-arable lands, and produce a higher quality and higher yield. However, according to the US Environmental Protection Agency (EPA), the agricultural industry accounts for approximately 10% of the total greenhouse gas emissions in 2019 [146]. As a result, a sustainable cropping method must be established by fully utilizing the benefits of nanotechnology. Another critical factor to consider when evaluating cropping methods’ sustainability is water and energy consumption. According to the UN Food and Agriculture Organization (FAO), agriculture accounts for approximately 70% of global water use, with 2600 km$^3$ of water used annually to irrigate crops around the world [147]. As a result, as previously discussed, the incorporation of nanotechnology with soilless farming could significantly reduce water consumption in the agricultural industry, thereby resolving the water shortage issue. However, another concern about soilless farming arises from its high-energy consumption.
Therefore, the energy efficiency of soilless farming must be improved in order to reduce reliance on nonrenewable energy sources.

Furthermore, nanotechnologies have a large potential for sustainable agriculture. The use of nanomaterials in agricultural practices and soil, on the other hand, raises concerns about potential health effects on humans and the environment. According to this point of view, the goal of achieving sustainable agriculture overlaps with the need to balance the benefits of nano-products in addressing environmental problems with the assessment and management of potential environmental, health, and safety risks due to their nanoscale materials. As a result, the applications of nanomaterials in agriculture necessitate further research in terms of the design and synthesis of safe nanomaterials that do not negatively impact plant growth and development, the environment, or humans, research into the precise mechanisms of nanomaterials absorption and mobilization in plants, and multidisciplinary approaches studies in the design and implementation of nanotechnology applications in plants.

As previously stated, one of the primary concerns in aerated nutrient solutions cultivation (i.e., hydroponic, aquaponic, and aeroponic) is nutrient availability; thus, using nutrient nanoparticles is able to minimize nutrient losses and improve nutrient uptake and bioavailability in crops. Control environmental conditions in soilless cultivation can also be improved by incorporating a nano-sensor, which provides real-time detection of pH, temperature, and nutrient amount. In the cultivation of soilless growing media, the incorporation of nanoparticles into the porous substrate can improve the overall quality of substrate culture as a crop cultivation growing medium. The incorporation of nanoparticles into the porous substrate in the cultivation of soilless growing media can improve the overall quality of substrate culture as a crop-cultivation-growing medium. The effect of nanomaterials application on plant trait improvement against environmental disease and stress, as well as plant nanobionics to alter or improve the function of the plant tissue or organelle in soilless farming, should also be investigated. Furthermore, nano-packaging combined with other preservation methods can be investigated in order to extend the shelf life of microgreens, thereby resolving the issue of microgreens' short perishability limit and shelf life.

8. Conclusions

In conclusion, soilless farming provides a sustainable and environmentally friendly approach because the cultivation reduces water use, pesticide use, with almost no herbicide use, as well as minimizes fertilizer waste and leaching, thereby, reducing water pollution, which has become a major concern in recent years. Meanwhile, nutrient nanoparticles may improve nutrient uptake and bioavailability in crops, thereby improving crop production, yield, and quality. Nano-sensing can be used to detect and quantify the amounts of supplemental nutrients required to ensure the availability of the desired nutrient throughout the cultivation process. The use of soilless substrate instead of soil could solve the problem of soil scarcity and limitation while also reducing the abundance of agricultural waste that could cause an environmental problem. The incorporation of nanomaterials in the soilless substrate could improve the substrate's quality as a growing medium. However, assessing nanomaterials before their application is critical to ensure that they are not toxic or harmful to crops, humans, or the environment. As a result, further research into the incorporation of nanotechnology with soilless farming and microgreen farming will benefit global food security and sustainability.

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Abbreviations

FAO: UN Food and Agriculture Organization; FDA: US Food and Drug Administration; EPA: Environmental Protection Agency; NPK: nitrogen-phosphorus-potassium; WUE: water use efficiency; EC: electrical conductivity; ROS: reactive oxygen species; SiO₂: silicon dioxide; ZnO: zinc oxide; ZnSO₄: zinc sulfate; HgSe: mercury selenide; Fe₂O₃: ferrous ferric oxide; Fe₃O₄: ferric oxide; Y₂O₃: yttrium oxide.

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