Nanotechnology in Soilless/Microgreen Farming

Subjects: Agronomy

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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 p H, 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. 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.

2.1. 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 1. Positive effects of high uptake of Fe_2O_3 nanoparticles on hydroponically grown spinach were observed; increased stem and root lengths, biomass production, and magnetic properties [8]. 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) [9]. 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). Haghighi 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 [10]. 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 [11]. 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 [12]. 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-} [13]. 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 [14]. 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_3O_4 nanoparticles, and nano-zerovalent Fe to hydroponically grown rice reduced arsenic uptake [15]. 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_3O_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 [16].

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 [17][18]. 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 [19]. 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) [20]. 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 [21]. According to Zhao et al., Y_2O_3 nanoparticles and released Y^{3+} did not affect rice germination rate. Low concentrations of Y_2O_3 nanoparticles (1, 5, and 10 mg/L) improved rice root elongation [22]. Notably, when the concentration of Y_2O_3 nanoparticles reached 20 mg/L or higher, root elongation was significantly inhibited. According to physiological and biochemical characteristics, Y_2O_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_2O_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 [23]. 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 [24]. 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 [25]. Nano-Se, Premix, spirulina, bentonite, $Ca(H_2PO_4)_2$, 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 [26]. 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 2. A patent has been filed, for example, to introduce the utility model of an indoor micro-bubble hydroponic device [23]. 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 seedling 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 [23]. 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 [23]. 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 [27]. 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 [28]. 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 [29]. The aquaponic system's fish culture water body was treated with a nano catalyst composed of TiO_2 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 1. 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_2O_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_2O_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_2O_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.	[8]
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.	[9]
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})	tomato (*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%).	[10]
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_2SiO_3 and H_4SiO_4 and control.	[11]
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).	[12]

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.	[17]
Fe_3O_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_3O_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.	[30]
Cu-Fe_2O_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_2O_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_2O_4 nanoparticles improved the absorption of Fe and Cu by cucumber tissues significantly.	[31]
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.	[32]

Table 2. 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.	[33]
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.	[34]
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.	[35]
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.	[36]

Patent No./Year/Title	Method of Soilless Cultivation	Invention	Ref.
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.	[37]
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.	[27]
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.	[38]
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.	[39]
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.	[28]
AU2016202162B2/2012/Plant nutrient coated nanoparticles and methods for their preparation and us	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.	[40]
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. For water quality filling, the fish and vegetable symbiosis device is outfitted with an artificial closed form of composite filter material-activated carbon nano silver photocatalyst.	[41]
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.	[29]

2.2. 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 [42]. 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.) [43]. 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 m^3 [44]. 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.

3. 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 [45]. 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) [46].

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 [47]. Li et al., for example, developed nano-packaging by coating ZnO nanoparticle powder into polyvinyl chloride (PVC) film [48]. 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 [49]. 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 [50]. Zhu et al., for example, introduced a silicon oxides nanoparticles-chitosan complex (NSSC) film for tomato preservation [51]. 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 [52]. Xu et al. studied the effect of 1-methylcyclopropene in combination with Ag nanoparticles on the preservation of king oyster mushroom (*Pleurotus eryngii*) [53]. 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.) [54]. 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.

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