agronomy

Review

Nano-Food Farming: Toward Sustainable Applications of Proteins, Mushrooms, Nano-Nutrients, and Nanofibers

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Abstract: The relationship between agriculture and food is very close. It is impossible to produce adequate crops for global food security without proper farm management. Farming practices represent direct and indirect controlling factors in terms of global food security. Farming management practices influence agro-food production from seed germination through to the post-harvest treatments. Nano-farming utilizes nanotechnologies for agricultural food production. This review covers four key components of nano-farming: nano-mushroom production, protein-based nanoparticles, nano-nutrients, and nanofibers. This provides a comprehensive overview of the potential applications of nanotechnology in agriculture. The role of these components will be discussed in relation to the challenges faced and solutions required to achieve sustainable agricultural production. Edible mushrooms are important to food security because they are a nutritious food source and can produce nanoparticles that can be used in the production of other food sources. Protein-based nanoparticles have considerable potential in the delivery of bioactives as carriers and other applications. Nano-nutrients (mainly nano-selenium, nano-tellurium and carbon nanodots) have crucial impacts on the nutrient status of plant-based foods. Carbon nanodots and other carbon-based nanomaterials have the potential to influence agricultural crops positively. There are promising applications of nanofibers in food packaging, safety and processing. However, further research is needed to understand the impacts and potential risks of nanomaterials in the food production system.

Keywords: agri-food production; carbon nanodots; food packaging; food safety; nano-farming; nano-selenium; nano-tellurium

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1. Introduction

Due to the world's growing population (more than 8.09 billion people), long-term global food security is a serious concern [1]. Such security requires a 70% increase in global food production by 2050 to meet projected population growth [2]. Global agri-food production faces many problems associated with intensive farming under climate change, including soil degradation [3,4], decreased water quality [5], and biodiversity loss [6,7]. Agriculture is humanity's main source of food [8]. Therefore, there is an urgent need for the conservation of the natural resources agriculture relies on, including soil and water [9]. Therefore, sustainable agriculture is a crucial approach to achieve global food security. Several strategies have been proposed to achieve sustainable agriculture, including genetic engineering of agricultural crops [10,11], use of nanotechnology [12–14], meeting the sustainable development goals [15], application of bacteriophages [16], nano-enabled precision farming [12,17], and nano-enabled seed treatments [18,19].

Several reports have been published on the benefits of nanotechnology for sustainable agriculture, such as controlling agro-processes [20], enhancing food quality and safety [21], reducing agro-inputs [22], effective agrochemical delivery [23,24], detecting abiotic/biotic stresses in plants [25,26], mitigating abiotic/biotic stresses in plants [17,27], and enhancing the uptake of nutrients from soil [28,29]. Therefore, nano-enabled technology has great potential for promoting sustainable agriculture by revolutionizing agro-practices, leading to reduced losses and increasing the efficiency of inputs [22]. Many agricultural nano-formulations are considered “new-age materials”, with a wide variety of nano-insecticides, nano-herbicides, nano-fungicides, and nano-fertilizers available [22].

Nano-farming can be defined as the application of nanomaterials during and post-farming to produce food products, or as the application of nanotechnology for agri-food production [21,30–32]. Research on nano-farming systems has focused on food production through cropping systems [33,34] and animal production systems [35,36]. This includes mushrooms [37,38], vegetables [39], row crops [40], cattle production [41], fisheries [42], and aquaculture like seaweed farming [43], among others. Traditional farming depends on the use of conventional agrochemicals, including fertilizers and pesticides, which have a lot of negative consequences for human and ecosystem health [44,45]. These traditional agro-practices contribute to problems including climate change, declining soil fertility, excessive reliance on chemical fertilizers and pesticides, and soil pollution [30]. Thus, there is a need to modify agriculture in a way that will avoid these problems. Nano-agriculture has shown promise for protecting soil and environmental health [46].

Reviews are crucial for keeping researchers and scientists up to date on pressing issues by providing information on and critiques of cutting-edge scientific breakthroughs. Therefore, this review discusses nano-food farming, focusing on selected sectors of nano-farming, including edible mushrooms, proteins, nano-agrochemicals (mainly nano-nutrients), and nanofibers. Nano-applications relevant to these sectors will be highlighted, along with their challenges and unknowns.

2. Toward Nano-Food Production

The Nano-Food Lab was established at Debrecen University in Hungary in 2008. The primary mission of this Lab is to investigate the use of nanotechnology in agricultural production and to commercialize the research results as new products. This strategy has produced many patents and publications in areas including nano-selenium, nano-tellurium, mushroom applications, nanofiber for biotechnology, and carbon-based nanomaterials (more details have been published by Sári et al. [34]). The nano-selenium production was biologically developed from dairy products. This technology was patented [47,48] and demonstrated as a commercial product that has been applied to applications such as nano-biofortification for human health [49], crop production under stress [50–52], and as a nano-bio fungicide agent [53]. The edible mushroom research has included mushroom farming systems and benefits [37], the role of mushroom as antimicrobial agents [54], the production of mushrooms for food and energy [55], nutritional and medicinal attributes of mushrooms [55], producing nanoparticles using mushrooms [56], and green biotechnology related to mushrooms [55]. Black foods, mainly banana and garlic, have received considerable attention at the Nano-Food Lab. Black foods can be found in both natural and processed forms, being present in our daily life for several years without being noticed. In addition, the chemistry underlying the black color of black foods has not yet been fully understood. More than 130 black foods are reported in the current review, which belong to 3 main groups and 12 sub-groups. In the studied black foods, melanins and anthocyanins are the primary pigments, along with other pigments such as chlorophylls, carotenoids, and tannins. The health potential of black foods is also discussed. Due to their high concentration of phytochemical and phenolic compounds, black-colored foods are beneficial in terms of preventing diseases and boosting the immune system. As a promising natural pigment and antioxidant compound source, black foods could be used as functional foods. Several questions on black foods are still open and need more investigation, especially the mechanisms by which the black color is formed in fruits and vegetables [57]. The biotechnological applications of nanofibers have been studied in our Lab and published about in relation to the agricultural sector [58] as well as the water and energy sectors [59]. The successful applications of nanofibers could be noticed in sectors such as producing clean water, sustainable energy, and safe food. The biotechnological applications of nanofibers may also include the production of fresh water and wastewater treatment, producing, converting, and storing energy, and different activities in the food sector. Furthermore, microbial applications of nanofibers in the biomedicine sector, and the most important biotechnological approaches, mainly plant tissue culture, are under processing for publication. Applying nanofibers in the field of plant tissue culture is a promising approach because these nanofibers can prevent any microbial contamination under in vitro conditions, but the loss of media by evaporation is the main challenge in this application. Last but not least, the microbial production of a selenium–tellurium nanoalloy for medicinal application was achieved by Muthu et al. [60]. The main guideline in all these previous works was to use sustainable, green, nano-biotechnology to produce safe and healthy foods. Different applications of nanotechnology in agri-food production are presented in Figure 1, as well as some suggested farming systems, challenges, and solutions focused on types of mushroom farming. To overcome the main problems facing these farming systems, integrated farming practices and sustainable management are needed.

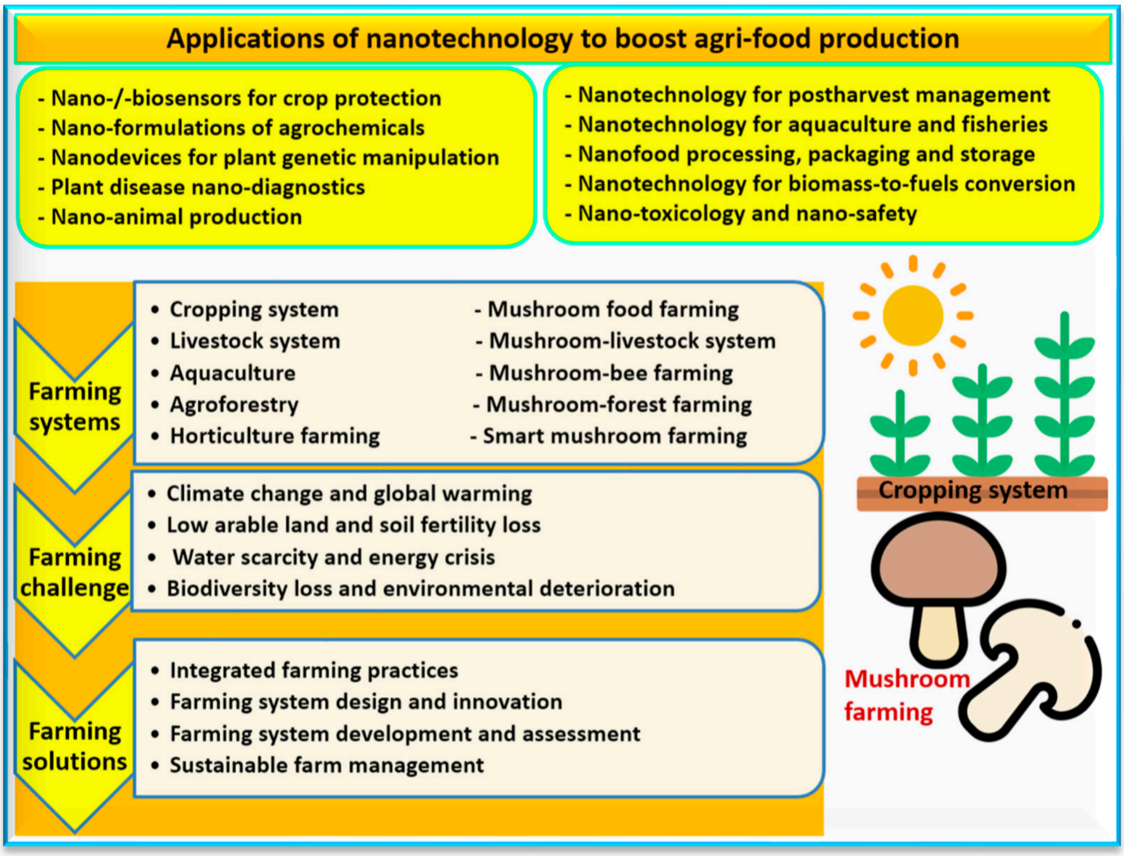


Figure 1. Some suggested farming systems, challenges and solutions focused on types of mushroom farming, as well as some applications of nanotechnology in agri-food production [30,61].

3. Global Food Crisis and Sustainable Agriculture

Agriculture is a major source of raw materials, foods, fuels, fibers, and other ecosystem services that are important for human survival [62]. However, the growing global population represents a stress on the agriculture sector, along with increasingly difficult challenges, including protecting the environment and mitigating climate change [61]. The FAO reported that about 828 million people suffered from hunger globally in 2021 due to an inadequate and non-healthy diet [63]. Several practices have attempted to address food production needs through the use of chemically based pesticides, herbicides, and fertilizers, but these have documented negative effects on agricultural biodiversity and natural ecosystems [61]. Key facts regarding global farming are shown in Figure 2 and important food products and their mode of production according to [64,65] are shown in Figure 3. Global farming has been a driving force behind climate change due to greenhouse gas emissions from agri-food systems during the last twenty years, as shown in Figure 2. Over the same period, the agricultural land area decreased by 86 million ha globally.

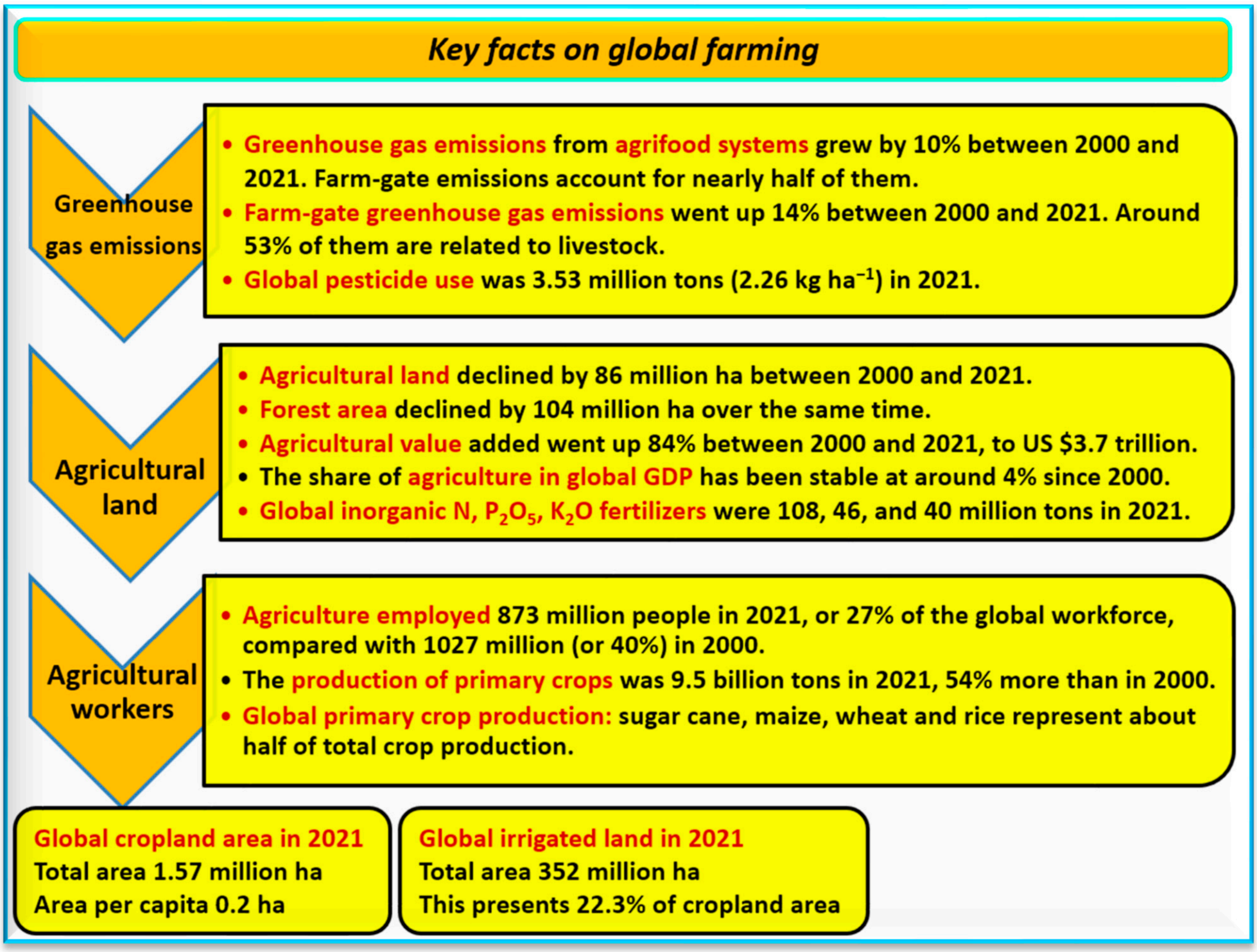


Figure 2. Some key facts about agriculture on the global level according to the FAO [65].

Many crops were important global commodities in 2021, including sugar cane, maize, paddy rice, wheat, oil palm fruits, potato and other crops, with production (in million tons) of 1859; 1210; 787; 770; 416; 376; and 4069; respectively [65]. Global mineral fertilizer use reached 108, 46, and 40 million tons for N, P_2O_5, K_2O fertilizers, respectively, in 2021 [56], with a trend of increasing fertilizer use over time [66]. The same trend of increasing use was also observed for the global application use of pesticides, which went from 2.178 to 3.535 million tons from 2000 to 2021 [56]. The harmful use of pesticides in agriculture over time has also led to the deterioration of both human health [44] and the broader environment, mainly non-target species in soil, air, and water [64]. Several efforts have been made to avoid these problems by moving toward the sustainable application of agrochemicals (pesticides), such as nano-formulation-based pesticides [67], green and microbial pesticides [68], and bio-pesticides [69]. The same trend exists for mineral fertilizers, where significant progress has been made toward sustainable fertilizer management through smart fertilizers [40], biogenic nano-fertilizers [29], nanocomposite-based smart fertilizers [70], and nano-biofertilizers [71].

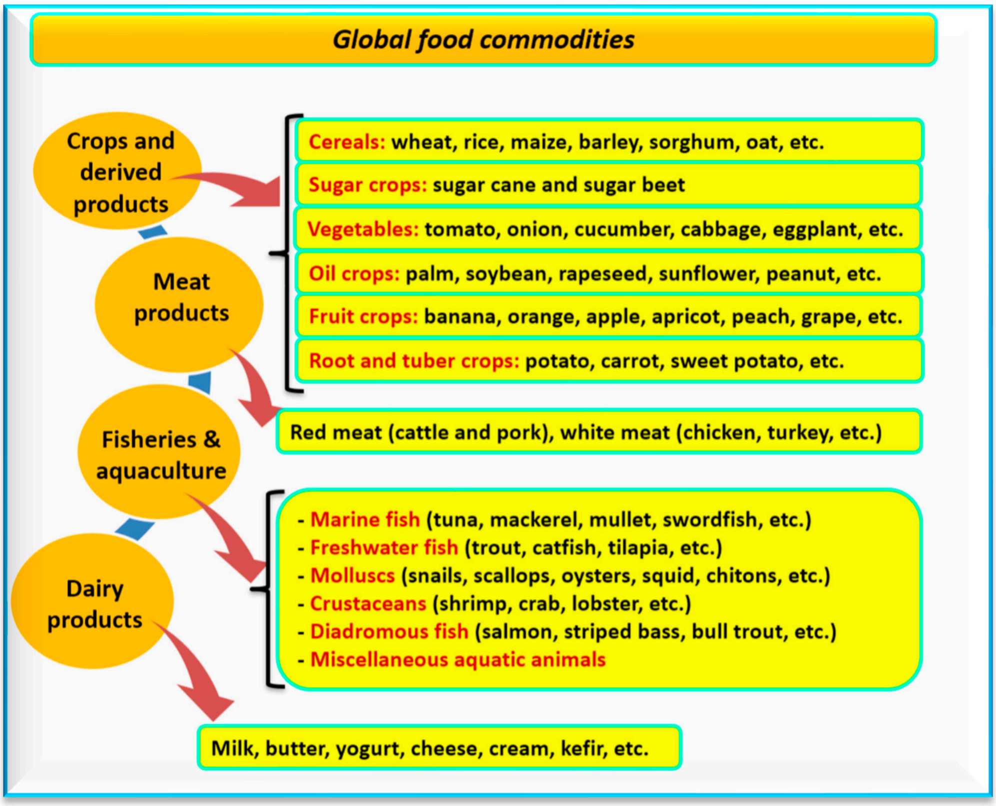


Figure 3. Major global food commodities according to the FAO [65].

Integrated farming practices are a critical tool for achieving sustainable farming and should be adopted. These practices may include no-tillage farming [72], crop rotations [73,74], and crop–livestock mixed systems [75], among others [76]. Sustainable farming cannot exist using only a single approach, as integrated and systematic technologies are needed to overcome the negative effects of single practices and avoid unhealthy and imbalanced effects on agro-ecosystems [61]. The new approaches are crucial for addressing the global food crisis through the application of proper nano- and/or bio-technologies along with integrated farming practices such as irrigation, fertilization, soil tillage, pre- and post-harvest, and pest management. The global food crisis has several dimensions, including economic [77], water security [78], global pandemics [79–81], and food loss and waste issues [82].

4. Nano-Food Farming: An Overview

The production of food utilizing nanotechnologies can be called nano-farming, and the applications are very diverse. The significant applications of nanotechnology in the food industry may involve three main groups: food security, food packaging, and food processing (Figure 4). Four crucial groups related to agri-food have been selected for detailed discussed in this review. The first group is edible mushrooms, the second group is protein-based nanoparticles, the third group is nano-nutrients, and the last group is nanofibers. The use of nanotechnology in agri-food production can be noticed in several sectors, such as nano-/biosensors for detecting pathogens [83], nano-management of agro-wastes [84,85], nano-enhancement of the shelf-life of agri-products [86], nano-identification and tracking of agri-foods [87], nano-agrochemicals for crop improvement [88], nanofibers for wastewater treatment [58,89], nano- or bio-remediation of soil and water [90], and nano-carriers to provide targeted delivery of treatments [91]. For example, the most common nanomaterial-based sensors include magnetic NPs, gold NPs, silica NPs, carbon nanotubes, peptide nanotubes, and quantum dots, which are used to detect different pathogens and their toxins [92].

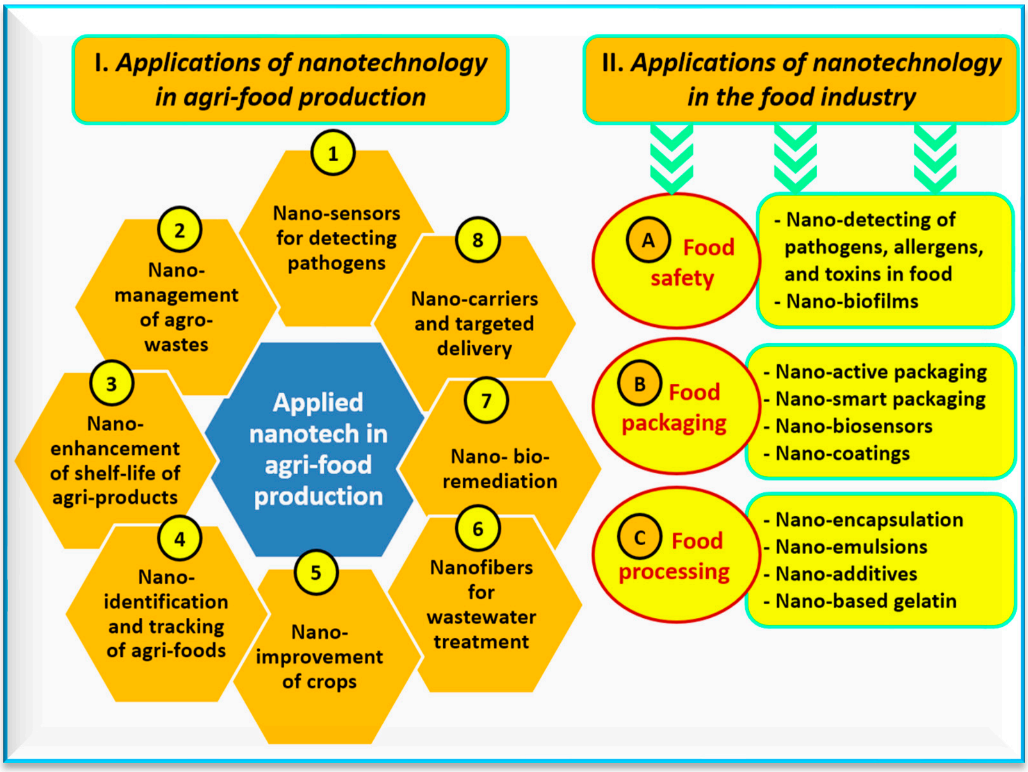


Figure 4. Applications of nanotechnology in agri-food production (part I) and in the food industry (part II) [21,31].

5. Protein-Based Nanoparticles

5.1. Protein-Based Nitrogen Nanoparticles

In an era where the quest for sustainable agriculture has never been more urgent, nanotechnology is emerging as a promising tool for more efficient and sustainable practices [93,94]. Nanomaterials (NMs) have distinctive properties, including a high surface area, reactivity, agglomeration, and penetration capability, along with a small size and structures that are useful [95]. Nanomaterials are able to provide controlled release of agrochemicals and site-targeted delivery of various macromolecules. This improves plant growth through efficient nutrient utilization, development, and protection via plant disease resistance [95] and reduced environmental losses [96]. Nitrogen (N) is the most common limiting element in agricultural production [97]. However, the nitrogen use efficiency of crops is very low (30–40%) because of losses via surface runoff, leaching, ammonia (NH_3) volatilization, N oxide (N_2O, NO, NO_x) emissions and long-term incorporation of mineral nitrogen into soil organic matter by soil microorganisms [74,98,99]. Therefore, NMs, with their unique properties, can regulate nitrogen transformations and reduce losses by adsorbing available nitrogen or changing the physical and chemical properties of the soil [74].

Among the N fertilizers, urea is a rich source of nitrogen and the most widely used globally [93]. Nano-N forms such as nano-hydroxyapatite, cellulose polymer nanocomposite [100], urea incorporated with cellulose-based hydrogel [101], and urea-doped nanofertilizer [93] have been used to reduce urea's high solubility and slow the release of the mineral nitrogen. More details on these NMs and other combinations, along with their ability to slow N release and enhance plant N uptake, were discussed by Abhiram et al. [96]. In the case of organic farming, the chemical and physical methods of NP synthesis cannot be used. However, the valorization of waste products and their transformation into NPs could be a practical solution, along with the biological synthesis of NPs [102]. Chitosan NPs extracted from shrimp wastes are considered an eco-friendly nano-N source that increases the wheat grain yield and most of its components as well as nitrogen and potassium concentrations [103]. Similarly, the foliar application of nano-NPK produced from agro-wastes at a 25% concentration significantly promoted the growth, yield, and harvest of pepper compared to the control and chemical fertilizer-treated plants in a study by Abdel-Aziz et al. [104].

Organic farming is generally regarded as one prototype to enhance the sustainability of modern agriculture and decrease its environmental impacts. Cereal/legume intercropping is one strategy for eco-functional intensification in organic farming because the legumes in this system reduce the application of chemical N fertilizer and improve the uptake and fixation of nitrogen [105]. Abou El-Enin et al. [97] studied the ability of nano-chitosan-loaded nitrogen to enhance the utilization of mineral N applied to a maize–soybean intercropped system. Based on the gross productivity of maize (grains) and soybean (seeds), total revenue, and net profit, fertilizing maize plants with 216 kg nitrogen ha^{-1} (the intermediate N fertilizer treatment in the experiment) plus nano-chitosan-loaded N in an intercropped rotation was more beneficial than utilizing the intercropped or mono-cropped systems with mineral N fertilization only [97]. Additionally, the nano-chitosan-loaded nitrogen composite reduced the need for nitrogen fertilizer application by approximately 25% of the recommended rate, which lowered the possibility of environmental N pollution [97]. In another study, the intercropping of cowpea with maize and fertilizing with 75% of the recommended dose of mineral N along with 25% nano-urea increased the productivity of maize by 17.03 and 14.11%, and the total fresh forage of cowpea by 32.11 and 38.94%, compared with mineral fertilization in the first and second seasons, respectively [106]. Promising results were found regarding the effectiveness of nano-fertilizers, particularly nano-nitrogen, over conventional fertilizers in organic farming. In particular, the application of a combination of organic manure and nanofertilizers resulted in higher yields of wheat, sesame, pearl millet, and mustard by 5.35, 24.24, 4.2, and 8.4%, respectively, and better plant growth performances when compared to fields under conventional chemical fertilizer practice [107].

Despite nano-encapsulation being more efficient and being considered more environmentally friendly and safer compared with pesticides, there are concerns about the survival of microorganisms and the possible disruption of the legume–rhizobium symbiotic system under nano-applications [108]. There are examples of instances when the toxicity and bioaccumulation of nanoparticles led to setbacks [95], which makes toxicological studies necessary [104]. In addition, to expand the availability of nanoparticles, particularly N-NPs, in the agricultural market, future research should be designed to find more accessible and applicable manufacturing methods [97].

A promising role for protein-based nanoparticles (PBNs) in modern farming is the application of soybean PBNs as nano-carriers for the encapsulation of bioactive substances [109]. These bioactives can be transformed by many nano-forms, including nanoparticles, nano-gels, nano-fibers, and other nano-structured substances, where the encapsulated bioactives in PBNs can be stabilized in different environmental conditions, such as heat, light, and others [110]. Furthermore, the use of proteins as substrates for the preparation of nanoparticles as carriers of bioactive ingredients has received increased attention in the drug and food industries due to their stability, good water solubility, and bioaccessibility [111,112]. Along with applications of PBNs, which are needed to enhance the oral bioavailability from food protein NPs [113], the delivery of bioactive compounds using

PBNs is a crucial issue [114,115]. Thus, the safety of PBNs and their biocompatibility as well as needed regulations were discussed in many studies focused on the rules of the US Food and Drug Administration (FDA) for approved nano-formulations. These studies addressed topics such as designing biocompatible protein NPs [116], functional protein nanoparticles [117], application of protein NPs to encapsulate functional food [118], and protein-based NPs for therapeutic nucleic acid delivery [119]. More studies are needed on foods, focusing on alternative proteins, sustainable packaging, food architecture, and precision nutrition [120].

5.2. Alternative Protein Nanoparticles

The rapidly increasing global population, demand for food production, generation of food waste, and need to establish a sustainable environment have renewed interest in animal-protein substitutes such as plant, algal, fungal, and insect sources [121,122] and in the development of effective waste management strategies [123]. In addition to these practices, nanotechnology has emerged as a promising tool due to the unique properties of nanomaterials [124] and by offering opportunities to make food production more sustainable [125]. Nanotechnology provides better sensors, membranes, and sorbents, novel materials for timed and targeted delivery of agrochemicals, and new materials for monitoring and improving animal health [125].

Among the alternative proteins, plant-based protein is the most well-established category [122]. The NPs generated from plant-based proteins are preferred over carbohydrates and synthetic polymeric-based materials for food or medical applications [126]. In general, zein and gliadin are the predominant plant proteins used to develop nanoparticles due to their easy solubility in aqueous conditions [126]. Sustainable nanotechnology can be established by using biodegradable waste [127]. For example, in the rice milling industry, rice bran waste is an under-utilized sustainable resource that has been used to prepare nanoparticles with chitosan. These nanoparticles showed interesting properties by delaying degradability in gastric conditions in the small intestine with good biodegradability. When loaded with curcumin, an improvement in solubility and an increase in the entrapment efficiency were noted. Additionally, they exhibited higher cytotoxicity compared to free curcumin for Caco-2 cells, which has great potential for application in hydrophobic active agent delivery [128]. Like plant protein, edible insects are also sustainable sources of proteins [129]. Study of the potential of insect proteins to form nanoparticles (uncoated or coated with chitosan) and protect hydrophobic nutraceuticals (curcumin) revealed a moderate interaction resulting in a moderate encapsulation efficiency but an efficient release profile [129]. Coating the protein nanoparticles with chitosan protected the curcumin in the gastric phase, proving their promise as a delivery vehicle [129].

Animal proteins can also have interesting characteristics. For example, gelatine biopolymer nanoparticles have significant potential use in the food industry due to the numerous available active group sites for attaching target molecules [130]. However, these animal proteins can be associated with immunogenic responses [126] and may be rejected due to sociocultural (including religious) and health concerns [130]. Salah and his collaborators [131] characterized the protein nanoparticles extracted from chicken feathers, which were prepared by the reduction technique with plant extracts followed by ultrasonic treatment. The nanocomposite of these proteins showed great potential application in the future development of textile finishing due to its high loading efficiency and targeting effect. In another study, improvement of the mechanical properties of biobased mullet scale gelatin–carbon nanoparticles occurred upon the addition of the carbon nanoparticles, showing an increase in the elongation at break (clear plasticizing effect) and a decrease in the stiffness [132].

6. Nano-Farming of Mushrooms

6.1. Mushroom-Based Nanoparticles

The exploration of mushroom-derived nanoparticles has gained considerable attention in the field of nanotechnology in recent years, as seen in Table 1. This can be observed particularly through the utilization of some significant bioactive compounds, such as β-glucan polysaccharides [133], chitosan [134], and carbon nanodots produced through advanced technologies [135]. Moreover, there is a burgeoning interest in the capacity to synthesize gold and silver nanoparticles [136]. Edible mushrooms are an important source of human food. β-glucan, one of the most significant bioactive compounds present in mushrooms, is a relatively large molecule produced through intricate biochemical processes that entail specific enzymes, specifically β-glucan synthases, and involve structural components such as glucose molecules. These processes result in the formation of the distinctive beta-1,3 and beta-1,6 linkages that characterize β-glucans within the fungal cells [54,137]. Beta-glucans exhibit differences in their macromolecular structure, glycosidic linkage, and functional characteristics, depending on their respective sources [138]. These can be formed into nanoparticles with advantages like an increased surface area, improved bioavailability, biodegradability, enhanced mechanical properties, and reduced environmental impact [133]. B-glucan nanoparticles from *Lentinula edodes* and *Pleurotus ostreatus* have demonstrated significant antitumor activity against colon and breast cancer cells. *L. edodes* has exhibited particularly high potential compared to *P. ostreatus* [139]. Chitosan has a high molecular weight and low immunogenicity. It is the product of the deacetylation of chitin that is present in the exoskeletons of crustaceans, insects, and fungal cell walls [140]. It is comprised of a blend of β-(1,4)-linked-D-glucosamine and N-acetyl-D-glucosamine. Its primary repetitive unit is characterized by β-(1,4)-linked-D-glucosamine [141].

Table 1. The characterization of mushroom-based nanoparticles and the potential applications.

Source/Produced Nanoparticles	Mushroom Species	Nano Size (nm)	Application	Ref.
Water-soluble β-(1→3)-d-glucan	*Sparassis crispa*; *Phellinus linteus*	150–390	Food, cosmetic, and pharmaceutical industries	[142]
β-glucans	*Lentinula edodes*	10–25	Cancer treatment and therapeutic interventions	[139]
β-glucans	*Pleurotus ostreatus*	40–50	Cancer treatment and therapeutic interventions	[139]
Chitosan nanoparticles	*Pleurotus eryngii*	2.25	Antimicrobial coatings, drug delivery systems, wound dressings, food additives	[143]
Chitin nanocrystals	*Lentinula edodes*	142–182	Biomedical applications, drug encapsulation, polymer composite, cosmetics, textile industry	[144]
Carbon nanodots	*Pleurotus* spp.	4.7–8.8	Cancer treatment and therapeutic interventions, antimicrobial coatings, drug delivery systems, wound dressings, food additives	[145]
Carbon nanodots	*Pleurotus* spp.	2–10	Ultrasensitive detection of Hg^{2+} ions and photoinduced bactericidal activity	[146]
Copper oxide nanoparticles	*Pleurotus citrinopileatus*	20	Biomedical applications (mainly antimicrobial and anticancer)	[147]
Silver nanoparticles	*Ganoderma* spp.	------	Antibacterial and therapeutic agents	[148]
Zinc oxide nanoparticles	*Cordyceps militaris*	1.83	Therapeutic investigations as antioxidant, antidiabetic, and antibacterial potential	[149]

Numerous researchers were involved in transforming these macromolecules into nanoparticles to improve bioavailability, control substance release, augment surface area, optimize the utilization of functional properties (excellent physicochemical, antimicrobial attributes) and quantum size effect [150], and contribute to sustainable development [134,141,151]. Carbon nanodots (CNDs) are nanoscale carbon-based particles smaller than 10 nm. They have attracted considerable attention due to their fluorescence, antimicrobial properties [152], and easy preparation [153]. They can be synthesized from mushroom extracts through hydrothermal synthesis [152,154,155] by reacting with precursor substances in a high-temperature and high-pressure aqueous environment [135,156]. The production of synthesized silver (Ag-NPs) and gold (Au-NPs) nanoparticles by microorganisms is an emerging field of nanobiotechnology, which offers a cost-effective, rapid, and environmentally friendly green chemistry method [136]. Several edible mushrooms have been explored for their ability to reduce metal ions and facilitate the formation of stable metal nanoparticles [157,158]. Fungi like *Agaricus* [153,154], *Ganoderma* [155,156], *Inonotus* [157,158], *Pleurotus* [142,143], and *Schizophyllum* [144,145] species have been used in the biosynthesis of silver and gold nanoparticles. The process involves the use of fungal extracts or biomass to achieve the reduction of metal ions to their respective nanoparticles.

6.2. Nano-Applications in Food Packaging

Nanotechnology, with its ability to manipulate materials at the molecular and atomic levels, is poised to revolutionize various industries, including food packaging [159]. Packaging plays a pivotal role in ensuring food safety. It represents a crucial step in the food supply chain [160] and plays a role in establishing sustainable value within food chains while mitigating food waste [161]. Its primary objectives include preventing spoilage and contamination, enhancing sensitivity through the facilitation of enzyme activity, and minimizing weight loss [160]. Biodegradable functional films are materials crafted from ingredients that possess the unique characteristic of breaking down naturally over time, contributing to a reduction in the environmental impact. These materials are specifically designed for applications that prioritize sustainability, aiming to minimize the ecological footprint associated with conventional packaging [162–164]. Mushrooms, renowned for their diverse and valuable components, play a crucial role in shaping the landscape of biodegradable functional films. Various studies have explored the potential of several mushroom compounds for application in biodegradable functional films. These approaches show promise in contributing to the development of environmentally conscious packaging solutions [137,152,165].

7. Nano-Food Farming: Role of Nano-Nutrients

The production of food from cropping and livestock systems needs an adequate supply of nutrients in the proper ratios for healthy growth. These nutrients vary widely from essential to beneficial nutrients for plants and animals. The movement and uptake of applied nutrients by plants represents an important issue for crop production (Figure 5). The pathway of applied nutrients into the soil rhizosphere depends on many factors that involve the plant, soil, growth media, environmental, and agronomic factors. The method of nutrient application to crops can also influence the bioavailability of nutrients. The nutritional value of plant-based foods mainly reflects the mineral composition of these plants, which depends on the plant genetics, growing environment, and management practices [166]. The mineral composition of crops results from the uptake of nutrients from soil and/or foliar applications. The proper method of nutrient application depends in part on the type of fertilizer being applied, whether it is mineral [167], organic [168], a biofertilizer [169], nanofertilizer [170] or nano-biofertilizer [71]. Plant nutrition is also influenced by the environmental conditions around the plants, including abiotic and biotic stresses [171]. Nutritious plant-based foods are essential for human health [172]. Several publications have reported on human diseases related to plant-based diets, such as cardiovascular disease [173,174], chronic diseases [175], dementia and depression [176], systemic inflammation [177,178], chronic kidney disease [179], and general health outcomes [180].

In general, the chemical and biological pathways for Se-NPs synthesis are well-known, with priority over the biological methods via microbes or plant parts. The biological methods are more sustainable and have lower toxicity. For nano-farming, it is preferable to apply biological Se-NPs to support crop and animal production for food safety and to improve animal and human health, especially under stressful conditions [181,182]. Se-NPs have direct and indirect impacts on multiple aspects of the agroecosystem, including the soil, cultivated plants, and the food chain [183].

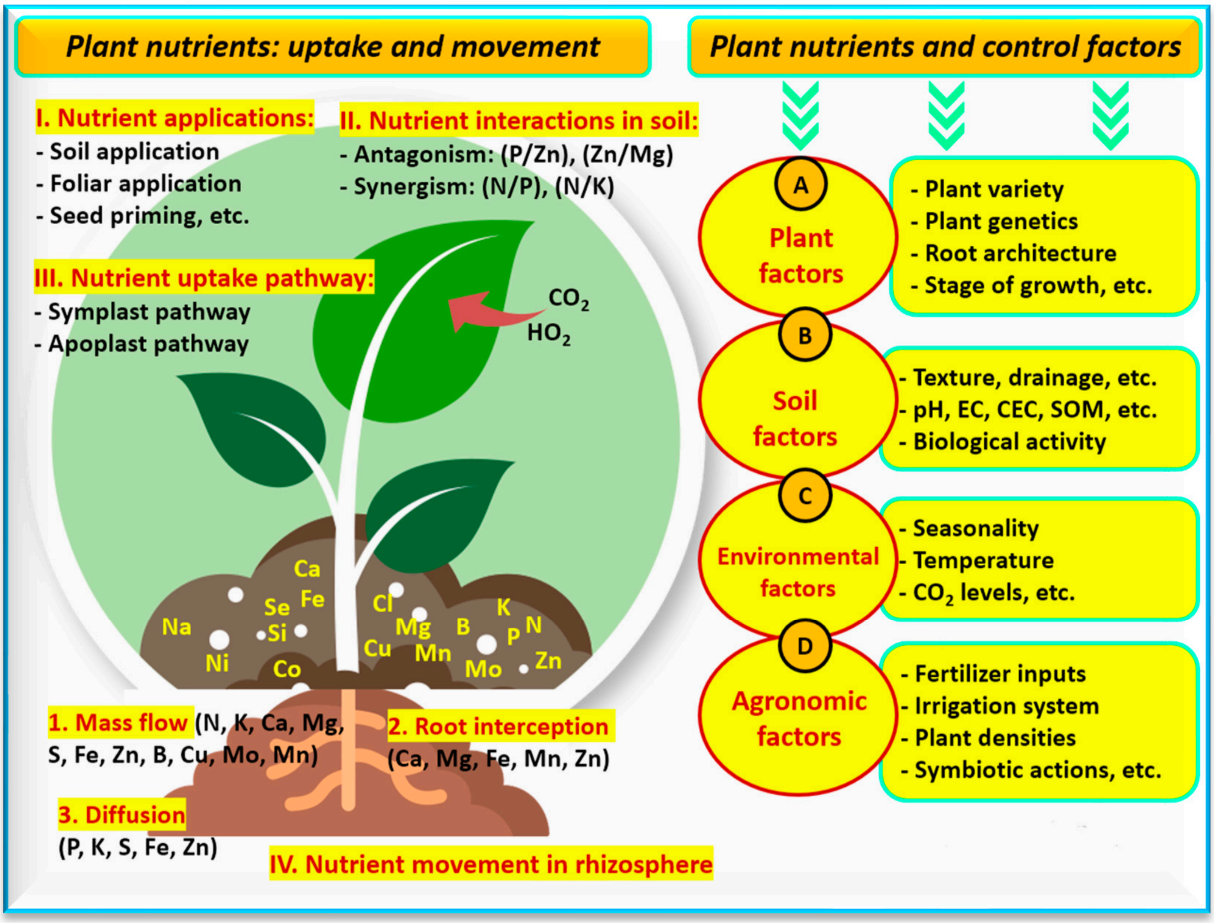


Figure 5. Mineral plant nutrients and their applications (part I), interactions in soil (part II), uptake (part III), movement in soil toward roots (part IV), and factors controlling uptake [166,184]. Plant image from https://www.cleanpng.com/png-biostimulant-fertilisers-agriculture-soil-foliar-f-5425521/, accessed on 6 January 2024.

The application of nano-nutrients in nano-enabled agriculture has received intense research attention. However, the mechanism of uptake, movement of these nano-nutrients in the rhizosphere, and entry into plants, plant cells, and organelles are still insufficient. Many recent reports have discussed the delivery of nanoparticles (NPs) at different levels, including at the whole-plant and single-cell levels [185–187]. More details on this topic are presented in Figure 6. The differences between the uptake of traditional or mineral nutrients (Figure 5) and nano-nutrients (Figure 6) can be explained by the factors controlling their uptake and movement. In general, the 4Rs of nutrient management present the right strategy for the optimum use of applied nutrients, which includes applying the right nutrient at the right rate, right source, right time, and right place.

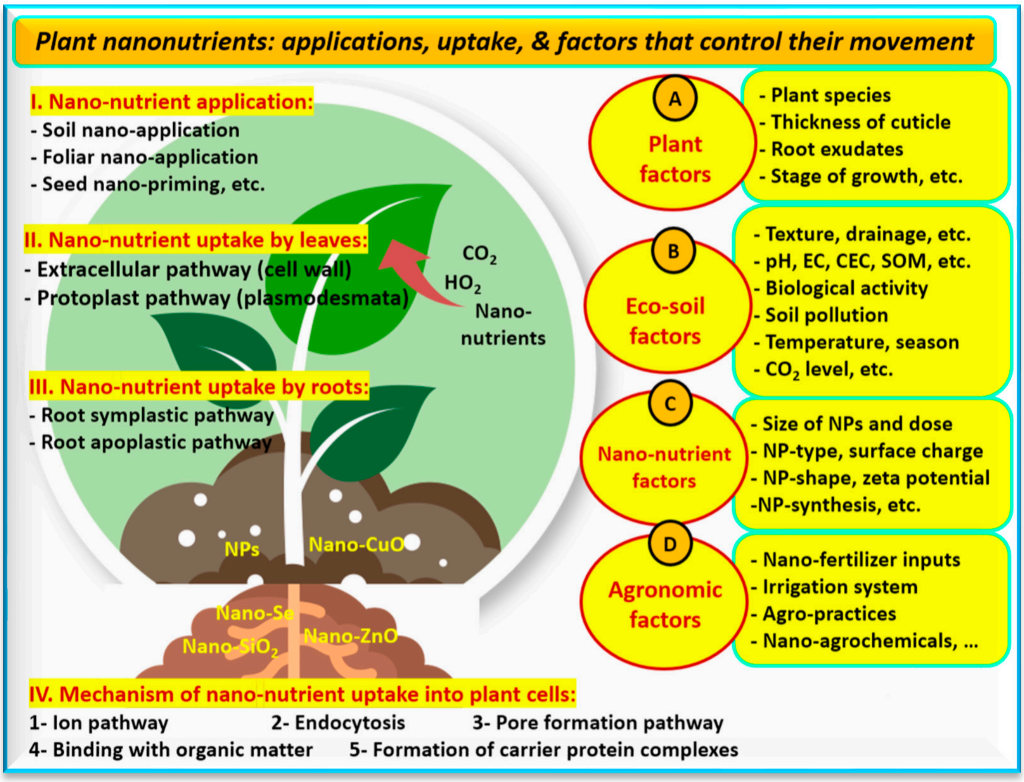


Figure 6. Plant nano-nutrients, methods of application (part I), their uptake by leaves (part II) and roots (part III), potential mechanisms of uptake into plant cells (part IV), and factors controlling this uptake [185–187]. Plant image from https://www.cleanpng.com/png-biostimulant-fertilisers-agriculture-soil-foliar-f-5425521/, accessed on 6 January 2024.

7.1. Nano-Selenium and Nano-Tellurium

Among the chalcogenide group, also known as the oxygen group, selenium (Se) and tellurium (Te) are similar elements that have many common proprieties (Figure 7). These include antimicrobial, antioxidative, antifungal, and anticancer properties, along with their ability to serve as drug delivery agents and to assist in bioremediation and bio-recovery. Alloys of Se and Te include similar crystal structures (hexagonal), electronegativity (5.88 and 5.50 eV), valences (+6), and atomic radii (117 and 137), respectively [188]. Both Se and Te are rare in the Earth's crust, with abundances of about 0.05 and 0.001 mg kg^{-1}, respectively. The high similarity in characteristics between these elements led to many similar applications for the bulk and nano-forms as well as their alloys, as reported by many studies [60,189–191].

Research has focused on the biological production of Se and Te nanoparticles [192–194] and the application of nano-Se for a variety of farming practices (Table 2). Applications of Te nanomaterials include electronics, opto-electronics, magnetoelectricity such as transistors, photodetectors, and sensors, and biomedicine [195]. Knowledge of the potential applications of nano-Te in farming is still in the very early stage. Research has been conducted on the myco-synthesis of tellurium nanoparticles [196] and production through *Alteromonas* sp. (a marine organism) under saline conditions [197]. The most promising application of biologically produced Te-NPs investigated to date has been based on the antimicrobial activity against pathogenic microorganisms [196], which may lead to meaningful applications in the farming and food systems. The highly efficient removal of pollutants like gallium from aqueous environments using biological nano-Te has been reported [198]. Biologically fabricated Te-NPs have been shown to have antioxidant, antibacterial, and cytotoxic applications [199]. Other studies have reported using yeast strains (*Yarrowia lipolytica* and *Trichosporon cutaneum*) to produce nano-Te [200].

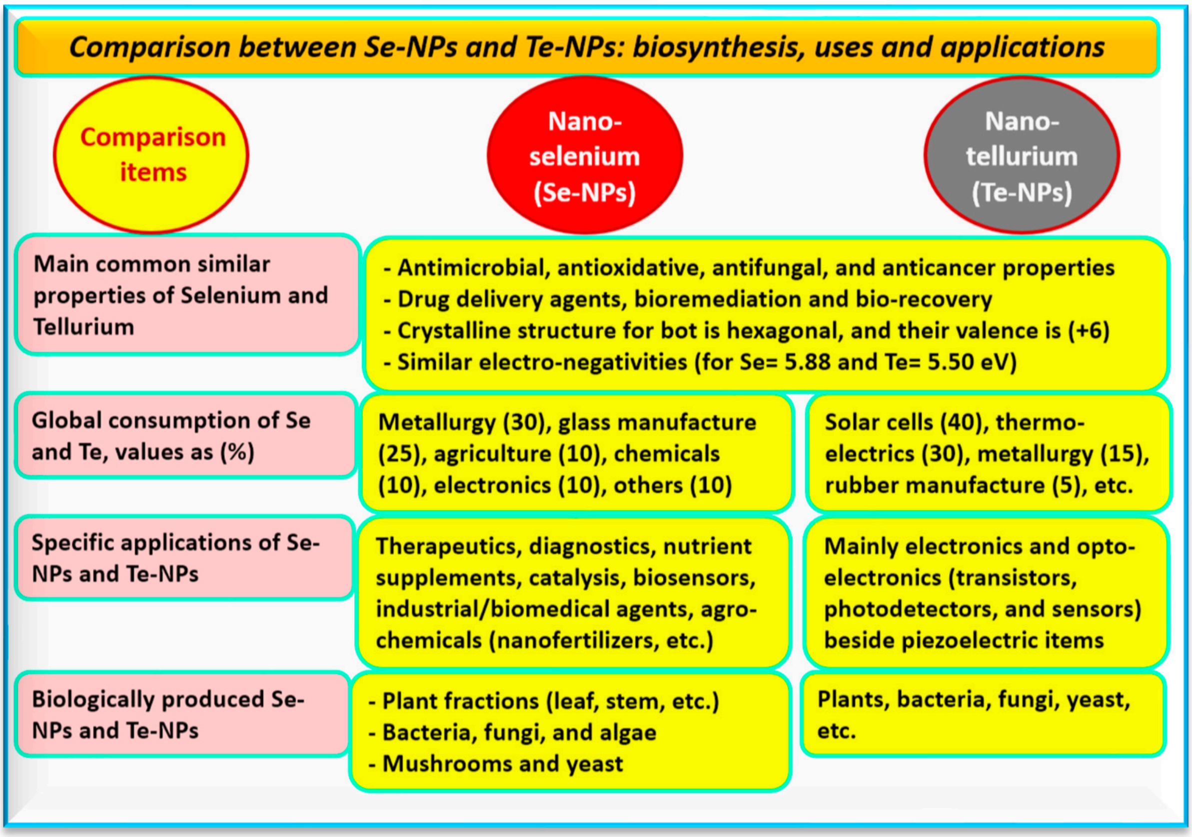


Figure 7. A comparison of selenium and tellurium, including their nano-forms and biological production [188,189,195,201].

Table 2. Applications of nano-selenium in different farming practices.

Crop	Applied Dose of Nano-Se	Farming Practices	Main Impacts of Nano-Se	Refs.
Sugarcane (*Saccharum* spp. hybrids)	Foliar application of 5 and 10 mg L^{-1}	Growing seedlings under biotic stress	Nano-Se enhanced antioxidants and jasmonic acid content; reduced accumulation of ROS and H_2O_2 under biotic stress as an eco-fungicide.	[202]
Lemon verbena (*Lippia citriodora* Kunth)	Foliar application of 10 uM nano-Se	Before full flowering stage	Nano-Se alleviated salt stress by improving secondary metabolites (protein, proline, and soluble sugars) and antioxidants.	[203]
Red Pitaya (*Hylocereus undatus*)	Foliar at 5 mg L^{-1} and soil at 3 mg L^{-1}	Biofortification of fruits and post-harvest	Nano-Se enhanced antioxidant capacity and nutritional value by boosting biosynthesis of amino acids, phenylpropanoid, and betalain.	[204]
Faba bean (*Vicia faba* L.)	Foliar application at 100 mg L^{-1}	Biofortification of bean seeds	Nano-Se improved the seed weight, yield and quality, and biofortification level.	[205]
Common Bean (*Phaseolus vulgaris* L.)	Applied 50 and 100 ppm nano-Se and nano-Si	Control Alternaria leaf spot disease	Applied nano-Se and nano-Si was an effective alternative to fungicide against the studied phytopathogen.	[53]
Caralluma tuberculata	In vitro containing 100 µg L^{-1} nano-Se	Producing secondary metabolites	Se-NPs elicited the production of antidiabetic metabolites (gallic acid, cumarin, ferulic acid, caffeic acid, catechin, quercetin and rutin).	[206]

Table 2. *Cont.*

Crop	Applied Dose of Nano-Se	Farming Practices	Main Impacts of Nano-Se	Refs.
Rice (*Oryza sativa* L.)	Applied nano-Se to soil at 0.1 mg·kg^{-1}	Rice seedling growth	Nano-Se enhanced root exudates and rhizobacteria, which promoted rice growth by increasing malic and citric acid content.	[207]
Rice (*Oryza sativa* L.)	Se bio-nanocomposite	Alleviating cadmium toxicity	Applied nanocomposite alleviated the inhibition of plant growth and Cd-oxidative stress by reducing Cd accumulation in rice plants.	[208]
Lettuce (*Lactuca sativa* L.)	Applied Se-NPs to the soil at 50 mg kg^{-1}	Enhancing plant disease resistance	Se-NPs suppressed *Fusarium*-induced wilt disease in lettuce by modulating the shoot metabolite levels of citrate, succinate, malate and upregulated jasmonic acid.	[209]
Strawberry (*Fragaria* × *ananassa*)	Nano-Se at 25, 50, 75, and 100 mg L^{-1}	Seedling production	Se-NPs enhanced growth of seedlings by promoting nutritional status, photosynthetic pigments, and enzymatic antioxidants.	[28]

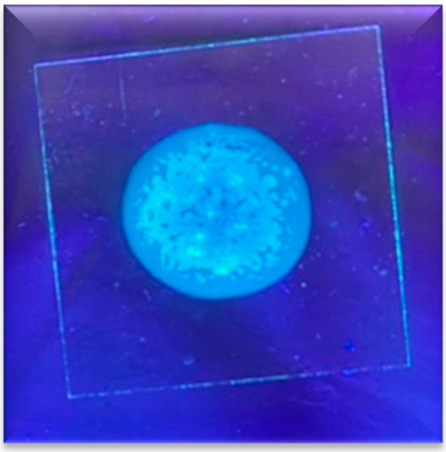
Nano-Se has many crucial roles in farming practices, especially under biotic and abiotic stresses (Table 2). Under biotic stress that resulted from *Xanthomonas albilineans* infection, nano-Se supported the growth of sugarcane as an eco-fungicide and improved the juice quality [202]. The suggested mechanism of nano-Se for plant disease resistance involves enhancing the capacity of antioxidants, inducing the pathway of jasmonic acid, reducing the accumulation of ROS and H_2O_2, and promoting the pathways for phytohormones signaling [171,202,210]. Many studies have confirmed the role of nano-Se in inducing the resistance of crops to phytopathogens such as *Botrytis cinerea* in cucumber [211], spot blotch disease in wheat [212], *Podosphaera xanthii* in melon [210], *Fusarium*-induced wilt disease in lettuce [209], and Alternaria leaf spot disease in the common bean [53]. Along with the mitigation of stress, other benefits that have been reported due to nano-Se in farming include nano-biofortification [204,205], improving the quality and shelf life of harvested crops [213], and mitigation of abiotic stresses, including salinity [214], heavy metals [215], and drought [216]. The beneficial role of nano-Se in animal production has been confirmed by many studies under traditional and stressful conditions [217,218].

7.2. Carbon Nanodots

Carbon, along with hydrogen and oxygen, represents the origin of life as a main component of any organic matter. Carbon is an essential nutrient for all living organisms. Therefore, producing food and feed with farming practices depends on carbon. Nano-farming has received a great deal of attention due to its promising ability to support sustainable agriculture [52]. Carbon can be formed into a variety of nanomaterials, including graphene, fullerenes, carbon black, carbon nanofibers, carbon nano-horns, carbon nanotubes (e.g., multi-walled carbon nano-tubes, and single-walled carbon nano-tubes), quantum dots as carbon dots, and carbon nano-diamonds [219–221]. Carbon nanomaterials have exceptional optical, electrical, mechanical, and thermal properties. They are also inert, non-toxic, have a high level of biocompatibility, long-term chemical stability, and are eco-friendly [219,222–224]. Along with the biomedical applications of carbon nanodots, there is great interest in using carbon nanomaterials in the agriculture sector [225,226]. This ranges from enhancement of crop productivity [227–229] to genetic alteration and acute cytotoxicity [230], nano-seed priming [231], and nano-remediation of polluted soil [232].

Carbon nanodots (CNDs) are a versatile and promising class of nanomaterials with a wide range of potential applications. Recent studies have identified the presence of CNDs in various food products, including caramels, bread, jaggery, sugar caramel, cornflakes, and biscuits [233]. CNDs were also found in Coke (Figure 8A) and in soil used to grow mushrooms (Figure 8B). A model of CND formation is given in Figure 8C. CNDs have been found to interact with agricultural crops, influencing their growth, physiological functions, and production [234]. These interactions can lead to changes in the crop yield, metabolite production, and gene and protein expression [234]. The size and concentration of CNDs can significantly impact their effects on crops [234]. However, the potential risks of these interactions, such as the accumulation of CNDs in edible parts of crops and their potential impact on animal and human health, must be carefully evaluated [222]. The effects of CNDs vary depending on the nanomaterial type, concentration, and exposure time [235]. The unique properties of CNDs, such as low toxicity and high biocompatibility, make them promising for use in agriculture [236]. Some farming applications of CNDs are presented in Table 3. Further research is needed to understand these interaction mechanisms better and evaluate the potential benefits and risks of using CNDs in farming [237]. Therefore, while CNDs and other carbon-based nanomaterials have the potential to influence agricultural crops positively, further research is needed to fully understand their effects and potential risks.

(**A**)



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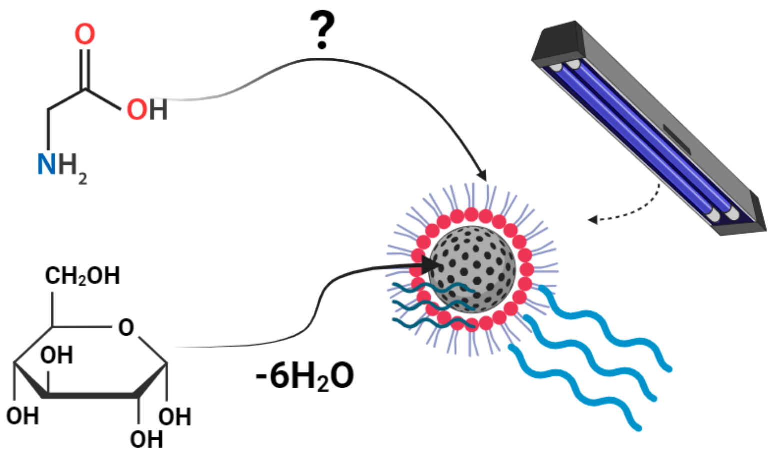

(**C**)

Figure 8. Carbon nanodots (CNDs) have been purified from Coke (photo **A**) and from soil used to grow Oyster mushrooms (*Pleurotus ostreatus* L.) (photo **B**). A suggested model of CND formation (Part **C**) as presented by the Nano-Food Lab, University of Debrecen, Hungary (Photos by Duyen H.H. Nguyen).

Table 3. Different applications of carbon nanodots for farming practices and food production.

Type of C Nanodot	Farming Practices	Main Impacts	Refs.
Multi-walled carbon nano-tubes (MCNs)	Seedling development	An application of 800 mg·L^{-1} MCN promoted maize root length, height, seedling dry weight, and photosynthesis enzymes related to nitrogen metabolism in maize seedlings.	[238]
Nano-carbon composites	Nano-pesticide against fungus	Applied nanocomposite of C-TiO_2 inhibited the fungus *Phytophthora palmivora*, serving as a disinfectant for agricultural plant pathogens.	[239]
Carbon nanomaterials (CNMs)	Amendment of sandy soils	CNMs applied at 200–400 mg kg^{-1} increased shoot biomass of lettuce, total chlorophyll content, photosynthesis activity, and bioavailability of soil nutrients.	[229]
Carbon nanoparticles (CNPs)	Soil fertility improvement	CNPs applied at 200 mg kg^{-1} enhanced maize growth by improving nutrient use efficiency, plant height, the uptake of nutrients, and biomass yield.	[240]
Carbon nano-tubes	Magnetic nano-sorption pesticides	Using magnetic nanocomposite cellulose for sorption agro-pesticide samples due to high porosity, high surface area and good reusability up to 15 times for the extraction of pesticides.	[241]
Carbon dots (CDs)	Seed nano-priming	CDs applied at 0.25–2 mg mL^{-1} accelerated germination of pea seeds, increased biomass accumulation and elongation of shoots and roots compared to the control.	[242]
Nitrogen -doped carbon dots (N-CDs)	Seedlings growth under salt stress (150 mM NaCl)	N-CDs enhanced Arabidopsis salt stress tolerance and induced plant growth, chlorophyll content, and reduced malondialdehyde content compared to the control.	[243]
Carbon quantum dots (CQDs)	Protecting agent against Cd-stress	Putrescine-functionalized-CQD-NPs increased the fresh and dry leaf weight of grapes and mediated Cd-stress by promoting enzymatic activity, anthocyanin. and phenolics.	[244]
Carbon nanodots	Food preservation	Carbon nano-dot/silk fibroin films were antibacterial and antioxidative films that increased fruit preservation as a multifunctional and eco-friendly packaging system.	[245]
MnO_2 nano-sheets and carbon dot (MnO_2-CD)	Nano-biosensor for food safety	The MnO_2-CD was an efficient nano-biosensor for *Staphylococcus aureus* having higher stability, good biocompatibility, and catalytic activity compared to natural enzymes.	[246]

8. Nano-Farming: Applied Nanofibers

Nanofibers are natural or synthetic polymeric fibers on a small (nano) scale that have certain properties (mainly a high surface-area-to-volume ratio, interconnected nano-porosity, and high mass transport properties). Natural nanofibers have animal, mineral, and plant sources. The properties of plant-based nanofibers depend on the plant fraction used to create them, such as leaves, stalks, seeds, and stems [59]. Nanofibers have been applied to several farming practices, including different growing stages [58] starting from seed germination [247], have been used to apply bioactives through nano-agrochemicals, including nanofertilizers [248] and nano-pesticides [249], and have been used post-harvest for the preservation of fruits and vegetables [250–254]. Nanofibers can also be used in the nano-remediation of polluted soil [255] and wastewater treatment [246,256] as well as in food safety, packaging and processing [257].

Several studies have investigated the use of nanofibers for farming and in the food sector (Table 4). The food sector investigations have included topics such as creating porous cellulose-acetate nanofiber hydrogels [258], starch-based nanofibers to monitor food freshness [259], poly-lactic acid nanofibers in food packaging [260], green nanofibers for the delivery of active foods [261], and natural cellulose nanofibers for fresh food packaging [257]. These nanofibers are good candidates for food packaging due to their biodegradability, ability to serve as exceptional barriers, and mechanical attributes [257].

These nanofibers can also reduce the food respiration rate and improve the rheological and antimicrobial properties, which extends the shelf life of food products [257].

Table 4. The applications of nanofibers in farming practices and the food sector.

Nanofibers (NFs)	Farming Practices	Main Impacts of NFs	Refs.
Natural multifunctional nanofibers from cellulose	Multi-functional air filtration	The NFs created an eco-friendly filter to remove indoor pollutants like volatile organic compounds and particulate matter.	[262]
Zein nanofibers coated by carbon dots	Dairy farming	NFs were able to detect the pathogen *Staphylococcus aureus*, which causes mammary infections in dairy cows.	[263]
Cellulose nanofibers based on lignin	Farmland drainage	This nanofiber can utilize crop straw through an $FeCl_3$-mediated deep eutectic solvent biorefinery and lignin-containing cellulose nanofibers flocculant fabrication followed by P-fertilizer production.	[264]
Cellulose and carboxy-methyl cellulose nanofibers	Slow-release fertilization	Urea-loaded hydrogel applied via nanofibers enhanced seed germination and plant growth through effective and sustainable transport of fertilizer and water.	[265]
Cellulose nanofiber with anthocyanins and carbon nanodots	Applications in food packaging	NFs extended the shelf life of packaged perishable food.	[266]
Poly-lactic acid nanofibers	Active food packaging	This NF has strong antifungal activity that suppressed the proliferation of microbes in the preserved grapes and improved their quality.	[260]
Citrus insoluble nanofiber	Producing fat replacers	A composite NF gel showed potential as a fat replacer and for inhibiting lipid digestion.	[264]
Green nanofiber	Delivery of active foods	Curcumin-loaded starch-based fast-dissolving NF showed promise in the pharmaceutical and food fields.	[261]
Chitosan-based nanofibers	Delivery of drugs	Cellulose and chitosan derivative-based NFs showed promise as biocompatible drug delivery systems.	[267]
Starch-based nanofibers	Monitoring of food freshness	NFs can reflect food freshness as a degradable, non-toxic, and smart food label with pH-sensitive nanofiber mats.	[259]

9. Nano-Food Farming Challenges

Due to their effective and sustainable applications, nanomaterials (NMs) have emerged as a key empowering technology for agro-production. The advantages may include their higher target rate and delivery efficiency, less coagulation/aggregation, and higher stability at reaction sites [268]. Several studies have reported on nano-enabled agriculture and have focused on issues such as nano-enabled precision farming [17], nano-enabled farming [12,268], the nano-food industry [269], nano-enabled seed treatments [19,270], nanostructured manganese oxides [271], nano-enabled agrochemicals [88,170,272], and nano-Zn-enabled cropping systems [16]. Along with nano-enabled farming, nano-processed food products have shown great promise for a variety of applications in the food industry [269,273,274] using organic compounds such as chitosan [275], cellulose [276], and proteins [277]. Inorganic nanoparticles have also been used in the food industry, including nano-selenium [278], nano-silver [279], nano-iron [280], nano-zinc oxide [281], and nano-titanium oxide [282]. The main challenges facing farming include climate change and global warming, soil fertility loss, water scarcity, energy security, biodiversity loss, and environmental deterioration (Figure 1). The suggested solutions include the integration of farming practices, more applied farming system design and innovation, farming system development and assessment, and sustainable farming management (Figure 9). For example, an integrated nanocomposite that used protein-based nitrogen-doped CDs/TiO_2-NPs was successfully utilized for the photocatalytic degradation of pollutants like Cr VI [283]. More studies on the integration between mushrooms, CDs, nanofibers, and nano-nutrients are needed. The most important issue displayed in Figure 9 is the suggested integration among the four studied sectors (proteins, mushrooms, nano-nutrients, and nanofibers). Creating an integrated farming system is an important target that can be achieved utilizing these types of suggestions. This should be the subject of additional investigations in the future. For example, how can we maximize the benefits among these previously mentioned four sectors? Could we produce CNDs from mushroom mycelium, nanofibers enriched with nano-Se for therapeutic purposes, etc.?

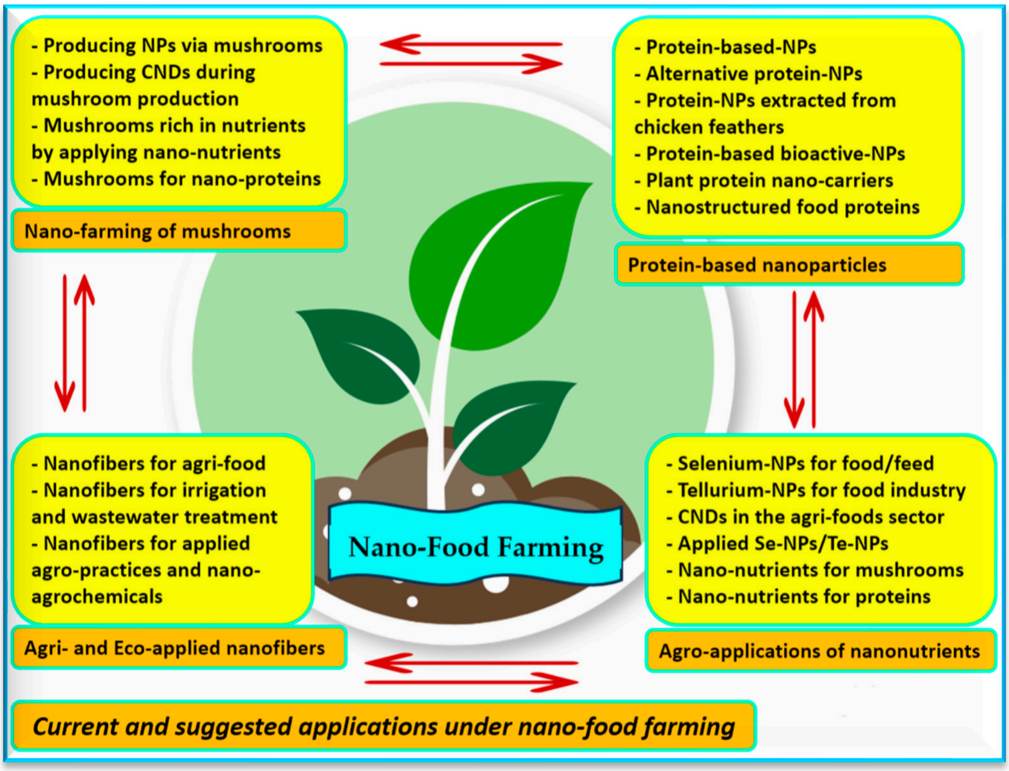

Figure 9. A diagram showing current and future suggested applications of the main sectors covered in this review (mushrooms, proteins, nano-nutrients, and nanofibers) that can be applied to nano-farming. Some selected applications are listed, focusing on the possible interactions among the four studied sectors (source: collected and summarized from references in the review).

The nano-farming journey is not yet finished but will continue into the future with enormous challenges left to overcome. These challenges are not only at the local, national, and global levels but also represent challenges translating discoveries from the lab to the field. Many of these challenges are summarized with the following questions:

- What are the main risks and benefits of nano-enabled agriculture?
- What are the full life-cycle studies of the nanomaterials utilized in agriculture?
- How do we effectively move our research from the laboratory to the field level?
- To what extent does the field scale remain a critical knowledge gap?
- To what extent is nano-enabled agriculture an emerging global issue for crop production?
- What are the knowledge gaps that should be addressed concerning nano-safety?
- To what extent can nanotechnology create safe and efficient delivery systems for food?
- What are the required regulations, biosecurity measures, and public concern issues related to manufacturing, packing, and consuming nano-based food?

10. Conclusions and Further Perspectives

In concert with the increasing global population, we need to produce more food to feed all people worldwide. At the same time, agriculture faces several obstacles that may cause a significant decline in global food production and delivery. Nano-farming offers promising solutions that could make significant progress toward increasing global food production while also increasing food quality and reducing food waste. This review of nano-farming focused on four sectors: proteins, mushrooms, nano-nutrients, and nanofibers. These sectors offer much opportunity to the agricultural industry. Each sector has the ability to supply the agricultural and food industries with essential requirements for human health. Protein-based NPs have promising applications in the food, therapeutic, and pharmaceutical industries. Due to their good water solubility, bioaccessibility, and stability, the nano-application of proteins has received increased attention in relation to their use as carriers of bioactive ingredients for food and drugs. Many nano-applications have been documented for edible mushrooms, including producing nanoparticles and bioactives within mushroom-based nano-applications. Selenium and tellurium nano-nutrients and CNDs offer several opportunities in the field of agri-food production beyond the obvious application of nano-nutrients in crop production. Nanofibers have incredible possible applications in irrigation and the food industry. It is important to note that there are still many unknowns regarding nano-farming and there are many challenges that need to be investigated so we can strike a balance between sustainable production and protecting the agro-environment from potential nanotoxicity. Studies on nano-farming need to move from the lab into the field and factory to address many of these challenges.

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