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Review

Nanofarming: Promising Solutions for the Future of the Global Agricultural Industry

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Abstract: The agricultural sector is a vital source of human well-being that provides the necessities of daily life. A variety of farming systems are utilized in agriculture, such as a wide range of tillage options, no-till, agroforestry, precision farming, organic farming, cover cropping, crop rotations, etc. Each of these farming systems has unique challenges, and nanotechnology has successfully improved on many of them. Agricultural applications of nanotechnology include nanofertilizers, nanopesticides, nanosensors, nanobiotechnology, and nanoremediation. This study focuses on the application of nano-farming technologies to different farming systems. Suggested practices include nano improvement of soil quality, crop nano-protection under biotic stress, nanoremediation of polluted soil and water environments, nanomanagement of agro-wastes, nano-agrochemicals, nano-precision farming, and nanobiotechnology for modern farming. This review also addresses expected problems that may occur due to over application of nanomaterials to farming systems, such as nanopollution and nanotoxicity of agroecosystem compartments. Several dimensions are emphasized in this study, such as green energy, sustainable development, the circular bioeconomy, land biodegradation, pollution, and the one health approach, as essential for the global goals of sustainable development. Nanofarming presents both benefits and obstacles to human life. The exact balance between these benefits and challenges needs more study.

Keywords: nanopollution; nanoremediation; nano-priming; nanopesticides; precision farming; nanotoxicology; nanobiotechnology

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Citation: El-Ramady, H.; Abdalla, N.; Sári, D.; Ferroudj, A.; Muthu, A.; Prokisch, J.; Fawzy, Z.F.; Brevik, E.C.; Solberg, S.Ø. Nanofarming: Promising Solutions for the Future of the Global Agricultural Industry. *Agronomy* **2023**, *13*, 1600. https://doi.org/10.3390/agronomy13061600

Academic Editors: Pablo Martín-Ramos and Baskaran Stephen Inbaraj

Received: 23 April 2023
Revised: 8 June 2023
Accepted: 12 June 2023
Published: 13 June 2023

1. Introduction

Farming includes growing crops and raising animals for food and raw materials, practices that are critical to human health and well-being [1,2]. To sustainably utilize agricultural resources, integrated farming systems should be established. Farming systems may include cropping, livestock, and agroforestry [3]. Types of agriculture include smart microalgae farming [4], seaweed farming [5], organic farming [6], agro-livestock farming [7], and mixed farming and agroforestry systems [3]. Farming has undergone a major transition over the last few decades for a number of reasons, including a global increase in population, urbanization, income growth, and development policies [8]. All opportunities for greater and more efficient production of cultivated crops and animals should be seized as many modern farms experience income stress [9]. Combined cropping and forestry farming can fuse economic and agroecological processes with temporal, spatial, and organizational integration across the farming enterprise [3]. Although intensive agriculture has increased food self-sufficiency, this has also led to rapid changes in the use of agricultural lands and affected the availability of water and its use [8]. Farming has many challenges due to climate change [10], eroding soil health [11], and global biodiversity decline [12]. Diversified farming systems incorporate different species and/or varieties of cultivated crops, fish, and/or livestock at multiple spatial and/or temporal scales to help address these challenges [13].

Nanotechnology has several applications in the field of agriculture [14]. The importance of nanotechnology has increased over time due to its fascinating solutions to overcome different obstacles (stresses) during the farming enterprise [15]. The application of nanomaterials (NMs) for farming practices is called "nanofarming". Nanofarming can supply several sustainable solutions under both normal and stressful conditions [15]. These nanofarming practices may include the preparation of seeds by nano-priming [16], applying nanofertilizers for plant nutrition [17], using nanopesticides, and detecting phytopathogens with nanosensors [15,18]. Nanomaterials have also shown promise in supporting crops under stress in a sustainable manner [19]. Nanotechnology can improve crop quality and reduce post-harvest losses of agro-products by extending their shelf-life, particularly for vegetables and fruits [14]. There is also the possibility of using nanotechnology to generate sustainable energy from agro-wastes [20]. Removing pollutants from soil and water using nanoremediation is a promising technique to restore degraded agricultural soils under the nanofarming approach to achieve sustainable management of national resources [21]. However, the overuse of NMs during farming practices may lead to nanopollution [22]. Therefore, it is important that we understand the best ways to utilize NMs to enhance the conservation and restoration of degraded soil and water resources in agricultural systems without creating new problems.

Many recent studies have discussed nanofarming with a focus on only one or two issues, such as nanofarming for food production [14], nanofarming and nanotoxicity [15], nano-priming [16], nanofertilizers [17], or utilization of agro-wastes for nano-enabled energy applications [20]. There is a need to provide a comprehensive review of different farming activities using nanomaterials and synthesize the current state of knowledge. As far as we know, this is a unique assessment of nanofarming, including several nano-applications as utilized in different farming practices. This review also focuses on very up-to-date information, with the majority of the references reviewed and synthesized coming from 2020 through 2023.

This review focuses on nanofarming and its potential as a solution for wicked problems in global agroindustry. A variety of practices under many farming systems have been reported to show promise for management using NMs and nanotechnology, including fertilization, irrigation, cultivation, crop protection, precision farming, remediation of polluted soil and water, management of agro-wastes, biotechnological approaches, and sustainable energy.

2. Methodology of the Review

Principal research database sources were utilized to search the literature for relevant publications, including Scopus (Elsevier), Web of Science (Clarivate), PubMed (National Institutes of Health (NIH), ScienceDirect (Elsevier), Frontiers, and MDPI. Keywords were identified that covered the main ideas investigated, such as "farming system", "agro-farming industry", "nanofarming", "nanofertilizers", "nanopesticides", "nanofungicides", "nanosensors", "stress", "smart fertilizers", "smart irrigation", "precision farming", "agro-wastes", "nanomaterials", "nanoremediation", "polluted soil and water", "nanomanagement", "nanobiotechnology", "nanotechnology", and "sustainable energy". The main steps followed for the study were: (1) create the main aim or theme of this study, (2) put the suggested keywords and searches into the global research databases, (3) build the table of contents (TOC), (4) re-check these contents based on the available information in databases, (5) ensure that the TOC provided a good fit to the topics identified, (6) select recent articles (mainly the last 4 years) for additional review, (7) priority was given to articles published in high impact factor (primarily Q1) journals, and (8) creation of figures and tables to organize and communicate themes discovered during the review. There are several farming practices that can utilize NMs for their management, but this study focused on the more common among them.

3. Nanofarming: An Overview

Farming involves growing crops (cropping) and keeping animals (animal husbandry) for the production of food and raw materials (Figure 1). There has been a global increase in intensive farming systems, which are characterized by their specialization and production on a large scale [3]. These specialized systems have produced foods in unprecedented quantities due to advanced agrochemicals, machinery advancement, breeding programs, and globalized supply chains [3]. Initially, this intensive agriculture led to a diminished threat of global hunger and malnutrition, but with challenges, such as the COVID-19 pandemic, climate change, and the increased number of conflicts over the last decade, the number of undernourished people and food prices is on the rise [23]. Approximately 10% (828 million people) of the world's population was affected by hunger in 2021, an increase from 8% (678 million) in 2019 [24]. Given this development, it is desirable that we find new ways that will allow us to make additional progress so we can meet the United Nation's goal of zero hunger [25].

The simplest farming systems are cropping, livestock, and forestry systems. There are several combinations among these systems, and they can be integrated, such as integrated crop-livestock, livestock-forestry, crop-forestry, and crop-livestock-forestry systems [3]. Additional examples of farming system combinations can be found in Figure 2. It is very important to minimize the environmental problems that result from farming practices. This could be achieved by reducing the use of inputs (mainly agrochemicals) and replacing them with alternative management practices, such as zero-tillage and applying manure, and NMs as more eco-friendly practices [3]. Using nanoscale agrochemicals can significantly reduce the overall applied rates to the field and minimize the pollution caused by traditional agrochemicals [26]. These approaches are needed, especially in climate-smart agriculture [27].

Nanomaterials have shown the potential to improve a number of practices or properties related to farming, including soil quality, smart fertilization, precision farming, production under stressful conditions, remediation of polluted soil and water, management of agro-wastes, and production of sustainable energy (Figure 2). Agro-nanotechnology has been recognized as a novel and innovative approach to developing sustainable farming practices that address a wide range of challenges (e.g., pollution and degradation, and climate change) facing modern farming [15].

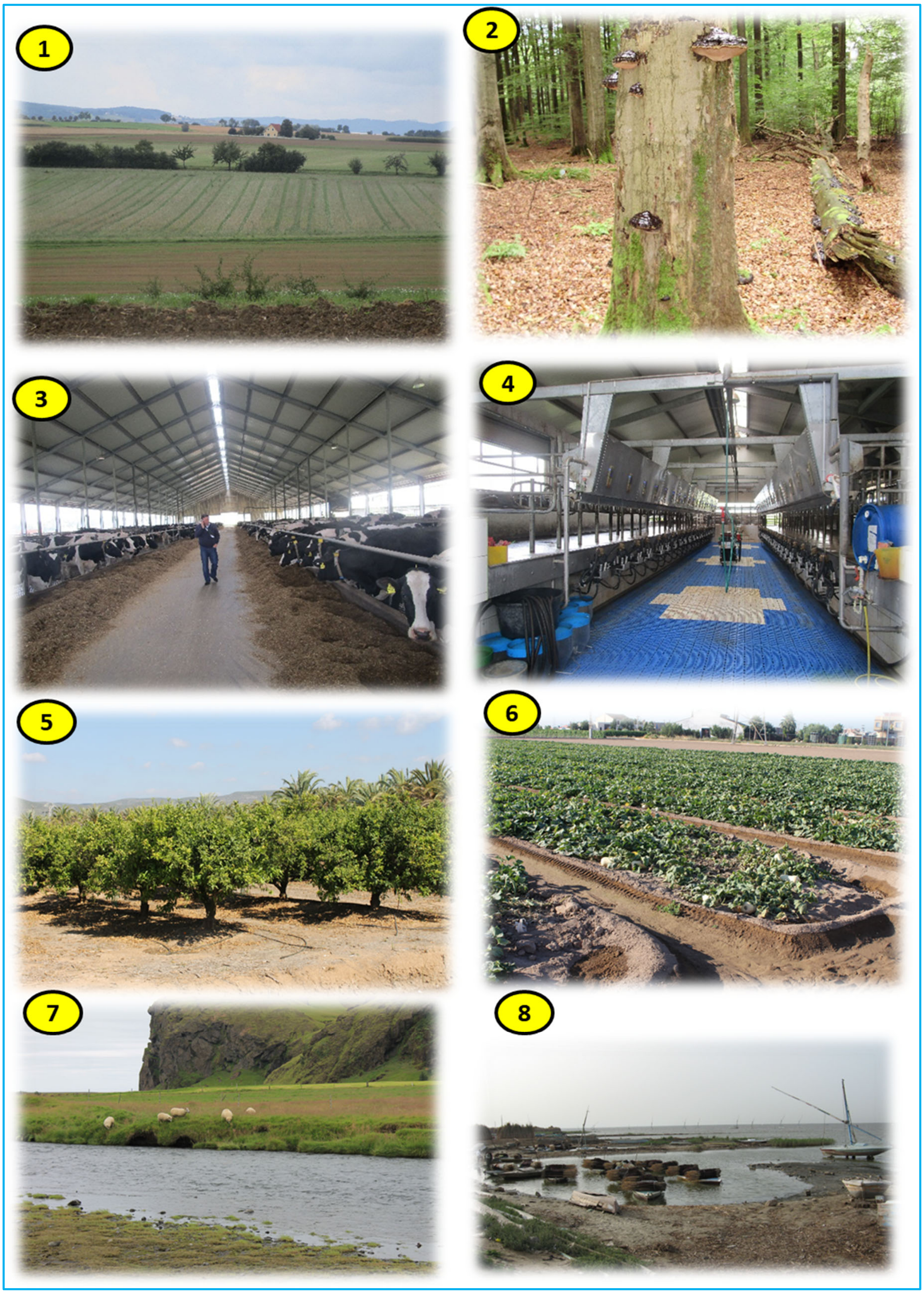

Figure 1. Farming is an essential activity to produce food and feed for humans and animals. There are many different types of farming and farm management, such as (**1**) cultivation of grain crops, (**2**) agroforestry, (**3**) raising animals for meat production, (**4**) dairy production, (**5**) fruit production, (**6**) vegetable production, (**7**) sheep production for meat and wool, and (**8**) aquaculture. Photos (**1**–**4**) from Göttingen, Germany and 8 from Burullus Lake, Egypt by El-Ramady. Photos (**5**,**6**) from Spain, and (**7**) from Iceland by Brevik.

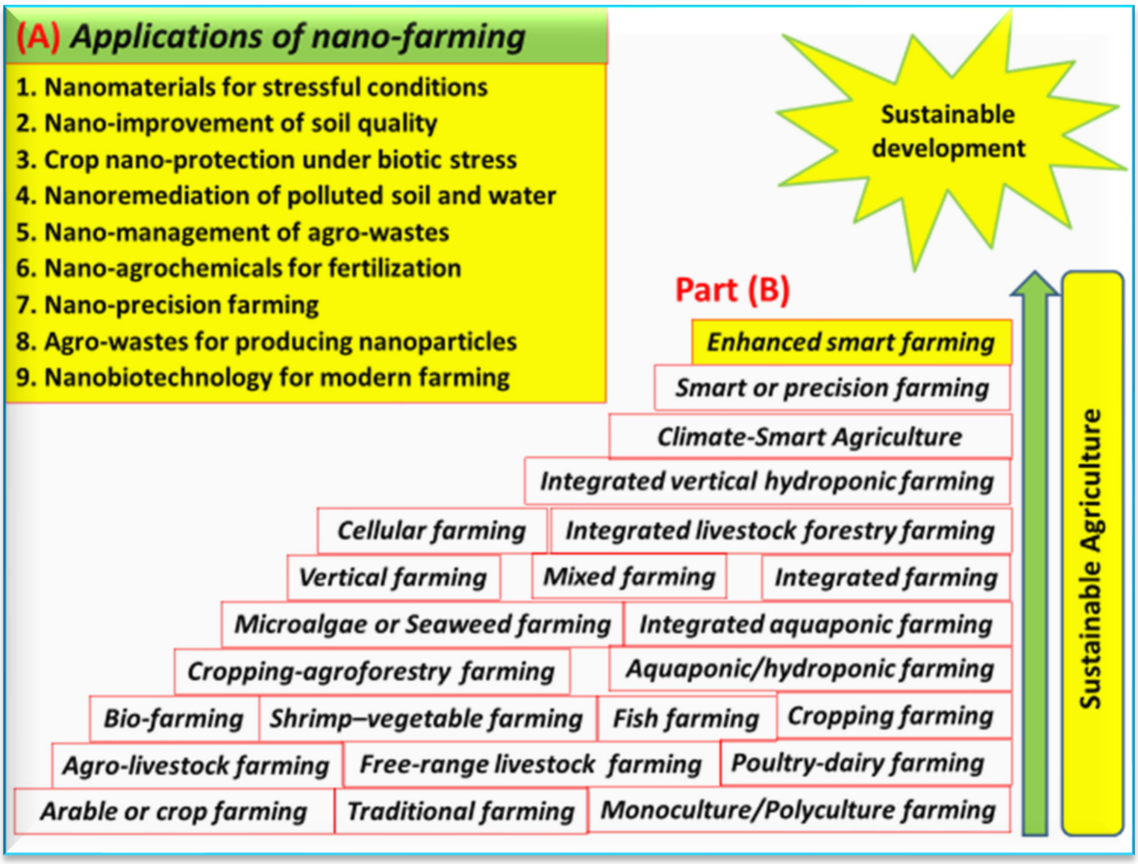

Figure 2. The suggested applications of nanotechnology for different types of farming with the goal of achieving sustainable agricultural development (Part (**A**)). Part (**B**) presents different types of farming in a pyramid form, where common 20th-century large-scale practices form the base (e.g., monoculture farming) and sustainable practices are at the top (e.g., enhanced smart farming).

4. Nanomaterials for Stressful Conditions

Crop production can face several stresses that negatively impact plant productivity (Figure 3). These include abiotic (e.g., drought, salinity, heavy metals, water logging, climate change) and biotic (e.g., viruses, bacteria, fungi, parasites, harmful insects, weed pressure) stresses [26]. Such stresses can alter the physiological, morphological, genetic, and biochemical processes that take place in plants [14]. Strategies to manage these stresses have included plant breeding, genetic engineering approaches, agrochemicals, integrated pest management, and a variety of tillage options, among others. Nanotechnology has shown promise for managing these stresses as well and may include nanopesticides [28], nanofertilizers [17], nano-based biostimulants [29], nano-encapsulated plant growth regulators [19], and nanosensors [18]. These nanomaterials (MNs) have low cost, high surface area to volume ratios, are eco-friendly, and possess unique physicochemical properties [30]. Nanomaterials can regulate plant protective responses through synergistic actions, regulate phytohormone signaling, and modulate the gene expression of phytohormones involved in plant growth under stress [31].

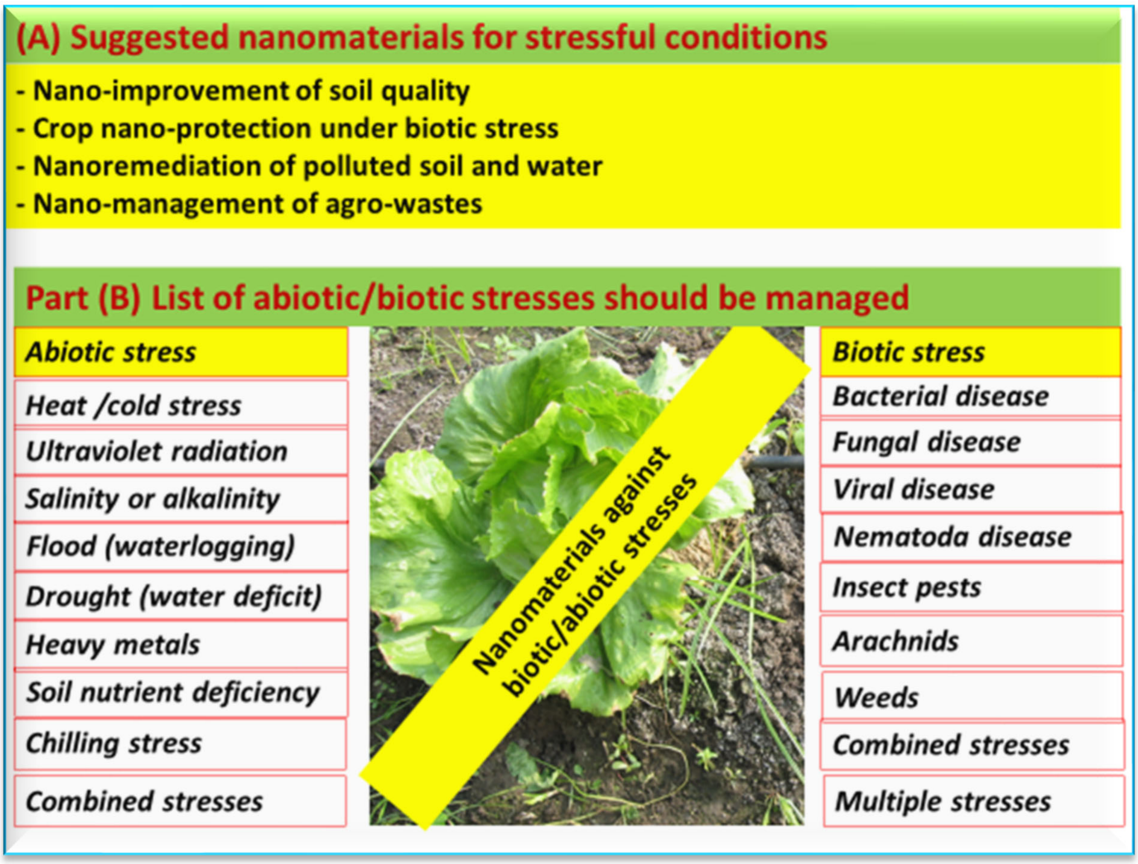

Figure 3. Nanomaterials (NMs) provide a promising approach to support cultivated plants under stressful conditions through many activities, including improving soil quality, protecting plants against stress, removing pollutants from soil, and managing agro-wastes through the application of NMs (Part (**A**)). Some examples of different biotic/abiotic stresses that cultivated plants face are given in Part (**B**).

4.1. Nano-Improvement of Soil Quality

Soil is a vital resource that supplies humans with needed food, fuel, and fiber [2]. There are several kinds of soil, and each should be managed according to the crop being produced and the soil's characteristics, such as acidic, alkaline, saline, and saline-sodic (Figure 4). Soil health is defined as "*the capacity of soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health*" [32]. Additionally, soil health is controlled by soil's physical, chemical (e.g., soil pH, CEC, EC, SOM, and texture), and biological changes. However, few studies have focused on changes in low molecular weight soil compounds and their impacts on soil health, such as soil metabolomics and soil microbial communities [33]. Soil is the final sink for many agrochemicals, including NMs. Nano-agrochemicals can be used to improve soil health and perform an essential role in sustainable agriculture [34].

Many types of nanomaterials can improve soil quality, including nanobiochar, nano-hydropolymers, nano-gypsum, nano-sulfur, nano-silica, nano-calcium, nanohydroxyapatite, nano titanium dioxide, nano-clay, nano-zeolite, nano-zinc oxide, nano-enhanced materials, nano zero-valent iron, nano-plant hormones, and nano-rock phosphate (Table 1). These nanomaterials have the ability to solve various soil quality challenges by improving soil biological, chemical, and physical properties. For example, the proper nano-enabled biofertilizers can manipulate the soil microbial community in a way that enhances plant growth and improves crop productivity [34]. This, in turn, can assist in the production of healthy food.

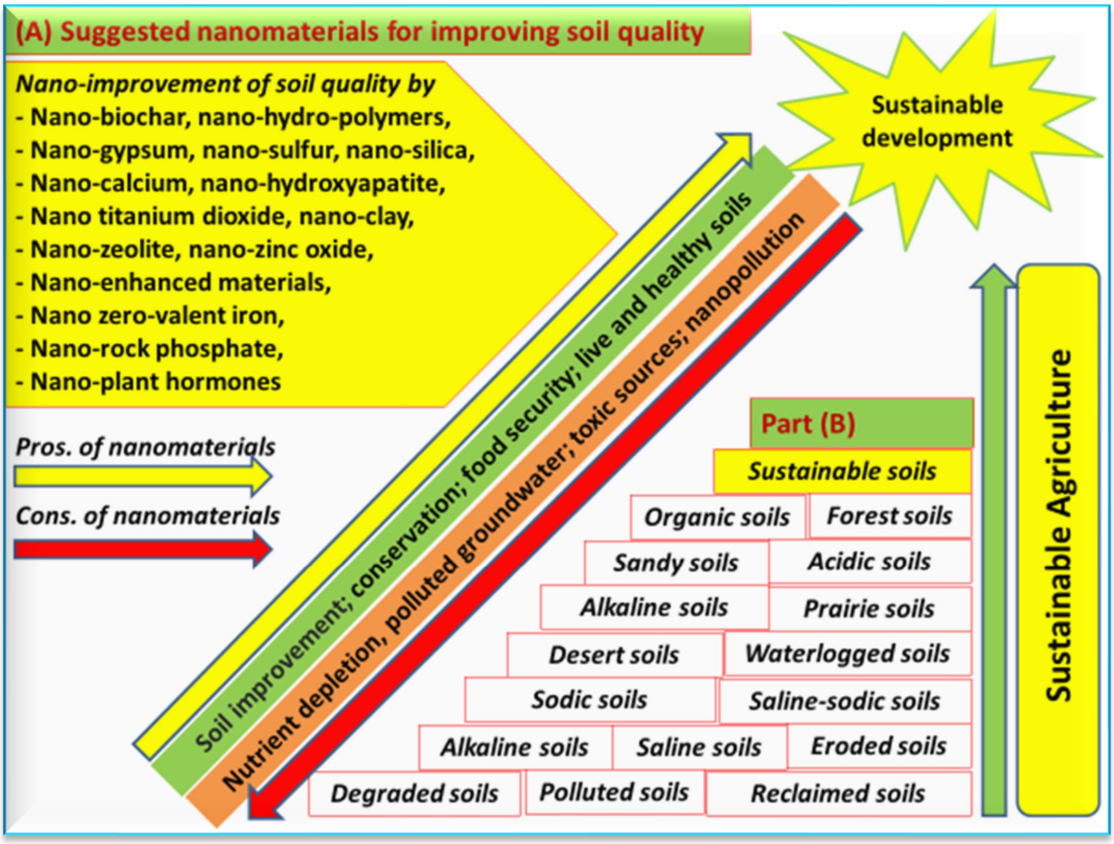

Figure 4. Examples of selected nanomaterials (NMs) that can improve soil quality are presented in part (**A**), while part (**B**) presents some examples of different kinds of soils. The soils in (**B**) are arranged with degraded or polluted soils at the bottom and sustainable soil at the top. The benefits of good NMs management (green area) and problems caused by overdoses of NMs (red area) are presented as well.

Table 1. Some published studies on the potential of nano-agrochemicals to improve soil quality.

Nanomaterials	Applied Dose	Soil Studied	Main Findings	Ref.
Nanohydroxyapatite (nano HA)	10, 50, and 150 mg P kg^{-1} soil	pH = 5.7, available Fe = 107.9 ppm	Nano HA increased the soil content of many low molecular weight metabolites, such as sugar and sugar alcohols, amino acids, and phenolic acids.	[33]
Nanozeolite and biochar	Biochar (5, 10, and 20 $g{\cdot}kg^{-1}$); nanozeolite (5, 10, and 20 $g{\cdot}kg^{-1}$)	Soil polluted with cadmium	Combined application increased soil pH and organic matter; reduced the exchangeable Cd in soil and its bioavailability; reduced oxidative damage in pak choi plants.	[35]
Nanogypsum	15, 30, and 45% GR	Degraded saline soil, pH = 9.32, SAR = 24%	Nanogypsum effectively reduced soil pH, EC, and sodium adsorption ratio (SAR), with a high ability to reclaim salt-affected soil.	[36]
Nanomanure from sheep and poultry	P nanocontent in sheep and poultry manure (5.96 and 578 g L^{-1}, respectively)	Soil saturated with P (200 mg L^{-1})	Nano manures reduced the degree of phosphorous (P) saturation and its colloidal release by increasing P adsorption on studied soils.	[37]

Table 1. *Cont.*

Nanomaterials	Applied Dose	Soil Studied	Main Findings	Ref.
Thiol-functionalized nano silica	4% as a mass fraction	Soil polluted with metals (Cd, Pb, Cu)	Nano SiO_2 significantly reduced the uptake of Cd, Pb, and Cu into pak choi by 92.02, 68.03, and 76.34% and into lettuce by 89.81, 43.41, and 5.76%, respectively.	[38]
Nanohydroxyapatite (NHAP)	The applied dose of wollastonite was 5 g kg^{-1}	Wollastonite-amended soil (180 mg P kg^{-1} soil)	NHAP significantly increased plant biomass by 643–865%, decreased Cd uptake by 74.8–75.1%, increased soil pH from 3.94 to 6.52–6.63 in the presence of wollastonite.	[39]
Hydroxyapatite nanoparticles	Nano HA at 0.25, 0.5, and 1.0 g L^{-1}	Applied NPs to the soil in 23.6 nm	Improved rosemary productivity as P-nanofertilizer can enhance plant growth and essential oil production.	[40]
Titanium dioxide -NPs (TiO_2-NPs)	500 mg kg^{-1} of anthracene	Soil polluted by anthracene	TiO_2-NPs and bacteria (*Alcaligenes faecalis* HP8) can bio-degrade anthracene pollutants through nano-assisted bacterial remediation.	[41]
Zeolite nanocomposite hydrogel	Zeolite (0.25 g) + guar gum (0.75 g)	Zeolite nanocomposite 30.76–62.01 nm	Nanozeolite can act as a soil conditioner and nutrient carrier and can be used in arid and semi-arid regions due to its high K-content and high-water absorption capacity.	[42]
Biochar (BC) and bentonite (BE) nZVI composite	15 g kg^{-1} nZVI-BC-BE	Soil polluted with Cd, Cr, and Pb at 11.69, 811.41, and 949.05 mg kg^{-1}, respectively.	Reduced bioavailability of Cd, Cr, and Pb in soil by immobilization through reduction, adsorption, co-precipitation, and complexation; reduced Fe leaching.	[43]
Nanorock phosphate	1140 kg P ha^{-1}	Abandoned agricultural site with sandy loam soil	Nanorock P encapsulated with bacteria is a sustainable approach to enhance maize production in degraded soil by promoting plant growth and biochemical P fertility.	[44]
Nano plant hormone–HormoGroe® Auxin (HG-A)	50 ppm HG-A; 50 ppm standard indole acetic acid, 50 ppm HG carrier as phosphatidylcholine	Sandy and clay loam soils	Nano plant hormones applied to soil increased microbial diversity in soils and vegetative propagation.	[45]

Abbreviations: nano zero-valent iron (nZVI), GR = Gypsum Requirement compared with 100% conventional gypsum; the NPs were in nm in their diameter.

On the other hand, the excessive application of nanomaterials to soil may cause environmental problems, including nutrient depletion, soil and groundwater pollution, and the accumulation of toxic levels of a variety of compounds in the environment [34,45–47]. Collectively these problems are referred to as nanopollution. The toxic effects of NMs largely depend on the types of NMs rather than enzyme variety. The exposure doses and their time, soil pH, and organic matter content are also considered key factors controlling how NMs affect soil [46]. Nano-Ag, -Cu, and -C have shown greater toxic effects on soil enzyme or microbial activity than nano-Fe and -Zn, which either stimulated the soil microbiome or had little inhibitory impact [46]. The efficiency of many agrochemicals is increased when combined with the right microorganisms [41,44,45]. Therefore, many lines of research are still needed to understand all the implications of utilizing nano-agrochemicals in food production.

4.2. Crop Nano-Protection under Biotic Stress

Reducing plant biotic stress by inhibiting plant diseases is the main mission of bio-control agents. These biocides can boost the productivity of stressed plants while being eco-friendly and degrading quickly [28,48,49]. Crop nano-protection refers to using nano-agrochemicals to protect crops against biotic stresses (Figure 5). Crop nano protection can be achieved using nanofungicides, nanopesticides, nano-herbicides, nano-based sensors, metal- or metalloid-based NMs (e.g., silicon, selenium, silver, zinc, copper, titanium, etc.), nano-based biostimulants, and nano-encapsulated plant growth regulators (Table 2). These NMs not only directly kill many phytopathogens but have also shown their role as biotic elicitors by modulating plant immune response and oxidative stress [50]. Microbial NM products are also promising nano-agrochemicals that can contribute to the sustainable protection of crops [50]. Nano-based biostimulants can promote plant resistance/tolerance to biotic/abiotic stresses, improve plant development, and minimize environmental damages [29,51]. More positive impacts of crop nano protectors are listed in Table 2. Many elements can support cultivated plants in their nanoform as nanopesticides, such as copper [52], titanium [53], zinc [54], selenium [52], silicon [55], iron [56], and silver [57].

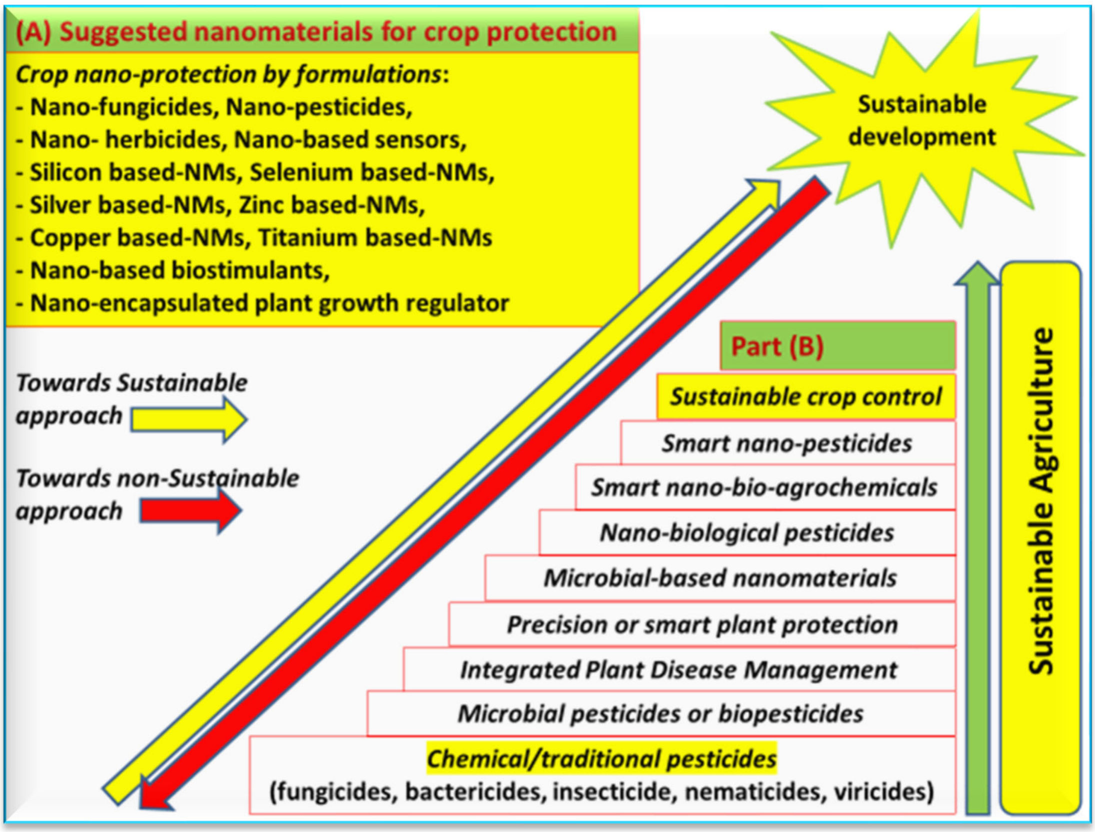

Figure 5. Different approaches for crop protection using nanomaterials with a focus on different formulations of nanopesticides (Part (**A**)). Part (**B**) presents a list of selected words related to crop protection, starting with (from the base) traditional pesticides, then moving towards the smart nanopesticides and sustainable crop control to achieve sustainable agricultural development.

Table 2. Some published studies on the potential of nanopesticides under nanofarming systems.

Nanoformulations	Phytopathogen	Plant Species	Main Findings	Ref.
Nano-Se (2.5, 5.0, and 10.0 mg·L^{-1})	Powdery mildew	Melon (*Cucumis melo* L.)	Nano-Se (5.0 mg·L^{-1}) had the best pathogen (powdery mildew) resistance by improving antioxidant capacity as a biostimulant and insecticide.	[58]
Nano-Se (5.0, and 10.0 mg·L^{-1})	*Xanthomonas albilineans* bacteria	Sugarcane (*Saccharum* spp. hybrids)	Nano-Se enhanced plant resistance and crop quality by improving juice quality; reduced the accumulation of both ROS and H_2O_2.	[59]

Table 2. *Cont.*

Nanoformulations	Phytopathogen	Plant Species	Main Findings	Ref.
Nano-Se and nano silica (nano-SiO_2)	Leaf spot disease (*Alternaria alternata*)	Common bean (*Phaseolus vulgaris* L.)	Combined application of both nanonutrients decreased the disease severity by increasing the enzymatic capacity of CAT, POX, PPO, and antioxidant activity in bean leaves.	[52]
Nano chitosan encapsulated *Pseudomonas fluorescens*	Tomato wilt (*Fusarium oxysporum*)	Tomato (*Solanum lycopersicum* L.)	Defense enzymes increased in tomatoes by increasing SOD, POX, chitinase, and glucanase after applying nanofungicide.	[60]
Chitosan-Salicylic acid and and $ZnSO_4$ nanoformula	Stripe rust (*Puccinia striiformis* f. sp. *tritici*)	Wheat (*Triticum aestivum* L.)	This nanoformulation is eco-friendly, effectively used against yellow rust disease in wheat by increasing tyrosine ammonia lyase, phenylalanine ammonia lyase, and polyphenol oxidase enzymes.	[61]
Nanochitosan (50, 75, 100, and 200 µg mL^{-1})	Potato and tomato bacterial wilt (*Ralstonia solanacearum*)	Potato and tomato (*Solanum* spp.)	100 µg ml^{-1} of nanochitosan reduced disease incidence and severity in studied plants as an eco-friendly nanopesticide.	[62]
Green synthesized MgO-NPs	Alternaria leaf blight (*A. dauci*)	Carrot (*Daucus carota* L.)	MgO-NPs (100 mg L^{-1}) reduced leaf blight indices and disease severity, improved plant length, shoot, and root dry weight, and plant fresh weight.	[63]
Nano chitosan encapsulation (CEO + PE)	Early blight (*Alternaria alternata*)	Tomato (*Solanum lycopersicum* L.)	*Carum copticum* oil (CEO) and *Peganum harmala* (PE) extract encapsulated with chitosan as a nanofungicide successfully controlled *A. alternata* under both in vivo and in vitro conditions.	[64]
Nanocapsules of chitosan and alginate (NCs)	Chicory (*Cichorium intybus*) as a weed	Maize (*Zea mays*) plants	Atrazine caused foliar damage on chicory plants but not maize plants, whereas nanocapsules are considered harmless to the health of the plants.	[65]
Green ZnO-NPs	Fruit rot disease (*Rhizoctonia solani*)	Grapefruit (*Citrus paradisi*)	ZnO-NPs inhibited fungal growth at 1.0 mg/mL concentration of green NPs, in vitro and in vivo.	[66]
Chitosan fabricated bio-NPs of silver	Bacterial leaf spot disease (*Xanthomonas campestris*)	Tomato (*Solanum lycopersicum* L.)	Treatment with the NPs is safer for the ecosystem, provided crop protection, and had higher levels of lycopene and beta-carotene than infected tomato plant fruits.	[57]
Ag-NPs and CuO-NPs	Brown planthopper, (*Nilaparvata lugens* (Stål)	Rice plants (*Oryza sativa* L.)	Applied NPs reduced brown planthopper, its survival, and enzymatic activities and enhanced rice plant defense and control of insect pests.	[67]

NPs—nanoparticles.

Nanomaterials have dual benefits, including monitoring plant health and phytopathogens detection for the management of plant diseases [68]. Many techniques are used to apply nano-agrochemicals, such as nanoencapsulation of biocontrol agents [49,60], nano-biopolymers [49], microbial-assisted product NMs [50], and nano-encapsulated plant growth regulators [29]. The encapsulation technique can guarantee a controlled release of different bioactive materials [49]. Despite several advantages of nano-agrochemicals in crop protection, certain risks are expected under intensive application causing eco-toxicity and phytotoxicity, depending on the applied dose of NMs. Thus, extensive research on nano-agrochemicals is required to monitor their impacts on microbiota and determine safe consumption levels for plants and animals [50]. Furthermore, appropriate regulations are needed concerning the use of nano-agrochemicals [69]. The risk-associated factors of microbial nano-agrochemicals may depend on their cost, scaling-up, and optimal microbial conditions for the biosynthesis of these NMs, especially before their application on a large-scale [50]. It is important to understand the NMs-plant-microbiome nexus with a focus on the possible mechanisms underlying NMs-mediated changes in microbiome diversity for the next generation of crop health [70].

4.3. Nanoremediation of Polluted Soil and Water

Soil and water pollution is one of the most pressing global issues facing humanity. This pollution threatens human and environmental health [71,72]. A variety of organic and inorganic pollutants are constantly increasing in the environment due to anthropogenic activities, such as agrochemical application (mainly pesticides and mineral fertilizers), fossil fuel combustion, mining, and the release of industrial wastes [73]. Improving soil and water quality could be achieved through physical, chemical, and biological remediation. Remediation types focused on NMs include membrane filtration [74], phytoremediation [75], bioremediation [76], phyto-bioremediation [77], nanoremediation [78–81], and nano-bioremediation [82,83] (Figure 6).

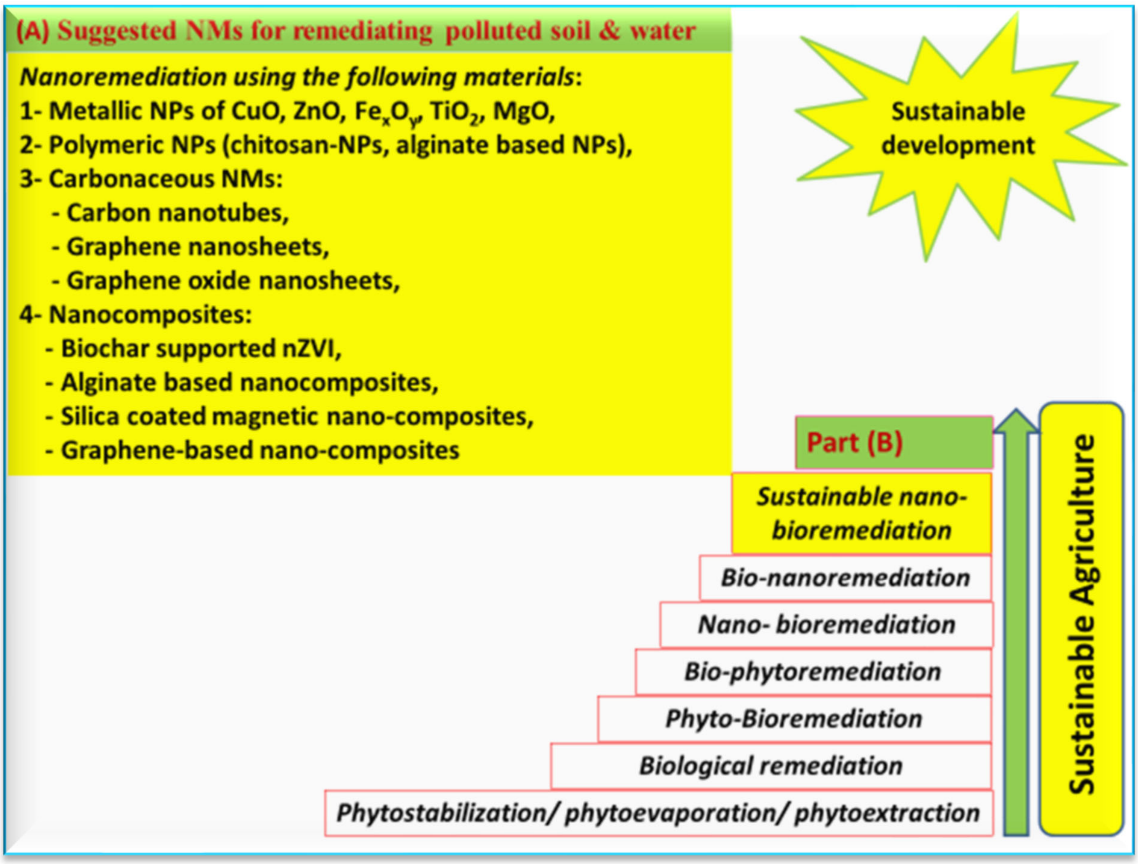

Figure 6. Nanoremediation of soil and water using selected nanomaterials (NMs) are presented in Part (**A**). Part (**B**) includes some common terms in the remediation field, starting with the common mechanisms of phytoremediation, such as phytoextraction, then moving to bioremediation, and finally, sustainable nano-bioremediation as a promising technique for achieving sustainable agricultural development.

Nanoremediation can be defined as a cost-effective and eco-friendly approach that uses NPs to detoxify pollutants/contaminants in soils and other environmental compartments [83]. Nanoremediation has many exceptional features, including cost-effectiveness, large surface area to volume ratio, electronic characteristics, sensitivity, and enhanced catalytic features [84]. It is worth mentioning that a process has been developed in nano-bioremediation that conjugates various NPs with microbes to clean hazardous environmental pollutants that results in a high efficacy and eco-friendly strategy to create sustainable environments [83]. Nanoremediation includes many mechanisms for removing or immobilizing pollutants from soils, such as adsorption, heterogeneous catalysis, electro-nanoremediation, photodegradation, and nano-bioremediation, using the following materials [85]:

- Metallic NPs (CuO-, ZnO-, FexOy-, TiO_2-, MgO-NPs);
- Polymeric NPs (chitosan-NPs, alginate-based NPs);
- Carbonaceous NMs (carbon nanotubes, graphene nanosheets, and graphene oxide nanosheets);
- Nanocomposites (biochar supported nZVI, alginate-based nanocomposites, silica-coated magnetic nanocomposites, and graphene-based nanocomposites).

Many studies have been published on the role of nanomaterials in the remediation of polluted environments, including soil and water (Table 3). The nanomaterials may have multiple potential uses in pollution remediation, including removing pollution, nanosensors for detecting pollutants, and causing nanopollution due to intensive application of NPs [86,87]. Due to unsustainable nano production in different fields, nanopollution concerns have become a global issue. An increase in the number of published articles on nanopollution has been noticed in recent years, with a focus on different points of view regarding nanopollution [87], the problems of green mitigation of nano-plastic pollution [88,89], and the fate and impacts of nano glass pollution on the food web [90].

Table 3. Some published studies on the potential of nanomaterials for nanoremediation of soils.

Nanoformulations	Soil Pollution Type	Main Findings	Ref.
Ni^0 and Cu^0-NPs	Diesel contamination	2 mg dose of Ni^0 + Cu^0-NPs removed 98.73 and 99.38% diesel contaminants.	[91]
Biochar and bentonite nZVI	Cd(II), Cr(VI), and Pb(II)	NMs improved immobilization of Cd, Cr and Pb in soils by 70.95, 100, and 100%, resp.	[43]
Nano Fe_3O_4 activated C-composite	Polycyclic aromatic hydrocarbons (PAHs)	2% NMs adsorbed PAH at 153.5 µg/mg for the total PAHs as adsorbent in soil washing to remove the hazardous PAHs from soil	[92]
Nano-ZVI	Heavy As pollution (1807 mg kg^{-1})	Nano-ZVI at 2 and 5% reduced soil pollution as indicated using soft computing models of extreme learning machines with particle swarm optimization.	[93]
Bio-nano sized FeS	Arsenic (As) and uranium (U)	Over 3 cycles, the removal rate of As was 12%, whereas very low rate (1.59%) was recorded for U.	[94]
Thiol-functionalized nanosilica	Pb, Cd, and Cu polluted soil	Nano SiO_2-SH was not bio-toxic to the soil ecosystem but also improved the soil environment, inhibited the movement of HMs into the soil solution.	[38]
Sulfidated nano zero-valent iron (nFeS/Fe^0)	Alkaline Cr(VI)	Reductive efficiencies of water-soluble Cr(VI) reached 99.7, 99.3, and 99.8% in 3 tested soils with initial contents of 439, 3307, and 4626 mg kg^{-1}, respectively, after 15 d of nFeS/Fe^0 treatment.	[95]
Bimetallic Zn/Fe^0 NPs	Diesel contamination	Maximum diesel removal efficiency of 83.8% was obtained by Zn/Fe^0 bimetallic NP-stabilized Rhamnolipid (12 mg/L) foam.	[96]
Nanohydroxyapatite (NHAP)	Cadmium (Cd)	NHAP may be an appropriate P-fertilizer, soil Cd was immobilized using wollastonite, which decreased Cd uptake by 74.8–75.1%.	[39]
Nano Fe-based persulfate, heterogeneous	Tetra-bromo-bisphenol A (TBBPA)	Removal efficiency of 82.07% with the fastest reaction rate of degradation within 0.14 h^{-1} in the presence of plant leaf extracts.	[97]
Nanovesicle and microbial activity	Heavy metals (HMs)	*Sporosarcina pasteurii* bacteria can precipitate calcite, form NPs, and remediate multiple HMs to enhance the growth of various plants.	[98]

4.4. Nanomanagement of Agro-Wastes

Agriculture includes several activities that prepare the soil to support seeds or seedlings until harvest. Some of these farming activities are major sources of pollution in the agriculture sector. Thus, the accumulation of mismanaged agro-wastes has created environmental issues, especially in developing countries [99]. Agro-waste should be addressed to safeguard the environment and preserve renewable resources (Figure 7). The benefits of doing so may include: (1) improving soil fertility and crop productivity; (2) reducing dependence on mineral fertilizers; (3) reducing dependence on fossil fuels; (4) producing protein-based feedstock for animal feeding; (5) producing bioactive compounds; (6) producing both nanomaterials and nanoparticles; (7) producing pharmaceutical compounds; (8) use as feedstock in fermentation industries; (9) producing asphalt binder or as natural aggregate in concrete; and (10) producing nano-adsorbents [99]. On the other hand, many environmental problems can happen when these agro-wastes are mismanaged, causing pollution of soil, water, and air. This pollution may cause hypoxia, harmful algal blooms, and eutrophication in water bodies, which may pose health risks and economic costs [100,101].

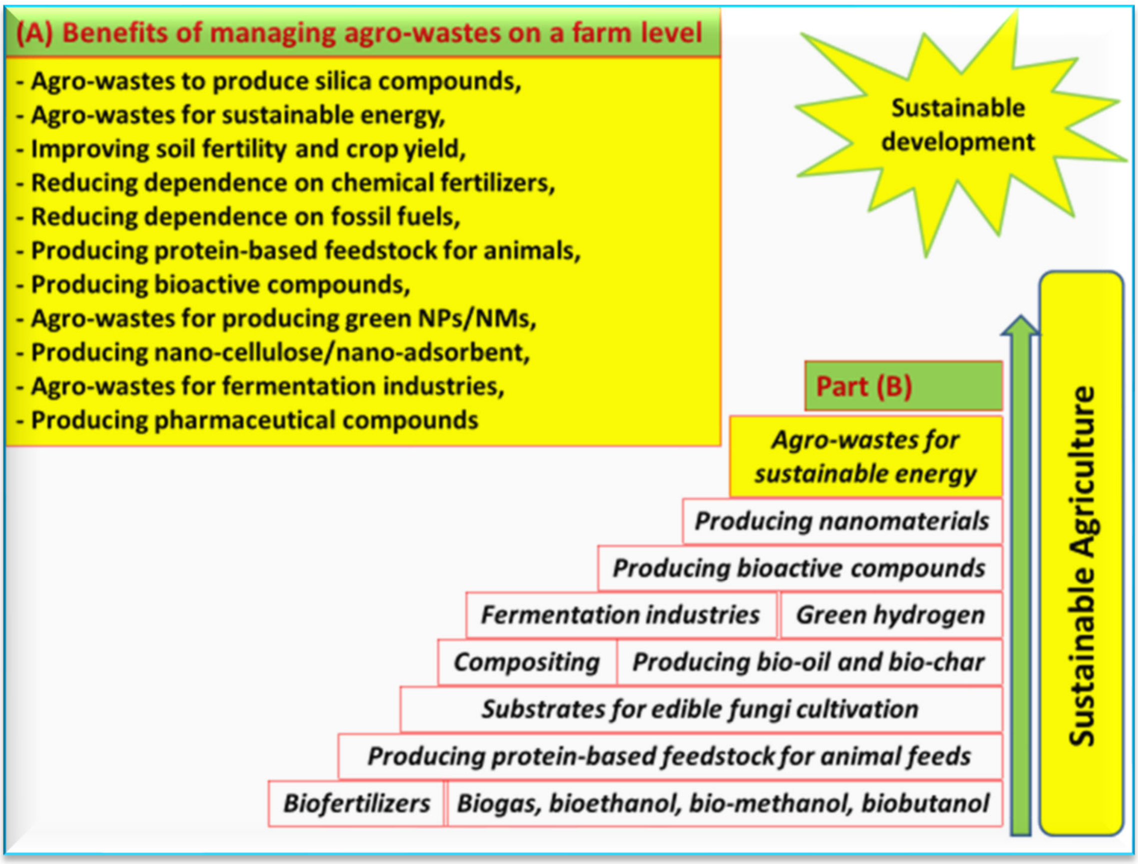

Figure 7. Suggested management of agro-wastes on the farm level, including the nano applications of agro-wastes under the waste-to-wealth concept (Part (**A**)). Part (**B**) presents some common terms related to agro-wastes and their handling for producing energy of agro-wastes and progressing to sustainable management as a promising target of sustainable agricultural development.

A strong relationship between the energy crisis and the management of increasing amounts of solid wastes due to the growing global population will lead to environmental deterioration. Under the circular economy concept, it is important to consider certain strategies for converting agro-waste into energy, including nanotechnology-based processing, to meet sustainable development goals [20]. Therefore, many recent studies focused on converting agro-waste into sustainable energy within a circular economy (e.g., [102–104]), a green strategy of converting agro-wastes into nano-enabled energy applications [20] and producing nanomaterials or nanoparticles from agro-wastes (Table 4). Agri-food wastes can pose a threat to human and environmental health. Annual food wastes generated globally total around 2 billion tons, with about 1.3 billion tons, which represents one-third of global food production generated by the food industry [105].

Table 4. Some studies on the potential of agro-wastes as a feedstock to produce nanoparticles.

Type of NPs (Nanoparticles)	Method of Synthesis	Types of Agro-Wastes	Main Findings of the Review	Ref.
Silica nanoparticles	Biological methods	Rice straw and others	Nanosilica has many remarkable applications in environmental clean-up, water treatment, and other types of nanoremediation.	[106]
Nano Silica	Biogenic synthesis	Groundnut shell, coconut husk, banana peel, orange peel, and walnut shell	Coconut produced a higher content of biogenic silica compared to the other agro-wastes.	[107]
Nickel oxide nanoparticles (NiO NPs)	Green method	Extracts from *Persea americana* seed, *Zea mays* silk, and *Eucalyptus globulus* leaves	*Eucalyptus globulus* leaves were recommended to produce NiO-NPs as compared to other studied agro-wastes. The NiO-NPs could be used as a bacterial inhibitor.	[108]
Super paramagnetic iron oxide NPs	Bio -fabrication	Paddy rice and wheat straws	Biogenic iron oxide NMs have good magnetic and antioxidant properties for novel drug and biomedical applications.	[109]
Nano graphene oxide	Green method with azolla help	Coconut husk and sugarcane bagasse	Biodiesel generation was effectively using graphene oxide nanocatalyst derived from agro-waste by transesterification using azolla.	[110]
Nano silica and lignin	Acid precipitation process	Rice paddy straw	Spherical nano silica NPs (17 nm) provided protection from environmental pollution, with negligible mineral contaminants.	[111]
Cellulose nanofibers	Acid and enzymatic hydrolysis	Agro-industrial wastes from *Salicornia ramosissima*	*S. ramosissima* wastes were considered a renewable source of nanofiber production for circular economy concepts.	[112]
Multi-nanoparticles	Biological processes	Fruit and vegetable processing wastes	NP application provided smart agro-waste management for green energy applications, such as generating and storing energy from agro-wastes.	[20]
Nanostructured iron oxide	Green synthesis	Lime and banana peels	It can use in sustainable agriculture and medical fields because it is non-toxic, biocompatible, and does not include any harmful substances.	[113]
Cellulose nanocrystals	Chemical method/acid hydrolysis	Cut garlic stalk, corncob, and giant cane wastes	Produced nanocellulose for application as new materials for food packaging, purification, and multiple industrial sectors.	[114]

5. Nano-Agrochemicals for Fertilization

Fertilization is an important farming activity that exerts important controls on crop production, especially under intensive agriculture. There are several kinds of fertilizers, which include traditional (chemical/mineral and some forms of organic), bio-, and nanofertilizers (Figure 8). These fertilizers have different roles in achieving sustainable agricultural development. It could be noticed that bio- or nano-fertilizers (mainly biological synthesized nanofertilizers) are more sustainable than organic fertilizers and preferable due to their benefits on the economic and environmental level. Engineered nanomaterials (ENMs) have been applied in many fields in recent years, including medicine and human health [115], water desalination [116], renewable energy [117], cosmetics [118], textile fabrication [73], environmental cleanup [119], and electronics [120]. Due to intensive application, there is an urgent need to consider the environmental implications of using NMs, appropriate regulation of engineered NMs [69], and environmental remediation issues [74]. Furthermore, the commercial production of several nanomaterials has generated toxic wastes, which may create health and safety risks [19].

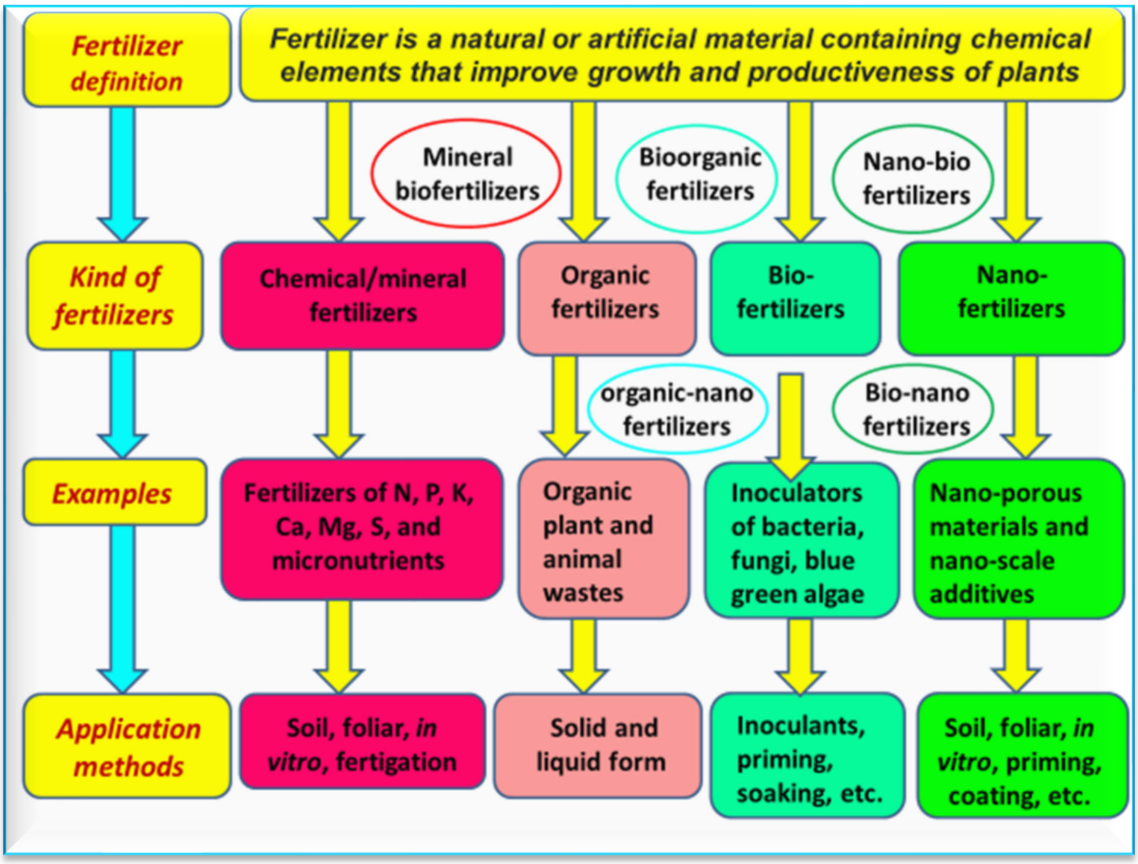

Figure 8. Important information about fertilizers, including the definition, different kinds, examples of each, and the expected methods of application for cultivated crops (adapted from El-Ramady et al. [121]).

Fertilization and irrigation are important farming practices that apply NMs to the environment [122]. Nanomaterials have been applied as fertilizer in many different forms, including chitosan nano-capsules, nanocomposite-based smart fertilizers, nano silica-rich biochar formulations, nano-based slow releasing fertilizers, urea coated with nano-bentonite, nanoengineered metal-based fertilizers, nanometal oxide fertilizers (e.g., nano-Se, nano-CuO, nano-ZnO, etc.), nano soy-protein microcapsules, nanobiochar slow-release fertilizers, and nanohydroxyapatite (Figure 9).

Smart fertilization/irrigation is a fertilization/irrigation system that depends on both the weather and soil conditions to define fertilizer/watering requirements [123,124]. Fertilization and irrigation are very common farming practices that often depend on each other. Fertilization is a process by which amendments supply nutrients to crops. These amendments can be applied by irrigation systems, including surface, sub-surface, drip, sprinkler, or micro-irrigation. Smart agrochemicals are chemical substances that can be applied while controlling the timing, rate, and duration of this application in response to fluctuations in soil moisture, temperature, acidity, or other relevant conditions [125]. Smart agrochemicals can include NMs [126,127]. The main benefits of smart nanofertilizers in the soil–plant system include high nutrient efficiency, lower applied fertilizer doses, high solubility of the fertilizers, time-controlled discharge of nutrients, reduced eco-toxicity compared to most other fertilizers, simple delivery, and reduced nutrient leaching and volatilization. Nanofertilizers can be applied through many different methods, such as nano-priming of seeds or seedlings, nano-foliar application, or plant nano-root nutrition (Table 5). Nanotoxicity, oxidative stress, nutrient losses, and elevated reactive oxygen species (ROS) are the main expected drawbacks that result from the excessive application of nanofertilizers. Agrochemicals, including NMs, can be applied through smart irrigation. The main features of smart irrigation management include soil monitoring, crop water modeling, the use of high-quality water, the use of drones to assist in field monitoring, applying weather forecasting to irrigation planning, and irrigation scheduling [128]. Smart farming, including smart irrigation, is considered a crucial approach to developing sustainable agriculture [129], especially under a nanofarming from farm-to-fork strategy [130].

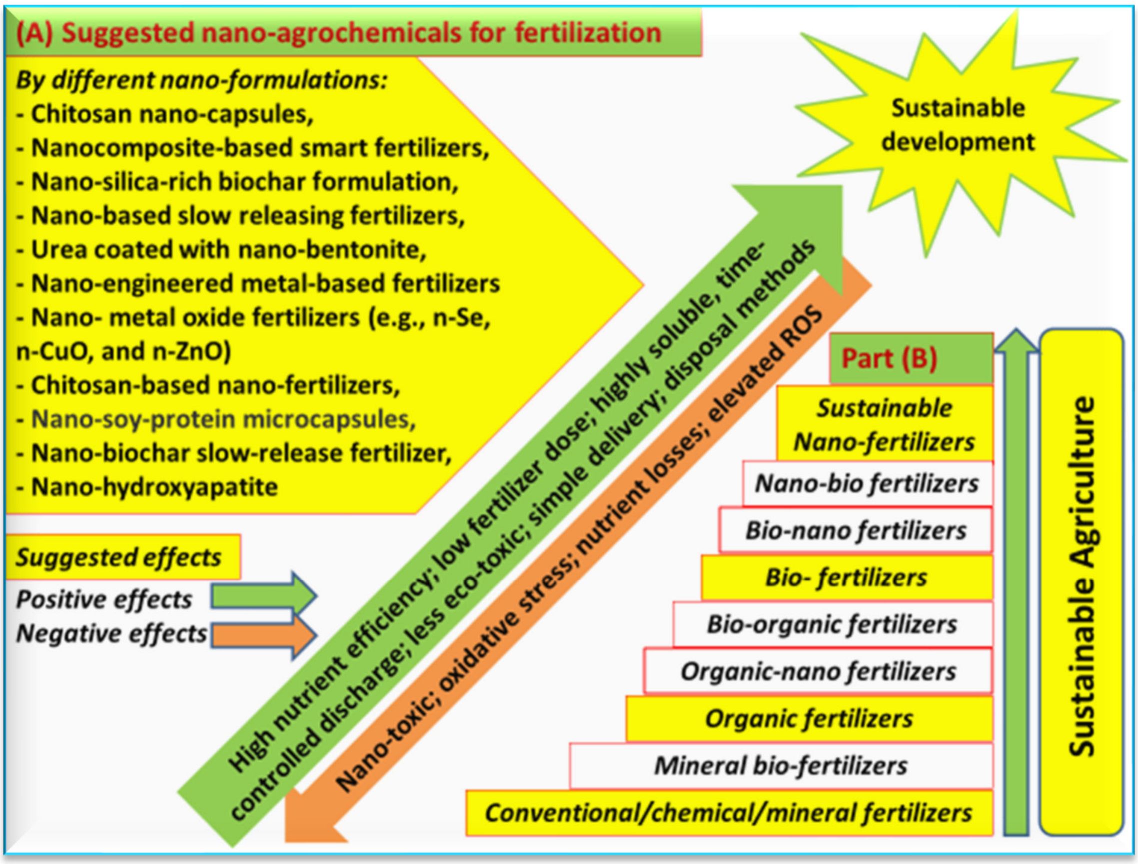

Figure 9. Some nanomaterials that can be used as nanofertilizers or for smart fertilization (Part (**A**)). Part (**B**) presents some suggested terms related to fertilizers. Traditional fertilizers may be associated with a lower sustainability level, whereas higher sustainability levels may be achieved with nanofertilizers.

Table 5. Some published studies on the potential of nano-agrochemicals on the nano-priming process.

Nanoformulations	Applied Dose	Plant Species	Main Findings	Ref.
Nano carbon dots (CDs)	From 0.25 to 2.0 mg ml^{-1}	Pea (*Pisum sativum*)	Plastic waste-derived carbon dots as nanopriming agents accelerated the rate of seed germination and seedling development in a sustainable, cost-effective way.	[131]
Nano chitosan	Priming with 571 µg mL^{-1}	Mung bean (*Vigna radiata*)	Nanopriming prevented seed-borne fungal infection (*Aspergillus flavus*) and improved the seedling vigor.	[132]

Table 5. *Cont.*

Nanoformulations	Applied Dose	Plant Species	Main Findings	Ref.
ZnO-NPs	ZnO-NPs 100% (100 mg L^{-1} dissolved in DW)	Rapeseed (*Brassica napus* L.).	ZnO nanopriming enhanced the development of seedlings by osmotic protection, biosynthesis of pigments, reducing ROS accumulation, antioxidant enzymes, and enhancing the economic yield under saline conditions.	[133]
CeO_2-NPs and selenium-doped CeO_2	100 and 300 ppm	Horse gram (*Macrotyloma uniflorum*)	Nano biocatalyst Se–CeO_2 with high protein plant source enhanced the yield of horse gram seed compared to CeO_2 without raising cytotoxicity.	[134]
Bio-MgO-NPs	10, 25, 50 and 100 mg L^{-1}	Green gram (*Vigna radiata* L.)	MgO-NPs green synthesized with brown alga acting as a nanopriming agent enhanced seed germination and seedling vigor in green gram plants.	[135]
Bio-ZnO-NPs	50, 100, 150, and 200 mg/L of ZnO-NPs	Black gram (*Vigna mungo* L.)	Nanopriming with ZnO-NPs efficiently alleviated As-stress in black gram by reducing root-shoot arsenic translocation.	[136]
CaO-NPs	25, 50, 75, and 100 ppm	Canola (*Brassica napus* L.)	Seed nanopriming improved germination parameters of canola plants under drought stress by improving plant growth and antioxidant defense.	[137]
TiO_2-NPs	40, 60, and 80 ppm	Maize (*Zea mays* L.)	Seed nanopriming enhanced leaf water status, seed vigor, and antioxidant enzymes under salinity stress.	[138]
Carbon nanotubes and SiO_2-NP suspensions	Suspecsions of 25, 50, 75, 100, and 125 µg/ml	Indian mustard (*Brassica juncea* L.)	Nanoprimed seeds under field conditions increased the yield depending on dosage and also the type of used nanomaterials.	[139]
Ag-NPs	20, 40, and 80 mg L^{-1}	Chinese cabbage (*Brassica rapa*)	Nanopriming significantly increased the germination rate. Ag did not bioaccumulate in edible tissues, was a bio-safe agent, increased crop yield and nutritional quality.	[140]
MgO NPs	10–150 µg/ml	Chickpea (*Cicer arietinum* L.)	Nanoprimed seeds increased enzymatic and non-enzymatic antioxidants depending on dose as nanofertilizers for sustainable production.	[141]
ZnO-NPs	500 mg L^{-1} ZnO-NPs for 24 h	Maize (*Zea mays* L.)	Alleviated Co-toxicity via nanopriming of maize; mitigated Co-phytotoxicity by decreasing Co-uptake; conferred stability to photosynthetic apparatus.	[142]

Nano-agrochemicals are common materials that can be used during farming activities [143]. These activities may include germination through nano-priming [16], growing of seedlings using nanofertilizers [144,145], protecting growing plants with nanofungicides [52], improving rooting of seedlings with nanofertilizers [146], enhancing of acclimation of seedlings [145], enhancing the photosynthesis process [147], increasing yield under stress [144], enhancing the quality of harvested fruits [148], and enhancing quality during the post-harvest period [102]. Nano-soaking of seeds can initiate seed priming and form nanopores for the uptake of nanonutrients. These pores increase water uptake by seeds, whereas nanonutrients induce enhanced seed metabolism. Nano-priming can also enhance oxidative respiration resulting in ROS generation, which acts as signaling molecules to trigger germination-related metabolic processes. Gibberellic acid activates α-amylase to fasten starch hydrolysis into highly soluble sugars, which support embryo growth, germination of seeds, and thereby, the vigor of seedlings [16].

6. Nano-Precision Farming

Precision agriculture or precision farming (PF) represents the management of different farming practices through near "real-time" observation using analysis tools and technological sensors to reduce labor time and increase crop productivity and the efficiency of fertilizers, irrigation practices, and other inputs [18]. This system of farming needs analyses of different parameters, including soil water content, soil organic matter content, topography, nitrogen, and other nutrient levels, pH, soil salinity, crop yield, etc. This can assist farmers and researchers in locating and creating maps of the spatial variability of inputs and how they relate to yield [18]. The main benefits of PF include the detection of weeds and diseases in the fields, yield prediction, and productivity estimation [149]. Precision farming can apply best management practices, such as soil preparation, crop fertilization, proper irrigation, management of pests and diseases, and harvesting and storage of crops in a site-specific fashion using modern agro-technologies [149]. Due to its promising applications, nanotechnology has been applied to precision farming to improve the quality of agri-products, reduce post-harvest loss, mitigate stressful conditions, and enhance crop protection ([14]; Figure 10).

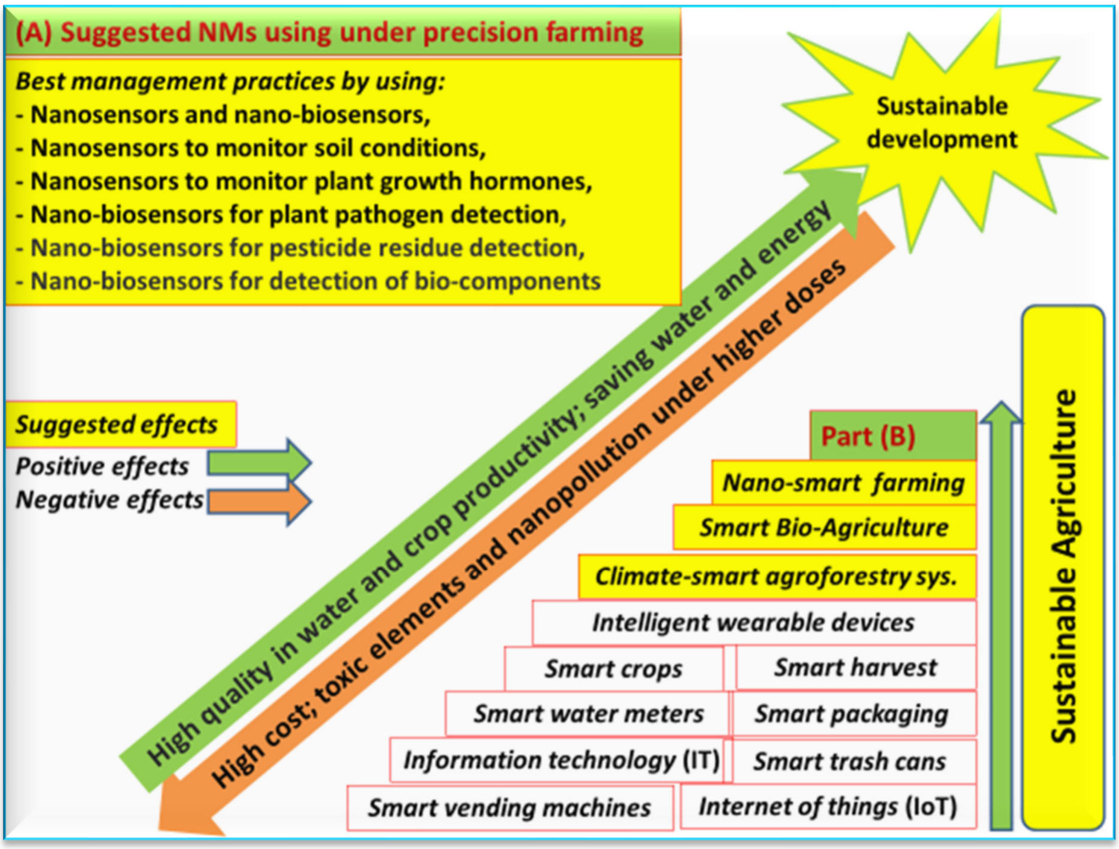

Figure 10. Different ways to apply nanomaterials (NMs) for smart and/or precision farming are listed in Part (**A**). These NMs may include nanosensors and others as promising approaches for the development of sustainable agricultural practices. Part (**B**) shows terms related to smart fertilizers, starting with Global Positing System (GPS), smart vending machines, and nano-smart farming as high-level approaches towards sustainability. Some positive and negative effects of nanofarming are also shown.

Nanosensors are "smart delivery systems" that can promote precision farming by guaranteeing the timely application of agrochemicals, potentially in a remote and self-regulated way, with spatially targeted, pre-programmed, and multifunctional characteristics [150]. These sensors are promising and powerful tools for converting any biological response into an electric signal. A biosensor is a device that can detect biological components (e.g., antibodies, enzymes, and organic compounds) and/or organisms from an analyte using a transducer [151]. Nanosensors have the ability to detect plant pathogens and pesticides and monitor soil conditions and plant growth hormones [151]. Precision farming utilizes a variety of sensors, computers, global satellite positioning systems (GPS), geographic information systems (GIS), unmanned aerial vehicles (UAV), global navigation satellite systems (GNSS), and remote sensing devices to measure highly localized environmental conditions. This can help achieve maximum efficiency in crop production by identifying the nature and location of potential problems in a precise manner. These smart sensors may allow enhanced agro-productivity of crops and livestock by helping farmers make well-informed decisions [152,153].

Ten technologies are most commonly used in precision agriculture. These are (1) global positioning systems, (2) multimedia devices, (3) nanosensors, (4) remote sensors, (5) other sensors, (6) unmanned aerial systems, (7) unmanned aerial vehicles, (8) unmanned ground vehicles, (9) variable rate technology, and (10) wireless sensor networks [154]. Recently, several studies focused on the crucial use of nanotechnology for precision farming, such as its role in changing the future of agriculture [152], nanofarming [15], precision agriculture applications [155], the detection of phytopathogens [156], smart nano-agrochemicals [127], nano-precision farming [18], nanocomposite-based smart fertilizers [157], and the future of farming [158]. The main advantages of smart farming include saving time, reducing the use of agrochemicals and environmental problems from leaching, runoff, etc., and improving crop productivity and water protection. The limitations include a lack of standard protocols regarding applied doses of nano-agrochemicals, few studies at the field level, limited information concerning the fate, release, and ecotoxicity of these nano-agrochemicals into the environment, and limited safety assessment data [158].

7. Nanobiotechnology for Modern Farming

The combination of interdisciplinary fields that address different applications of biotechnology to nanotechnology is called nanobiotechnology (NBT). Applications of NBT can be found in the fields of agriculture, health, medicine, imaging, drug delivery, immune-proteomics, tissue engineering, cosmetics, pharmacy, and more [159]. Nanobiotechnology has great potential for the development of new nano-biosensors, drug delivery and gene therapy tools, nano diagnostics, nano crop protection and management, nano postharvest processing, and bio-compatible nanodevices (Figure 11). Nanomaterials and nanoparticles can be biosynthesized using biological methods, which have several applications during farming practices, such as:

1. Using nano-biosensors and biosensors to detect diseases and their outbreaks through wastewater-based epidemiology [160,161]. This is important when wastewater is used in farming applications.
2. Biorefining agro-wastes through agri-nanobiotechnology approaches to produce lignin-based nanomaterials for use as fertilizers, agrochemicals, soil conditioners/modifiers, and mulching. These applications can promote crop productivity and manufacture high-value bio-products from lignin [162,163].
3. Using nanobiotechnology to diagnose plant and animal diseases, such as cancers and inflammatory diseases [164], or nano-biosensors in sustainable agriculture [165].
4. Nanobiotechnology is very important for PF as it allows regulation of many practices starting with the preparation of soil for cultivation, nanodelivery of agrochemicals for crop production, and plant adaptation to stressful conditions [15,102,166].
5. Nanobiotechnology has great potential to reduce food loss during post-harvest management and promote agricultural production with environmental safety, premium quality, biological support, and financial stability [102].

6. Gene delivery and plant micropropagation using promising nano-vectors for delivery of genes in the engineering of the plant genome [167,168].
7. Applications of nanotechnology for bio-based packaging and bio-nanosensors-based packaging of food products. These nanosensors can monitor the quality of packed foods and allow the use of biodegradable packaging, which can increase the shelf life of foods [169,170].
8. Green synthesis of NPs using plants, fungi, algae, and bacteria for metal recovery as a cost-effective and eco-friendly approach to recover several valuable metals that may be polluting soil or water resources [171].
9. E-waste management by recovering high-added value materials from these waste components, producing high purity metals, nanostructured alloys, nanoparticles, and nanocomposites [172,173].
10. Nanotechnology-enabled biosensors as diagnostic tools for food safety and clinical applications, such as rolling circle amplification in DNA nanotechnology [174,175].

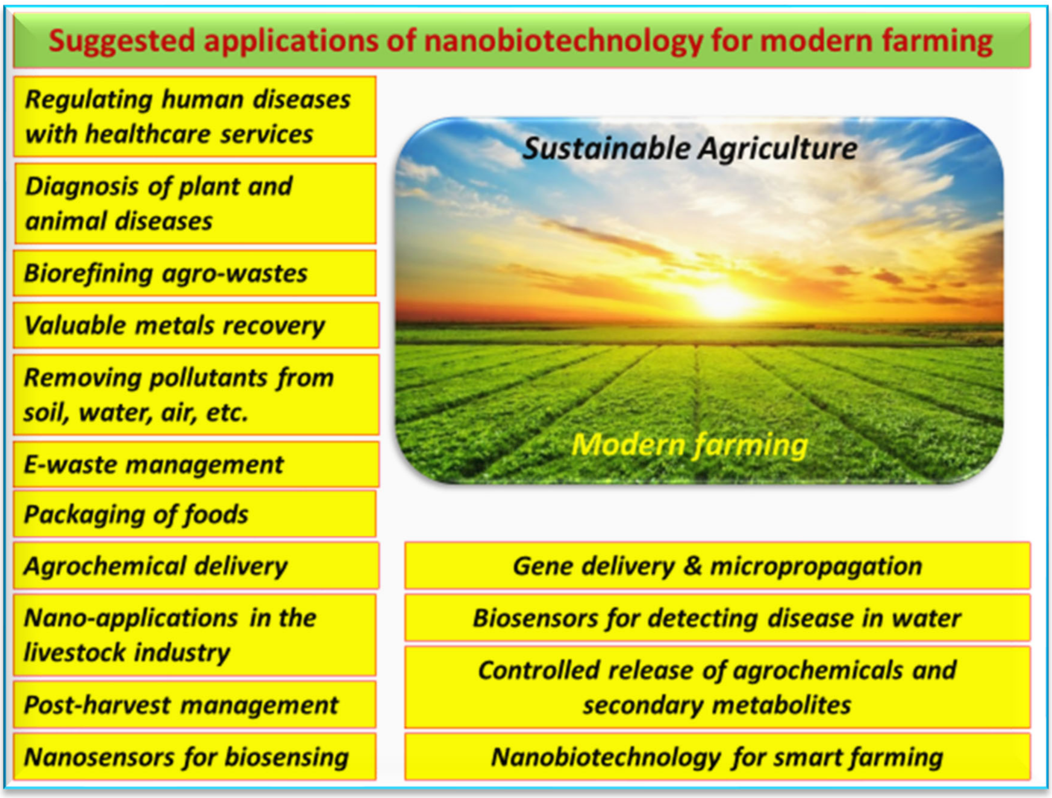

Figure 11. Nanobiotechnology (NBT) is an emerging science that may support sustainable agriculture. NBT includes several applications in different fields. Many terms are related to NBT, including diagnosis of plant and animal diseases, biorefining agro-wastes, nanosensors for biosensing, nanobiotechnology for smart farming, and so on.

8. General Discussion

Nanotechnology is considered an emerging and exciting new field of science that has a number of potential applications in various areas of our lives. Nanotechnology has shown the potential to improve the agricultural sector by enhancing crop productivity and its quality. This review highlights some of the main questions concerning the application of nanotechnologies to farming. They include: What are the possible applications? What benefits arise from nanotechnology? What are the different subdivisions of nanotechnology that may have applications in agriculture? Additionally, what are the expected problems that may be encountered when using nanofarming practices? Several farming practices have already been investigated using different nanomaterials or nanoparticles and have shown many potential benefits (Figure 12). These farming practices may start with soil preparation for cultivation, which would allow the incorporation of nanofertilizers or nano amendments, such as nano-gypsum [36]. Nano-gypsum has proven to improve saline-sodic soils at lower doses (up to 960 kg ha^{-1}) compared to traditional gypsum due to its greater solubility/efficiency of use. Gypsum does this by decreasing soil pH, EC, and bulk density while increasing soil hydraulic conductivity, stable aggregates, and Na-removal efficiency [176]. The germination of seeds (at the pre-sowing stage) also has been improved by applying nano-agrochemicals (nanofertilizers, nanopesticides, nano-amendments, or nano-biostimulants) as nano-priming in the case of many crops, such as carbon nanodots on peas (*Pisum sativum*) [177], TiO_2-NPs on mung beans (*Vigna radiate*) [178], and nanohydroxyapatite on cluster beans (*Cyamopsis tetragonoloba* L.) [179]. The reasons may trace back to the enhanced role of NMs in increasing the antioxidant enzyme activities of seeds, chlorophyll content, carbohydrate content, and seedling vigor index [131]. This synergistic role of NMs is clear under both normal and stressful conditions as reported by the following studies: TiO_2-NPs on maize (*Zea mays* L.) under salinity stress [138], CaO-NPs on canola (*Brassica napus* L.) under drought stress [137], and ZnO-NPs on *Vigna mungo* L. under arsenic stress [136].

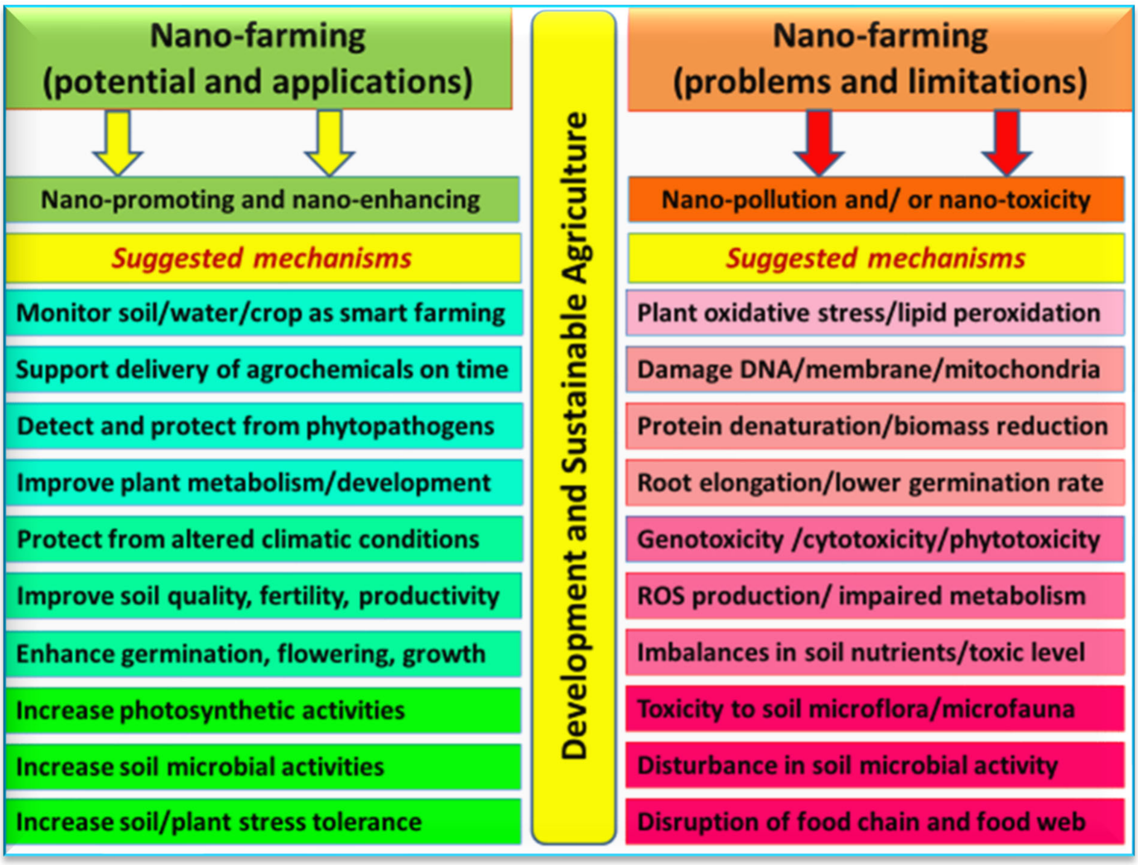

Figure 12. A general overview of nanofarming, including different applications, expected problems, and their suggested mechanisms. The grade of red color represents the potential level of toxicity or problem, whereas the green shades the desirable benefits from nanofarming. Darker colors indicate greater effects. Sources: [14,15,22,180].

Farming activities using NMs include the growing stages of cultivated crops and the use of NMs in nanoremediation of polluted soil, water, and air. This topic may include the cultivation of polluted soils [80,85], irrigation of cultivated plants with low-quality irrigation water [148], or nanoremediation of polluted groundwater through the detoxification of pollutants by nano-adsorbents [181]. Agrochemicals in nanoform (i.e., nanofertilizers, nanopesticides, nano-herbicides, nano-phytohormones, etc.) represent the main source of nano agro-pollutants in terrestrial environments. These pollutants need to be nano-remediated as they can cause undesirable changes in the fertility and quality of soil and groundwater [78]. The nano-remediation of agro-pollutants depends on the kind of agro-pollutants and the type of NM remediation used. Nanomaterials work for remediation because they have high surface areas and are relatively safe with high detoxification, degradation, and transformation potential as regards the NM pollutants found in the environment [78]. It is worth noting that cultivated plants are considered a part of the solution when using nano-phytoremediation, especially plants that are tolerant to the types of pollutants present. Soil microbes are considered promising agents as biosurfactants that can be applied as nano-biosurfactants for bioremediation processes [80]. Furthermore, both cultivated plants and soil microbes may contribute to detecting nano agro-pollutants as they can serve as nano-biosensors. These smart nano-biosensors are important for detecting nanopollutants and phytopathogens and sensing plant hormones and metabolites, soil health, pesticides, fertilizers, and heavy metal ions in the soil [182].

The relationship between agro-wastes and their nanomanagement is a crucial global issue. Lenses through which this relationship can be viewed include the circular economy, energy crisis, sustainable goals, food production and preservation, and management of agro-wastes. Agro-wastes may represent a real threat to the entire environment when proper management is absent because they increase problems, such as harmful insects, nutrient pollution, and nutrient binding. The sustainable management of agro-wastes has the ability to produce many useful products, especially energy production and other biorefinery approaches using nanobiotechnologies [162]. Converting these wastes into sustainable energy would provide major benefits [106]. There is an urgent need to manage waste within smart and sustainable systems so that the utilization of our scarce natural resources is maximized to achieve the global goals of sustainable development. The One Health approach should be integrated into several development programs and policies as a catalyst for sustainable development [183].

There are many potential sources of nanopollution under nanofarming management. This may result from activities before, during, and/or after cultivation due to the excessive application of nanomaterials. Nanopollutants may include nano-glass, fibers, plastics, biologics, metals or metal oxides, etc. Nanoparticles of glass can result from waste windshield glass, and nano-plastics are a major threat to environmental and human health. Nanoparticles of glass have been shown to inhibit the germination of wheat seeds and the length of roots and shoots and reduce chlorophyll content [184]. The impacts of nano-plastics on terrestrial plants are negative, particularly during early development stages (i.e., germination and root growth). These negative effects have been documented in many plant species (e.g., lettuce, maize, rice, and wheat), irrespective of the size and polymer type of the nano-plastic. This has been attributed to the negative influence of these nano-plastics on chlorophyll content, and the formation of free radicals or ROS [185]. Due to the wide range of applications of nanomaterials, there are also abundant possibilities for environmental nano-pollution, and this increases as the use of NMs increases. Nanoparticles can end up in water, air, and soil and may pose a major threat due to their small size. Therefore, this threat should be controlled and managed [22,26,177]. Nanopollution is called "invisible pollution" because NPs can easily penetrate the cells of plants, animals, and through human skin, leading to serious consequences. They can also accumulate in plants, entering humans via the food chain and causing health problems [22].

Concerning the main mechanistic pathways of nanoparticles under different agricultural practices, this mechanism mainly depends on the kind of nanoparticles, the agricultural practice, or the plant growth stage. For example, the germination of seeds is considered one of the most important periods or stages in agricultural production. Applying nanomaterials to seeds through nano-priming can be used to enhance germination through a special mode of action (Figure 13). This mechanism mainly depends on inducing enhanced expression of aquaporin genes and alteration in seed metabolism, which promotes enzymatic activity to convert stored starch into soluble sugars that move to the embryo. Increasing oxidative respiration and forming reactive oxygen species (mainly H_2O_2), which are converted from O_2—through the enzyme superoxide dismutase, followed by diffusion to the embryo, allows interplay between H_2O_2 and phytohormone gibberellic acid (Kandhol et al. [16]).

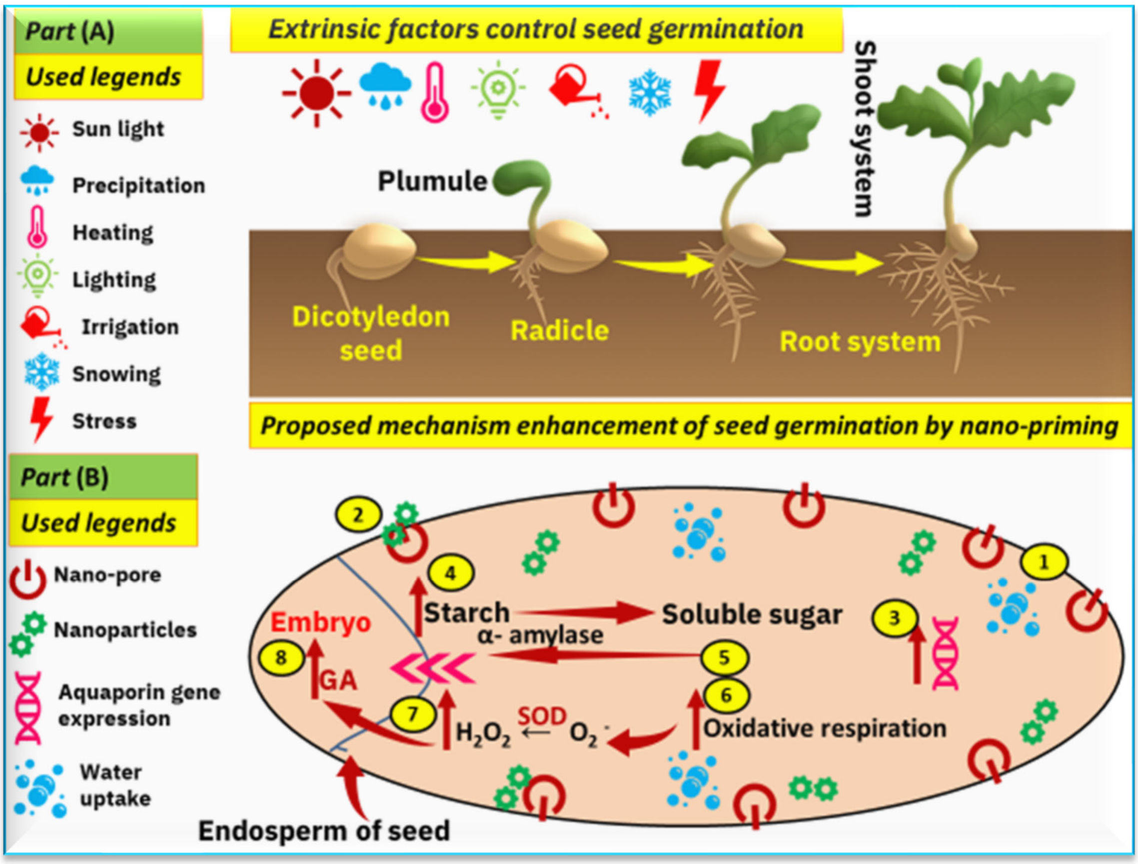

Figure 13. (**A**): The factors that control seed germination. (**B**): Suggested nano-priming mechanism: soaking seeds with nanoparticles (NPs), followed by high seed uptake of water, allows NPs uptake (steps 1 and 2), which reduces stress during germination. NPs also enhance the expression of aquaporin genes and alter seed metabolism (3), which enhance enzymatic activity that converts stored starch into soluble sugars (4) and moves to the embryo (5). This increases oxidative respiration and the formation of reactive oxygen species (mainly H_2O_2), which convert from O_2—due to superoxide dismutase (SOD) and H_2O_2, followed by diffusion to the embryo which allows interplay between H_2O_2 and phytohormone gibberellic acid (GA). Source: image of seed germination from https://www.pexels.com/ (accessed on 15 March 2023) (adapted from Sári et al. [186]).

Many questions still need to be answered concerning the toxicity and nanopollution from farm practices. Due to this review included several farming practices; each practice itself has many open questions, including the germination, growing, flowering, and harvesting, and post-harvest of crop farming. The same is true for different kinds of farming, such as animal and forestry farming, which could include many applications of nanotechnology. These fields are not only the suggested areas to be included in open questions but also different anthropogenic activities on the farm, environment, and global level. Related questions about the agroecosystem are also needed, including climate change or greenhouse-gas emissions, pollution, loss of biodiversity, water crisis, soil degradation, and disruption of aquatic ecosystems. Lastly, these questions will need to be answered for nanofarming to reach its full potential. The suggested questions on farming research may include the following:

To what extent can nanopollution be controlled at the farm level?

What practices are the main sources of nano-pollution on the farm level?

Which parameters control nanopollution under greenhouse cultivation?

What are the differences between greenhouses and open fields?

Which nanomaterials are the most efficient, innovative, economic, and reliable to remediate environmental pollutants?

What are the expected potentials of nanobiotechnology for micropropagation of rare plants?

What are the promising nanomaterials for mitigating stress on farming crops?

What are the global regulations on applying nanomaterials should be issued to protect food security?

What are the global regulations on nanofertilizers/nanopesticides that should be implemented?

To what extent can nanofarming be a solution for sustainable energy production and storage?

9. Conclusions

Throughout its history, agriculture has advanced from a simple system of sowing seeds and harvesting crops to a true science that extends from pre-planting to post-harvest, with each step formulated to get the maximum possible yield of nutritious food to sustain human life and health. Utilizing nanotechnology to advance this goal is called nanofarming. The application of NMs in nanofarming can begin with seed and soil preparation prior to planting and extend to the use of NMs to reduce food spoilage during storage and transport. All the steps in between, including removing any growth restrictions, enhanced flowering, phytopathogen resistance, fertilization/irrigation performance, crop nano-protection under biotic stress, nano-improvement of soil quality, removing pollutants from soil and water, management of agro-wastes for energy and other nanomaterials production, the performance of precision farming, etc., may be addressed with nanotechnologies. Nanobiotechnology can also support modern farming with safe and healthy agro-production. The negative sides of nanofarming present a great challenge that needs to be carefully investigated. Nanofarming should be discussed from different points of view, including the economic, social, and environmental aspects.

Author Contributions

Conceptualization, H.E.-R., J.P. and N.A.; methodology, D.S., A.F. and A.M.; software, Z.F.F.; validation, E.C.B., S.Ø.S. and J.P.; formal analysis, Z.F.F.; investigation, N.A.; resources, J.P.; data curation, E.C.B. and S.Ø.S.; writing—original draft preparation, H.E.-R.; writing—review and editing, E.C.B. and S.Ø.S.; visualization, Z.F.F.; supervision, N.A.; project administration, H.E.-R.; funding acquisition, S.Ø.S. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thank Inland Norway University of Applied Sciences, Norway, for funding this work.

Data Availability Statement: All data are available in the submitted manuscript.

Acknowledgments: The research was supported by the Stipendium Hungaricum Scholarship Program.

Conflicts of Interest: The authors declare no conflict of interest.

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