agriculture

Review

Mitigating the Impacts of the COVID-19 Pandemic on Crop Farming: A Nanotechnological Approach

Fadekemi O. Akinhanmi [1,*], Opeyemi I. Ayanda [1], Eze F. Ahuekwe [1] and Gabriel A. Dedeke [2]

1 Department of Biological Sciences, Covenant University, Ota 1023, Nigeria
2 Department of Pure and Applied Zoology, Federal University of Agriculture, Abeokuta 111101, Nigeria
* Correspondence: hazelfadekemi@gmail.com or fadekemi.akinhanmipgs@stu.cu.edu.ng

Abstract: COVID-19 is a highly infectious respiratory disease that resulted in a global pandemic that has affected every stage and sector of life. Although it is mainly seen as a health issue, its impacts and ripple effects also resonated in the education, technology, agriculture, and research fields, creating socio-economic disruptions across the globe. In a bid to curb the wide spread of the disease, diverse sudden restriction measures were adopted, which had implications on food security and food availability via supply shortages and agricultural disruptions. Scientific studies such as those regarding nanotechnological developments, which had been underway for improving food quality and crop improvement, were also slowed down due to the complexities of the pandemic and global restrictions. Nanotechnology is a developing and promising field for further development of crop productivity by enhancing the proficiency of agricultural resources, thereby increasing food yield and food security. The application of nanotechnology crop farming involves the use of nano-scale materials that can be formulated into nano-emulsion, nano-capsule, nano-fertilizer, nano-pesticide, and nano-biosensor applications for improved agricultural productivity. In as much as the challenges of nanotoxicity could raise health and environmental concerns, advances in the biosynthesis of nanomaterials potentially allay such fears and concerns. Furthermore, these ideas will help in bridging the gap created by the pandemic on food availability, food security, and agriculture. This review focuses on the implications of the COVID-19 pandemic on nanotechnological applications for improved crop productivity and nanotechnological mitigation strategies on the impacts of the COVID-19 pandemic, risk assessment, and regulatory issues surrounding nano-crop farming, and this study provides an insight into future research directions for nanotechnological improvements in crop farming and the sustainable development of nano-enabled agriculture.

Keywords: COVID-19; crop improvement; food shortage; nanotechnology

Citation: Akinhanmi, F.O.; Ayanda, O.I.; Ahuekwe, E.F.; Dedeke, G.A. Mitigating the Impacts of the COVID-19 Pandemic on Crop Farming: A Nanotechnological Approach. *Agriculture* **2023**, *13*, 1144. https://doi.org/10.3390/agriculture13061144

Academic Editors: Muhammad Sultan, Yuguang Zhou, Redmond R. Shamshiri and Muhammad Imran

Received: 1 December 2022
Revised: 7 February 2023
Accepted: 7 February 2023
Published: 29 May 2023

1. Introduction

The recent coronavirus disease 2019 (COVID-19) put the world into sudden chaos with the need for survival as the threat was combated on all fronts. Although several coronavirus diseases existed before this time, only six have reportedly caused mild to severe respiratory tract infections in humans [1]. The coronavirus is a highly infectious virus that causes respiratory illnesses with a high probability of morbidity and mortality [2]. COVID-19 is a highly contagious infection caused by a new strain of coronavirus disease (SARS-CoV-2), which results in severe acute respiratory tract symptoms [3]. First discovered and recorded in Wuhan, China, in December 2019, this virus is highly infectious and was spread worldwide within a short time [4]. In light of this, the World Health Organization (WHO) declared it a global pandemic on 11 March 2020 [5]. About a month later, the WHO had reported over 2.1 million cases of COVID-19 in 213 countries, with the most affected countries including the United States of America, Italy, China, Spain, Germany, France, the United Kingdom, Canada, Turkey, Brazil, Belgium, and Russia [6]. Since then, the number of cases has continued to rise globally and has become a critical threat to public health.

As much as COVID-19 is a health issue, it has also affected every other stage and sector of life. For instance, the education sector suffered with the distance education process and researchers becoming active technological educators, which instructors had previously avoided. Laboratories that ought to have been coordinating experimental studies, reporting more scientific research, and conducting field trials of different technical applications were suspended due to the movement restrictions and lockdowns. However, this period of 'pause' is expected to provide new research approaches to new and developing research areas [7]. This global pandemic has also resulted in recognizable socio-economic disturbances and has defied racial issues and geographic discrimination [8]. Governments worldwide attempted to curb the spread of COVID-19 by implementing various curtailing measures such as quarantines and lockdowns, travel restrictions to the complete shutdown of many international airports, border shutdowns, business closures, and regulations of several social and economic activities. Unfortunately, these sudden measures, via multiple dynamics, have had profound implications on food security and availability, leading to supply shortages amplified by agricultural disruption [9]. Before the pandemic outbreak, factors such as climate change, increased global population, rapid urbanization, and economic growth in most developed countries led to limited natural resources responsible for agricultural activities and productivity. About two billion people face food insecurity and malnutrition at the moderate or severe level, with the number increasing since 2014, rising by 60 million over five years [10]. The measures engineered to curtail and curb the spread of the virus also led to agricultural disruption via labor shortages and delays in the food supply. Scientific studies, which had been underway for enhancing practicable and applicable technologies to improve crop productivity, food quality, and quantity, were also slowed down due to the complexities of the global restrictions [10]. However, mitigating the challenges of food insecurity and the setbacks caused by the pandemic requires continuous, practical, productive, and sustainable agricultural development. In addition, the rising awareness of consumers of food and agrarian items and their health advantages is convincing researchers, industrialists, and farmers to discover methods that potentially enhance food quantity and quality while maintaining its vital nutritional benefits [11]. The developing field of nanotechnology has shown latent capability for further crop farming development by enhancing agricultural resources' proficiency and proffering solutions to agrarian challenges for improving food yield and security [12].

Nanotechnology is a multidisciplinary field of science that can be described as the fabrication of carefully organized particles formed from atoms that can change their material properties at a particular size of 1 nm–100 nm (nanoscale) [13]. Several industries and sectors, such as the medical services and pharmaceutics, textile, food and agricultural, information technology, and renewable energy fields, have had significant contributions from nanotechnology because of its promising capability to make most products more proficient. Moreover, nanotechnology approaches are still being studied to further combat the spread and management of COVID-19 through personalized medicine, artificial intelligence, and nano-therapies [14]. Recently, the recognition of nanotechnology in crop farming, a rapidly developing field, has gained significant ground because of its capacity to offer prospective answers essential for viable and sustainable agriculture [15]. Although progress in nanotechnological advancements in crop farming has been steadily increasing, the issue of delay in field applications and, more so, pandemics could serve as a 'clog in the wheel' of progress. Nanotechnology manages nanomaterials that have a minimum of one dimension on the nanoscale. Tested nanomaterials in crop farming include inorganic (metal and metal oxide nanoparticles), organic (naturally occurring nanoparticles), and combined (i.e., nanohybrids) materials [16]. The use of nanotechnology in crop farming accentuates the goal of the development of clean, safe, precise, and environmentally friendly nanomaterials, utilizing biologically compatible and nontoxic solvents, biodegradable and natural grids, and energy-productive and viable procedures [17,18]. Nano-carriers are equipped to enhance active ingredients' solubility while protecting them from volatilization and degradation. Improving proficiency can produce better outcomes, utilizing lower dosages and several other applications, thus reducing environmental pollution and risks to human wellbeing [19,20]. Various nanomaterial formulations are utilized in crop farming, including nano-herbicides, nano-fungicides, nano-pesticides, nano-fertilizers, growth-promoting substances, and nanobiosensors, among other applications [21]. Engineering nanomaterials is the state-of-the-art research track that upholds the advancement of innovative farming fields by offering a more extensive surface area, which is vital for the viable improvement in agri-business [22]. Accordingly, nanotechnology can decrease the incertitude and organize the management techniques of agricultural production as a replacement for traditional methods while attenuating the lag caused by the COVID-19 pandemic. This present review discusses the applications of nanotechnology in alleviating the impacts of the COVID-19 pandemic on crop farming and crop improvement in battling food shortages and food security.

2. Implications of the COVID-19 Pandemic on Nanotechnological Advancement in Crop Farming

Despite ongoing research on nanotechnological applications in improving crop production and combatting food shortages, the COVID-19 pandemic undermined these efforts due to multiplex dynamics caused by the lockdowns and other actions intended to curb the spread of the disease. Although technology progressed at the speed of the scientific data obtained, the sudden outbreak of the COVID-19 pandemic hindered progress in scientific studies and related projects worldwide [23]. Instead, research efforts focused on ending the pandemic and economic giants were also geared towards investing in necessary experiments to permanently end the pandemic [24]. To this end, research is ongoing to harness the potential of nanotechnology to proffer solutions to the raging pandemic. The primary focus of the scientific community has been continuous investigation and development to improve the characteristics of already-in-use preventive, diagnostic, and treatment measures for the virus through the application of nanomaterials [25].

The impact of the pandemic also created conditions for significant disruption to food systems, giving rise to a dramatic increase in food insecurity and hunger [26]. The measures implemented to curb the spread of the disease severely impacted crop production, jeopardizing global food security [27]. Furthermore, the pandemic's impacts were felt in the form of rising food prices, unemployment, and income losses [28]. The effects of COVID-19 on crop production can be described as follows: (1) disruption of the input supply chain; (2) shortage of labor and mobility; and (3) a shortage of food occasioned by travel restrictions and the ban on movement of persons and food distribution from the production site to the consumers [7]. These inconsistencies exacerbated food security challenges, price hikes, and increased food losses. Although the restrictions did not directly affect agricultural activities, the agrarian sector was indirectly affected via its connections to the rest of the economy. For instance, businesses such as hotels, restaurants, and catering services, which are majorly fed by agricultural production, were significantly affected by the COVID-19 policy responses [9]. Moreover, farming activities require high demand for labor, but the restriction of movement and lockdown limited access to farmlands by laborers and farmers [29]. In addition, the lack of sufficient viable seeds and the delay in input procurement due to the disruption of the agricultural input supply chain, such as seeds, agrochemicals, and fertilizers, further reduced crop yields and the quality of agro-products [7].

Food quality and safety were also compromised by the increasing rate of COVID-19 cases, which reduced available human resources, necessitating inexperienced farm workers' engagement, poor farm management, poor crop yields, and decreased quality of the crops produced [28]. Crop productivity could also be affected in the future, especially if the virus is not fully contained and the restriction measures continue. With the vast array of applications of nanotechnology, it could also serve as a bridge to close the lapses and setbacks that resulted from the pandemic. Although nanomaterials have the potential to increase and promote sustainable crop production, the progress in agricultural nanotechnology is slow because of toxicity and safety concerns [30].

3. Mitigating COVID-19's Impacts on Food Security through Nanotechnology

The direct and indirect impacts of the COVID-19 pandemic on food security, farmers' income, food availability, and crop production have prompted measures to mitigate the further spread of the virus among crucial players in crop production and the food supply chain. In a recent publication by the WHO, recommendations were made on measures to hamper SARS-CoV-2 transmission and manage COVID-19 occupational outbreaks through worksite restrictions, physical distancing, isolation of infected persons, regular worksite disinfection, regular hand hygiene, environmental monitoring, and appropriate use of personal protective equipment (PPE) [31]. While these measures are pertinent, the complimentary application of technologies such as nanotechnology is important in crop production scenarios considering its large workforce and labor mobility issues. Major nanotechnological innovations, such as precision farming and artificial intelligence, nano-biofortification of food crops, genetic cargoes, and smart delivery systems, are emerging in crop production [32]. Although still in their infancy, these technological advancements have the potential to cushion the impacts of the COVID-19 pandemic on food availability, quality, and crop production. For instance, precision farming aims at the targeted delivery of nano agrochemicals, thereby improving nutrient-use efficiency, crop production and yield, plant resilience, and soil health. Nanotechnology-based processes such as nano-nutraceuticals and nanofood are emerging to increase the nutrient quality of crop yield, provide physiological health benefits, and enhance protection against chronic diseases [33]. Nanotechnology can also be applied to food packaging to improve its shelf life and maintain freshness for extended periods. Essentially, nano-based materials have the potential to double up crop productivity and availability, thereby alleviating the food shortage caused by the pandemic.

Some educational institutions in the United States are currently developing easy-to-use portable smart nanosensors to detect and monitor food quality [34]. Scientists working with the National Institute of Food and Agriculture (NIFA) are also developing eco-friendly processes for fabricating silver NPs that can be used in antimicrobial films and food packaging. While the potential risks of nanomaterials are still being studied to facilitate public acceptance, manufacture, and use, public awareness is being raised to incite society, industry, and governments to fund, fast-track the development of, commercialize and adopt nanotechnology globally.

Nanomaterials possess enhanced physical and chemical properties such as in color, hydrophobicity, melting point, flexibility, and reactivity. The applicability and efficiency of nanostructures are the changes in their properties with size and "size effects" [35]. The surface-area-to-volume ratio increases with the reduced size of the materials, thereby enhancing their surface reactivity, otherwise known as surface effects; alterations in the bandgap enhance their chemical properties due to quantum size effects [36]. These improved properties, coupled with their size, have made nanomaterials attractive candidates for the attention of researchers in every field. The application of nanomaterials has been reported in different areas, such as medicine, nano-therapy, energy production and storage, virology, communication systems, food and beverages, and so on. In addition, there are reports that nanotechnology has the potential to address the three significant challenges arising from the COVID-19 outbreak: disease prevention, prompt and early diagnosis, and treatment [14]. The COVID-19 pandemic triggered measures that have had and still have ripple effects on crop production and food supply, leading to food insecurity, hunger, and malnutrition. Nevertheless, innovation and research progress in nanotechnological advances can alleviate these challenges by safeguarding food security, safety, and preservation. Detailed discussions on nanomaterials and their applications in crop farming are stated as follows.

3.1. Nanomaterials and Their Classification

Nanomaterials (NMs) are objects whose measurement is between 1 nm and 100 nm (nanoscale). They may exist as particles, strands, wires, composites, flakes, chips, tubes, cylinders, or films [37]. One way of classifying nanomaterials is according to their dimension, as shown in Figure 1. Additionally, due to size control and the enormous surface area of these materials at the nano-scale, they are valuable and have outstanding performance in numerous fields of utilization. Nanomaterials display varying properties from their bulk analogs, representing their unique component, including a large surface-to-volume ratio and explicit physicochemical and natural characteristics [38].

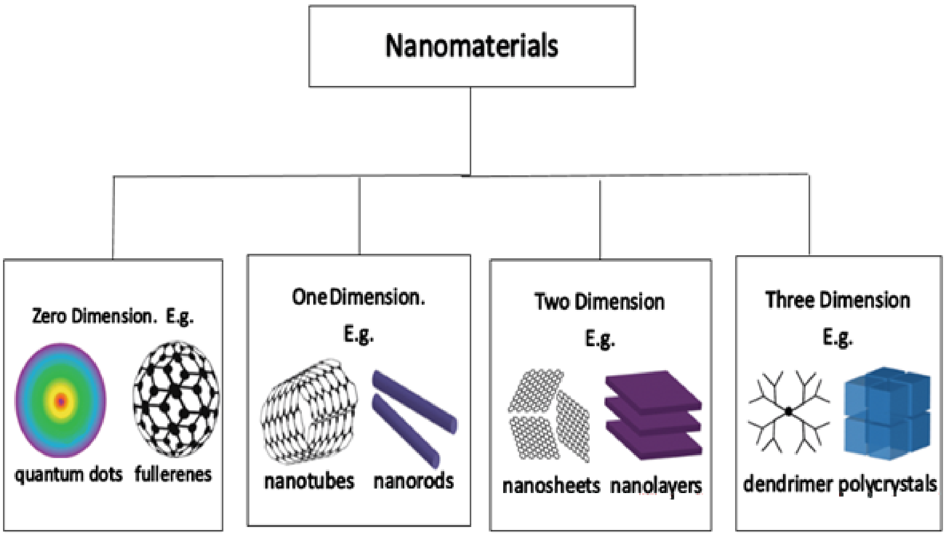

Figure 1. Classification of nanomaterials [37].

Synthesis of Nanomaterials

Some nanomaterials exist in the natural world due to processes of photochemical reactions, forest fires, volcanic eruptions, erosion, plant, animals, or even microbes. There are three basic approaches used in synthesizing nanomaterials.

1. Physical synthesis, also described as the top-down approach. This technique involves the breakdown of bulk materials into smaller and tiny particles, and this process is energy-consuming and takes more time to achieve thermal stability. Several methods applied in the physical synthesis of nanomaterials include the tube furnace, laser ablation, thermal dehydration, and thermal decomposition [38].
2. Chemical synthesis, also described as the bottom-up approach. This involves the buildup of nanomaterials from atoms and smaller particles. The chemicals and reducing agents used in this process pose a toxicity risk during their application. Nanomaterials' chemical synthesis methods include physicochemical reduction, wet chemical synthesis, and electrochemical techniques.
3. Biological synthesis, also referred to as "green" synthesis. This involves the production of nanomaterials from biogenic materials or substances. The biosynthesis of nanomaterials can be from the following: The use of microorganisms such as fungi, yeast, and bacteria; the use of plant extracts or enzymes; or the use of templates such as DNA, membranes, viruses, or diatoms. This process is cheaper, easier, and produces safer and more environmentally friendly nanomaterials [37].

3.2. Dimensions of Nanomaterials in Crop Farming

Nanotechnology is an emerging technology with potential applications in our daily existence, implementing the change in society. The rapid advancement in nanotechnology has been aiding the transformation of the conventional crop farming framework with the help of different innovative components such as nanoparticles, nano-biosensors, nanosensors, antivirals, antimicrobials, and nano-fertilizers [11]. Nanotechnology has been suggested to positively influence crop science and nutrition by improving crops' shelf-life, supporting tracking systems for contaminants, shaping better techniques for food storage, and aiding in the development of value-adding nutritional supplements or antimicrobial agents into food crops. Hence, nanomaterials may improve crop production with the help of different innovative methods and materials such as nanoparticles, nanoencapsulation, nanoemulsion, nanofiber, and carbon nanotube [39].

3.2.1. Nanoparticles

Nanoparticles (NPs) are objects or structures whose dimensions range between 1 and 100 nm (nanoscale). They may be fibers, flakes, wires, composites, films, and tubes. There are also structured nanomaterials such as quantum dots, nanoclusters, nanocrystals, nanowires, and nanotubes [38]. Because of their size and superior surface area, nanoparticles are promising tiny substances with enormous influence in the engineering, medicine, electronics, photonics, biotechnology, and agriculture sectors. They possess translucent or formless characteristics, which can act as conveyors for liquid droplets or gases and should be regarded as a unique state of matter other than solid, gaseous, liquid, and plasma states [37].

3.2.2. Nanoencapsulation

Recent progressions in nanotechnology include in the encapsulation methodology, which was initially used in biotechnology to improve quality production measures and to prompt the disintegration of generative cells alongside their by-products [40]. Eventually, encapsulation was introduced to nanotechnological advancements, which were discovered to be profoundly effective compared to regular encapsulation. Encapsulation is the innovative strategy of enclosing different active substances in matrices, ceding their payload under particular conditions at a specific rate. The techniques involved in encapsulation can secure the bioactive ingredients from environmental conditions and natural effects until the controlled delivery of the active ingredients is achieved. In other words, nanoencapsulation can be defined as the enclosing of active components inside nanometer-sized shells or capsules, also known as nanoshells or nanocapsules [41]. Nanocapsules vary in size and shape, depending on the materials and techniques used to produce the capsules or shells [42]. The design of encapsulated active components predominantly relies on the selected capsule material (pectin, zein protein, chitosan, lecithin, etc.) and the nanoencapsulation technique [42]. Furthermore, nanoencapsulation enhances the bioavailability of enclosed bioactive components and improves biological efficiencies [43]. Agrochemicals such as pesticides, herbicides, and fertilizers can be enclosed in nanocapsules for controlled release and targeted delivery of their active compounds for disease control, nutrient uptake, enhanced growth, and the development of crops [44].

3.2.3. Nanoemulsion

Nanotechnology applications have been investigated to improve global food security, such as crop conservation and protection, by providing consumable covering or seed preparation, essentially improving food quality [45]. Nanoemulsions are novel bioactive conveyance systems made up of emulsified water and oil stage (w/o) or oil and water stage (o/w) with droplet sizes within the range of 50 nm to 100 nm. The merits of a tiny droplet size in nanoemulsions include the assurance of even circulation and dissemination of the active components through the surfaces. Moreover, nanoemulsions further develop infiltration properties of bioactive components because of the low surface tension and high surface area of the emulsion [46]. The droplet size of nanoemulsions has merits over conventional emulsions because of better collection stability, better optical clarity, and improved bioactivity of emulsified ingredients [47]. The use of thymol nanoemulsion-loaded quinoa protein/edible chitosan coating was recently described to conserve the quality and safety of strawberries with reduced yeast and fungus load. Additionally, weight reduction was observed during the whole storage period [45].

3.2.4. Nanofiber

Most nanotechnology research has been limited to a few particles or molecules, but massive fabrication techniques and large-scale devices may also be developed for profit-oriented commodities. Nanofiber technology is a technique involving the synthesis and application of fibers with nanoscale dimensions. This technology assembles one- and two-dimensional nanomaterials for the large-scale production of macroscale nanostructures [48]. Nanofibers can be described as fibers with a diameter equal to or less than 100 nm. Nanofibers are essential and significant due to their specific surface area and adaptability, making them favored material structures for varying drug delivery and crop production applications. The adequacy of nanofiber application has been tested in tomato and lettuce seeds coated with nanofiber. It was observed that the rapid growth in the seeds resulted in improved seedling biomass for both plants, suggesting accurate delivery of agrochemicals, which further improves germination and seedling biomass for model seeds [49].

3.2.5. Carbon Nanotubes (CNTs)

Engineered nanomaterials have recently been implicated in nanotechnology advancement because of their extensive scope of utilization in different fields. Nanotubes belong to this category of engineered nanomaterials, with carbon nanotubes being an essential group [50]. Carbon nanotubes are cylindrically shaped rolled-up graphite sheets whose length is at the micrometer scale, with a diameter of around 100 nm. They are byproducts of carbon fibers and fullerenes with particles of 60 atoms of carbon organized in particularly enfolded cylinders. CNTs are of two kinds: single-walled carbon nanotubes and multi-walled carbon nanotubes. Where a highly detailed ratio is necessary for biological applications, CNTs are appropriate, and they are equally considered suitable for many applications [51]. Prominent applications of CNTs in crop farming include seed priming, rapid plant development, biosensor diagnostics and analysis, and pesticides [52]. It has been reported that CNTs can permeate the thick seed coat and prompt development [53]. In addition, optical sensors based on CNTs have been developed to screen the real-time detection of pathogenic microbes, organophosphate chemical warfare instruments, and pesticides [54].

3.3. Applications of Nanotechnology in Crop Farming

The recent advancements in nanotechnology can help us to accomplish sustainable agricultural development to further develop resource proficiency and efficiency, fortify resilience, and secure the agriculture field's responsibility. This technology, delivered via different techniques such as precision farming, crop improvement, and soil remediation, will be an economic force to be reckoned with to enhance current agricultural activities. Figure 2 elaborates on the application avenues in the agricultural sector. In addition, various delivery techniques of NMs include foliar spraying, seed priming and coating, irrigation, and hydroponics.

Foliar spraying describes NP entry through the leaves and sometimes through other non-reproductive parts of the plant. Upon contact with the plant, NP uptake occurs through natural plant openings (stomata, lenticels, etc.), and they are translocated via the apoplastic and symplastic pathways [32]. The apoplastic pathway promotes the radial movement of NPs through the cell membrane and is determined by capillary forces and osmotic pressure. On the other hand, the symplastic pathway enhances intracellular movement through the plasmodesmata, determined by endocytosis or ion channels. Although seed priming and coating with NPs have been investigated in *Oryza sativa*, *Glycine max*, and *Cucumis sativus* [55], the mechanism of NP action is still understudied. NPs can also be applied in hydroponics, wherein an adequate environment with accurate parameters can be maintained for enhanced uptake of NPs. For instance, ZnO NPs were administered by hydroponic treatment to improve the morphological and physiological parameters of *Nicotiana tabacum* seedlings [56]. Nanotechnology can reduce the utilization and misuse of mass agrochemicals and proffer more affordable solutions and environmentally friendly alternatives.

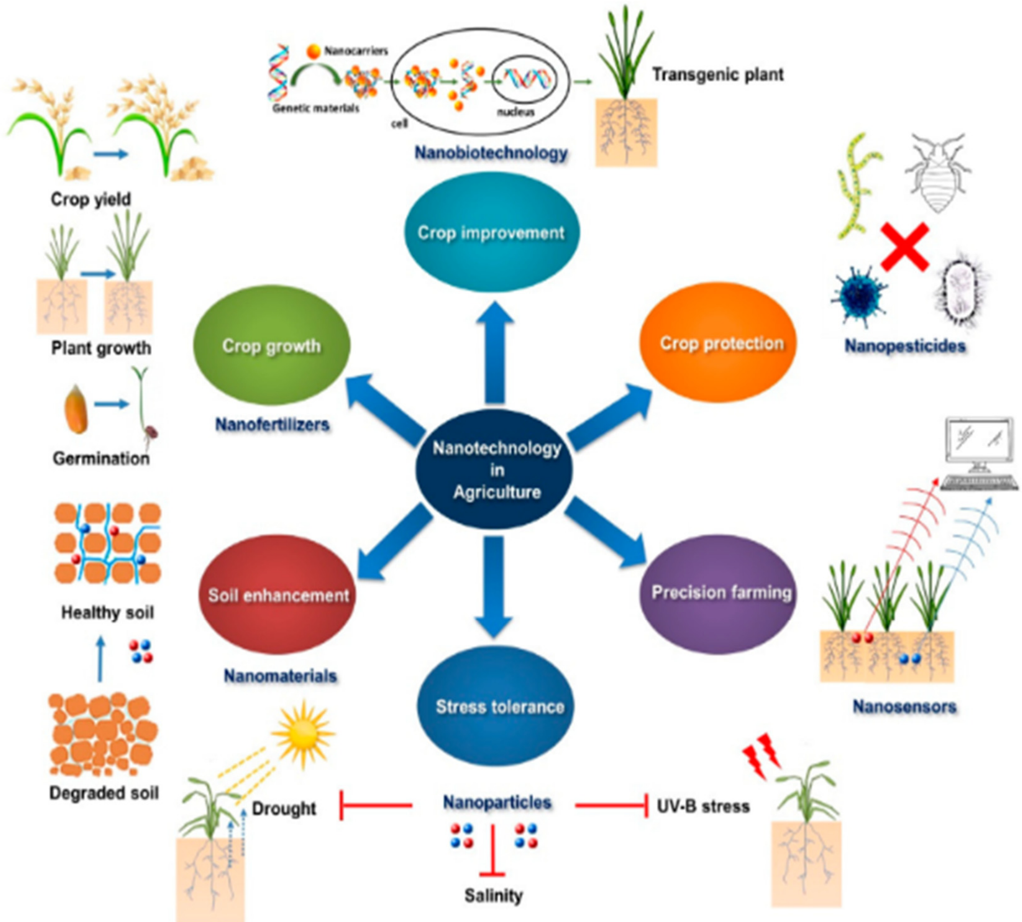

Figure 2. Nanotechnology applications in crop farming [57].

3.3.1. Precision Farming and Artificial Intelligence

Precision farming has boosted crop productivity and quality by utilizing reduced quantities of agrochemicals such as insecticides, herbicides, and fertilizers while targeting particular actions. This highly profound tool has merits over the use of supercomputers and remote sensing gadgets to detect crop problems, eventually resulting in cost-effective production and enormous advantages for farmers. Precision farming relies on thorough comprehension of modern innovations that enable harvesters to decipher the number of various components responsible for the low yield of crops while creating designs that will steer prompt decisions regarding the application and timing of inputs [57]. Moreover, precision farming is expected to minimize agricultural waste production and thus would be more eco-friendly compared to established farming practices. Nanotechnology is viewed as one of the main drivers of precision farming since the characteristics of nanomaterials will enable the improvement of more proficient strategies for crop management [58].

A recent publication suggested that artificial intelligence (AI) and machine learning modeling could drive progress in nano-enabled precision farming [59]. Although still in their infancy, these approaches are gaining regulatory acceptance for the safety assessment of nanomaterials, facilitating safe-by-design nanomaterials for a range of consumer products. The integration of AI in precision farming could accelerate development and provide the insights needed to overcome the current barriers in nano-enabled crop farming [59].

For instance, AI may predict the impact of NMs on the agricultural ecosystem and their performance in enhancing agricultural production by integrating experimental data from different soil conditions and plant species while minimizing pollution and ensuring a high safety profile for nanomaterials in soil and minimal residues in edible plants.

Precision agriculture based on nanotechnology uses devices such as the green seeker or normalized difference in vegetative index (NDVI) sensor. This device generates red and near-infrared light using nano-based light-emitting diodes and calculates NDVI values accordingly. This idea is based on the knowledge that healthy plants' chlorophylls absorb more red light during photosynthesis and reflect more near-infrared light than unhealthy plants [60]. Values for the NDVI are computed based on this difference. The agricultural sector may be positively impacted by precision farming, which enables real-time monitoring of field factors such as soil conditions, soil fertility, moisture level, temperature, crop growth, crop nutrient status, insect attacks, various plant diseases, and so on [60].

3.3.2. Improvement of Crop Productivity

Nanotechnological advancements have promising prospects for improving and enhancing crop productivity by ensuring superior plant management. This advancement involves the development of nano-fertilizers, nano-pesticides, nano-herbicides, nano-fungicides, nano-biosensors for pathogen and contaminant detection, etc. (Table 1).

Nanopesticide

Pesticides can be chemical or biogenic substances or compounds used to manage pests for enhanced quantity and quality of crop production [57]. Conventional pesticides are known for their poor specificity, high toxic potential, and environmental persistence attributes [61]. They pose severe ecological and public health hazards due to these factors. Since the main components of pesticides are prone to decomposition by varying environmental factors, abiotic factors, including salinity, temperature, and light, may alter pesticides' biological effectiveness and chemical dynamics [47]. Biotic factors, such as microorganisms, play the most important role in the decomposition and pesticide persistence in the environment [12]. The environmental problems caused by the overuse of conventional pesticides have led to the advent of nano-pesticides, potentially overcoming these issues through a possible reduction in chemical usage.

Moreover, nano-pesticides show valuable properties, such as optimized resistance, porosity, thermal strength, solubility, translucency, and biodegradability, which are important and necessary for viable agricultural production [62]. Essentially, the controlled and slow release of active components minimizes the chemical load of pesticides required to control pests. Over the years, various nanopesticide formulations have been developed and applied by scientists for more specific actions. Compared to conventional pesticides, nanopesticides have more effective control of pests while still being environmentally friendly [63]. Previous research has successfully tested the insecticidal efficacy of various nanoparticles against agricultural pests. Zheng et al. [64] reported the insecticidal efficacy of nanoparticles against red fire ants, *Solenopsis invicta*, which are insect pests of agricultural commodities. Their results showed an alteration and inhibition of digestive functions, eventually leading to death.

Nanoherbicides

The efficacy of conventional herbicides against weeds is limited to the shoot part, leaving the root area as a new source of weeds in the forthcoming season [22]. Nanotechnology has improved the effectiveness of chemical herbicides by precise delivery to receptors in the underground regions of weeds [71]. These nanoherbicides provide new entrance routes and active transport to various parts of the roots, which will eventually inhibit food glycolysis backup in the root tissues [80]. In addition, this technique will reduce the use of toxic chemical components such as imidazolinones and glyphosate. NMs, such as polymeric NPs, have been used extensively as nanocapsules or nanospheres for enclosing various conventional herbicides [70]. Research on two plant species, *Brassica* sp. and *Zea mays*, suggested potent growth inhibition of *Brassica* sp., which is the actual target organism, using nanoherbicide formulation.

Table 1. Applications of nanomaterials for crop productivity.

Nanopesticide	Agricultural Use	References
PQ-loaded CS-gated porous carbon nanoparticles	User-safe and efficient chitosan-gated porous carbon nanopesticides and nanoherbicides.	[61]
Zinc oxide nanoparticles (ZnO)	Nanoparticles enhance thiamethoxam insecticidal activity against *Spodoptera litura* larvae	[65]
Silicon oxide nanoparticles (SiO_2)	Insecticide properties against leaf worm (*Spodoptera littoralis*)	[66]
SiO_2	Maize nanofertilizer and low-dose pesticide for pests that can affect maize during storage post-harvest (*Sitophilus oryzae*, *Rhizopertha dominica*, *Tribolium castaneum*, *Orizaephilus surinamenisis*)	[67]
Silicon nanoparticles (SiNP)	Nanoosilicon enhances maize resistance against oriental armyworm (*Mythimna separata*) by activating the biosynthesis of chemical defenses	[68]
Si	Biological silicon nanoparticles maximize the efficiency of nematicides against biotic stress induced by *Meloidogyne incognita* in eggplant	[69]
Nanoherbicides		
PQ-loaded CS-gated porous carbon nanoparticle	User-safe and efficient chitosan-gated porous carbon nanopesticides and nanoherbicides	[61]
Poly(epsilon-caprolactone) nanoparticles	Application of poly(epsilon-caprolactone) nanoparticles containing atrazine herbicide as an alternative technique to control weeds and reduce damage to the environment	[70]
Chitosan/tripolyphosphate nanoparticles	Nanoparticles loaded with paraquat herbicide: An environmentally safer alternative for weed control.	[71]
Nanoatrazine	Nanoencapsulated atrazine inhibited the photosynthetic activity of the weed *Alternanthera tenella*	[72]
Nanofungicide		
Zinc oxide NP (ZnO)	Fungicidal activity against multiple pathogenic fungi of apple orchards (*Alternaria mali*, *Botryosphaeria dothidea*, *Diplodia seriata*).	[73]
Manganese oxide NP (MnO)	Antifungal activity against soil-borne pathogens (*P. nicotianae*, *T. basicola*) with a possibility to control other plant pathogens	[74]
Titanium oxide NP (TiO_2)	Antifungal activity against wheat rust.	[75]
Copper oxide NP (CuO)	Antifungal activity against the plant pathogen *Colletotrichum gloeoesporioide*	[76]
Nanofertilizer		
Zeolite/Fe_2O_2	Nanofertilizer with less toxic effect toward humans compared to other fertilizers.	[77]
Copper (Cu) nanowires	Fertilizer for improved plant physiological performance and agronomical parameters	[78]
Urea-loaded mesoporous $ZnAl_2SiO$	Nanofertilizer for slow delivery of urea and zinc	[79]
SiO_2	Maize nanofertilizer and low-dose pesticide for pests that can affect maize during storage post-harvest (*Sitophilus oryzae*, *Rhizopertha dominica*, *Tribolium castaneum*, *Orizaephilus surinamenisis.*	[67]

Furthermore, it has been reported that NP application could proficiently minimize the mobility of atrazine in the soil, reducing soil contamination [70]. NPs have also been used for the encapsulation of three triazine herbicides to minimize concerns regarding environmental contamination and toxicity [81]. Nanoencapsulation of these herbicides reportedly increased their efficacy and stability. Further investigations suggested the controlled and timely release of triazines from the nanocapsules, with reduced genotoxic impacts for the formulated nanoherbicides [82]. Likewise, chitosan/tripolyphosphate nanoparticles were utilized for encapsulating paraquat, and inorganic nanoparticles such as silica have equally been employed for nanoherbicide formulation [71,82]). Agricultural waste-based nanomaterials such as nano absorbents rice husk were sequestered and used as a nanocarrier for 2,4-dichloro phenoxy acetic acid herbicide. The results showed high herbicide sorption with optimal activity [83].

Nanofungicide

Fungal infestations of crops practically result in huge losses and low quality in crops yearly [12]. Nanomaterials such as cobalt and nickel ferrite nanoparticles have been developed with the potential to solve the problem of loss in crop productivity. These nanoparticles have reportedly shown antifungal efficacy against specific plant fungal pathogens, *Dematophora necatrix*, *Fusarium oxysporum*, and *Colletotrichum gloeosporiodes*, and can therefore be applied for the management of fungal plant disease [84]. Biologically synthesized copper nanoparticles were also used as a proficient antimycotic component under certain experimental conditions against *Neofusicoccum* sp., *Fusarium oxysporum*, and *Fusarium solani*. The generation of intracellular reactive oxygen species (ROS) was suggested as the cause of such antifungal activity [85]. Recently, nanocomposite utilization has broadened the scope of plant protection because of its high effectiveness and environmentally friendly nature. In one instance, a fungicide, antracol, was formulated with silver-incorporated chitosan nanocomposites. Increased antimycotic activity was observed compared to each component alone [86]. Copper nanoparticles were also tested against *Phytophthora infestans*, and the results showed their antifungal efficacy in tomatoes compared to the currently available non-nano copper formulations [87].

Nanofertilizers

Conventional fertilizers have availability and delivery problems, mainly due to a lack of synchronization between nutrient availability from the fertilizer and nutrient demand from the plant [88]. This eventually results in low nutrient-use efficiency, one of the solutions nanoformulations deliver. Nanofertilzer formulations are smartly designed delivery systems that can strategically deliver their payload of nutrients and substantially improve crop productivity by enhancing effectiveness, improving soil organic matter, and minimizing unbalanced propagation and nutrient deficiencies [89]. Nanofertilizers are predominantly produced by integrating nutrients with nanomaterials but can be applied in different formulations, depending on the peculiarity of use, as shown in Figure 3. The importance of iron in plant physiology is key to respiration and the formation of chlorophyll, and its deficiency in plants may result in chlorosis. Thus, iron delivery and availability in plants are necessary for their growth. In this regard, iron-based nanofertlizers have shown promising potential. A recent study on the treatment of *Catharantus roseus* with iron oxide nanoparticles showed significant enhancements [89]. It has also been reported that a nano iron (Fe) complex showed an optimum plant growth effect on tobacco under low iron supply [90]. Similarly, one of the vital micronutrients that plays a key role in plant nitrogenous assimilation is Molybdenum (Mo). Thus, Mo deficiency can result in increased nitric oxide accumulation in a plant, which is harmful to human consumption [91].

Mo-based NPs have been produced to enhance their proficient use. Synthesized Mo NPs have been observed to be more effective in increasing nitrate reductase (NR) activity compared with elemental Mo in *Spinacia oleracea*. As a result, nitric oxide accumulation was also minimized [92]. Osman et al. [93] also reported an increased seed yield of *Phaseolus vulgaris* after applying molybdenum oxide nanoparticles. Cabbage productivity was observed to be low in Iraq on a large scale [94], and this led to a study being carried out to examine the improvement in cabbage growth and yield by NPK nanofertilizers, boosted by commercial iron, zinc, and cerium oxide (CeO_2) nanoparticles (NPs) [95]. Metal nanoparticles enhanced the NPK nanofertilizer when used to increase the growth and yield of cabbage. The plants also observed higher chlorophyll content and enhanced NPK nanofertilizer uptake. As previously highlighted, polymeric nanoparticles have been used for coating biofertilizers, and these formulations have been observed to show resistance against leaching and desiccation [57]. This led to the development of water-in-oil emulsification technology that has been used to encapsulate and deliver nutrients to target sites. This procedure also minimizes evaporation, enhances cell viability, and improves controlled release dynamics.

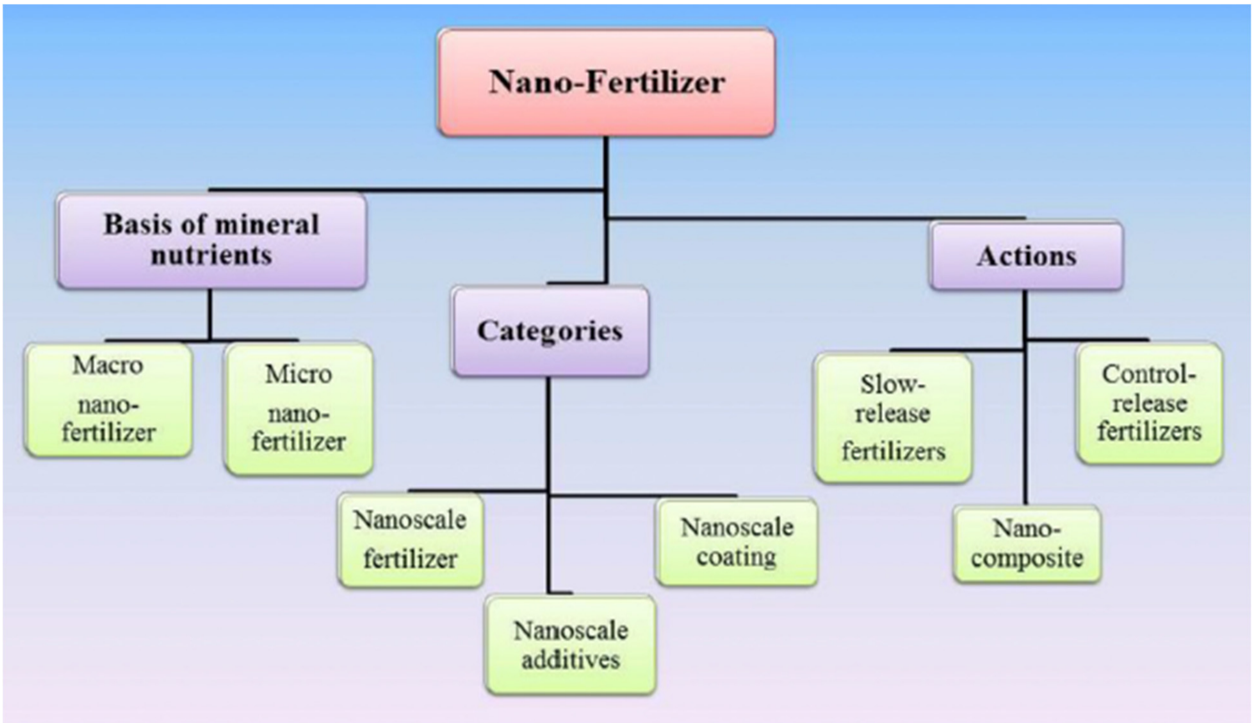

Figure 3. Types of nanofertilizers [88].

Furthermore, advances in green nanotechnology have changed global agriculture dynamics, and nanomaterials' use as nanofertilizers has aroused the potential to meet the projection of global food demand and viable agriculture. For instance, the application of carbon NP fertilizer can improve the grain yields of wheat, maize, soybean, rice vegetables, and maize [57]. Applying chitosan-NPK fertilizer increased crop yield and mobilization indices of determined wheat yield variables compared with control yield variables [96]. The application of nanotechnology in plant biology stimulates vital facets of study, as plants' primary nutrient access points are the plant root and leaf surfaces, which are more permeable at the nano dimensions. Essentially, nanofertilizer application can enhance the uptake of nutrients through these pores or by exploiting endocytosis or ion channels [97]. Moreover, it has been observed from various reports that the miniature size of nanomaterials facilitates an increased surface mass ratio of particles; thus, a large quantity of nutrients reaches the plants slowly and steadily for an extended period [98]. Hence, nanofertilizers ensure the balanced nutrition of crops throughout the growth cycle, eventually resulting in optimal agricultural production.

Nanobiosensors

Some devices can convert biological signals to electrical signals for quantitative data analysis via a microprocessor [99]. These gadgets are called biosensors. The vital component of this device utilizes biological molecules and living organisms, which serve as a communication device (bio-recognition motifs), an adequate transducer, and a signal detector. In a nanobiosensor, an analyte with a biorecognition element is exposed to the biorecpetor coated with NMs for enhanced sensitivity, and signals received are converted by a transducer to an electronic signal on the detector [57]. Some unique features of nanobiosensors include immobilization, fictionalization, and scaling-down that incorporates biological components of a transduction system into complex engineering to enhance the analytical capacity of NMs [98]. Nanobiosensors depend on an on/off mechanism, analyte detection within parts per trillion (ppt), and hinder the dissected matrix reliant on nano-formulation [100]. Using nanobiosensors permits easy detection compared to other regular biosensing methods with enhanced specificity and sensitivity, reducing rapid and exact detection time, and, more importantly, enabling real-time signal surveillance utilizing miniature compact devices. The significant applicability of nanobiosensors in the agricultural sector includes pesticide detection, food-borne pathogenic microbes, poisonous pollutants, heavy metal ions, etc. In addition, nanotechnology has been expanded to track and survey soil conditions, plant stress, plant growth, available nutrients, and food quality [101]. Fluorescent nanosensors were reported for organochlorine pesticide detection [102]. A gold nanoparticle-based colorimetric nanosensor for organophosphorus pesticide detection has also been reported [103].

Nanotechnology has similarly been utilized in electronic noses (e-noses), viewed as artificial intelligence frameworks and next-generation sensing devices. The frequency of its use in agriculture is used to track production procedures and to evaluate plant-related diseases, water/soil pollutants, and insect pest invasions [104].

Nanomaterials for Remediation of Contaminated Soils

Removing poisonous heavy metals from polluted water in wastewater treatment has become a significant problem for the agricultural sector. These metals pose a significant threat to human wellbeing since they can bioaccumulate in the food chain [105]. NMs can be applied in abiotic remediation and bioremediation of contaminated soils. The sorption–desorption reactions with soil constituents determine the toxicity and activity of these soil pollutants. Consequently, suitable alterations in contaminated soils can impact the toxicity and activity of soil contaminants [106]. These alterations can inactivate components that bind the soil contaminants, thereby reducing their activity and bioavailability [107]. For instance, nano zero-valent iron enhanced the soil washing performance of metal-polluted soil by adsorbing the metal and isolating it by magnetic separation [108]. In remediation experiments, adsorbent recovery offers a chance for contaminant recovery (either for their utilization as a resource or their ex situ treatment) and reuse. Furthermore, reusing nanomaterials in additional treatment cycles is gaining attention because it can minimize the cost of remediation. Therefore, the development of stable nanomaterials that could still retain their efficacy for numerous treatment cycles is highly challenging [109]. Nanomaterials are also used in advanced oxidation processes (AOPs), which use various oxidants to mineralize and catalyze organic contaminants. Iron nanoparticles can also be used, along with chelating agents. For instance, iron nanoparticles were used along with different chelating agents in Fenton oxidation to remediate pyrene-polluted soil [110]. The results showed varying oxidation efficiencies, dependent on the nature of chelating agents and were optimal for sodium pyrophosphate. Notably, depending on iron contents and soil nature, chemical oxidation can be effectively catalyzed by endogenous iron [111].

On the other hand, bioremediation is a natural, on-site, cheap, eco-friendly, and versatile technique for decontaminating harmful pollutants [112]. Nanomaterials are now integrated with bioremediation to proffer solutions to overcome associated limitations with this novel technology. Nanobioremediation holds excellent promise for decontaminating polluted soils with both inorganic and organic contaminants. Highly reactive NMs can be used in the dehalogenation or dechlorination process for remediating persistent organic pollutants, followed by bioremediation for more effectiveness [113]. NMs are also helpful in remediating soil organic pollutants by enhancing the availability of these contaminants to the biological agents used in bioremediation. Adherence of contaminants to nanomaterials could result in accumulation in plants with tiny nanoparticles and altered selective membrane permeability due to phytotoxic nanomaterials, which may also encourage organic contaminant uptake [105]. Nanobioremediation can also help improve the efficacy of phytoremediating heavy metals in polluted soils. The effect of titanium oxide nanoparticles on the accumulation of cadmium by soybean plants showed enhanced cadmium uptake and reduced toxicity of the same in the plants by preventing oxidative damage, which is due to scavenging free radicals produced as a result of cadmium contamination [114]. Nano-hydroxyapatite and nano-carbon black significantly minimized lead phytotoxicity to ryegrass while increasing its potential for phytoextraction [115]. It is worthy of note that various nanomaterials have different effects on the uptake of heavy metal or its toxicity in plants [105].

Nanomaterials as Plant Elicitors

Plant elicitors can be described as activated specialized metabolites important for plants' adaptation to environmental stress [116]. They can be biotic (insects, microorganisms, etc.) or abiotic (salinity, wounds, light, etc.) elicitors. Recently, it was reported that many nanomaterials could act as elicitors, enhancing the plant defense mechanism against abiotic (salinity, temperature, etc.) stressors and biotic stressors such as viruses and bacteria [117]. For example, iron oxide and gold nanoparticles reportedly promote tobacco resistance to mosaic virus disease [118,119]. Metal, metallic oxides, and carbon-based nanomaterials have shown potential in various experimental conditions. For instance, the medicinal qualities of *Calendula officinalis* improved when a combination of silver nanoparticles and methyl jasmonate was applied. These compounds increased the saponin content compared to the control treatment, while all treatments showed a reduction in anthocyanin and flavonoid content [120]. Additionally, several metallic alloys, such as silver, gold, and copper, were used in treating *Silybum marianum* at different ratios. Improved germination frequency and root and shoot development were observed in the treatments, depending on the nanoparticle [121]. In addition, the callus of *Stevia rebaudiana* treated with zinc oxide nanoparticles reportedly showed improved flavonoid and phenolic content and generation of reactive oxygen species, thereby boosting antioxidant responses [122].

Furthermore, carbon nanomaterials have shown high efficiency against abiotic stresses, enhancing crop performance. For instance, incubating carbon nanodots with *Oryza sativa* showed mitigation of salt stress with the assumption that the tolerance is caused by the nanodot's reactive oxygen species scavenging properties, which lowers the seedlings' exposure to these radicals and minimizes oxidative damage [123]. Other carbon-based nanomaterials, such as single-walled carbon nano-horns, have been used in testing different crops. The results revealed that carbon nano-horns could enhance the germination of selected plants and improve organ growth in crops such as soybean and tomato [53].

3.3.3. Nanotechnology for Crop Improvement

Nanobiotechnology

In recent years, crop improvement has been the most pressing need for plant breeders and farmers to meet the booming demand for products derived from plants [124]. An essential biotechnological tool, next-generation sequencing (NGS), is being promoted to support crop development initiatives. Genome-assisted breeding is an application of the NGS process, an integrated method for locating and choosing genetic variants. Currently, nanoparticles are employed to generate efficient carriers for gene transformation, and nanobiotechnology tools are expected to develop new strategies for replacing the genetic material of one species with another [125]. Nanotechnology application has been initiated in the era of genetic engineering, with the targeted delivery of CRISPR/Cas9 single guide RNA (sgRNA) innovation [57], and this procedure has been effectively utilized in genome alteration in plants [126].

Nanoparticle technology, being a useful biotechnological tool, has been applied to improve some plant species' agronomic parameters. Mukarram et al. [127] evaluated the optimum concentration of SiNPs and their potential advantageous effects on lemon grass agronomy, focusing on induced physiological responses along the way. Lemon grass is an industrially beneficial plant with medicinal properties and is exploited for its essential oil production [127]. The result showed that Si-NPs up-regulate gaseous exchange, photosynthesis, antioxidants, and nitrogen metabolism. A general trend of crop enhancement was triggered in lemongrass after the foliar application of SiNPs. In addition, some crop plant pest species, such as planthoppers, have developed high resistance to conventional pesticides and insecticides. Hence, there is an urgent need to develop green, economical, sustainable control and preventive technology for these pests. Cheng et al. [128] reported the uptake and translocation of SiO_2 nanomaterials, with the help of fluorescence technology, from root to shoot. SiO_2 nanomaterials induced the resistance of rice plants to planthopper, primarily via physical defense.

Nanobiofortification

Nutrient deficiency in food crops, commonly in developing countries, severely compromises human health. Yet, measures taken during the COVID-19 pandemic further reduced the production and availability of food crops, resulting in increased hunger and malnutrition. Biofortification of food crops with essential micronutrients is vital in improving food quality, improving its availability and promoting human health. Nano-biofortification of food crops is a budding biotechnological area that exploits the chemistry of plants and nanomaterials for controlled and sustainable nutrient delivery. These nano-nutrients can potentially mitigate humanity's struggle against diseases such as COVID-19. In addition, the promising use of nano-nutrients has distinguished opportunities to treat COVID-19 as anti-COVID-19 nanoparticles or nano-medicine [129]. Nano-biofortification can be achieved through agronomic nano-biofortification, selective breeding, and genetic manipulation with nanomaterials. Agronomic nano-biofortification may be applied through fertilizing food crops with nano-nutrients via direct physical application to the soil or indirectly through the foliar spray, seed priming, or seedling immersion into nano-fertilizer solutions [130]. Selective plant breeding practices such as plant-growth-promoting microbes can enhance micronutrient availability in soil and bioavailability in food crops by producing chelating agents such as siderophores [131]. Nano-biofortification can also be achieved using advanced tools such as genetic engineering to produce transgenic crops through direct gene transfer to modify target genes to precisely create desired genotypes. This strategy can optimize the accumulation of nano-nutrients in edible tissues without adversely impacting other physiological and developmental features of food crops [130].

Nanotechnology in Plant Stress Management

Agricultural productivity faces various environmental factors that can lead to plant stress conditions [132]. Stressed conditions can arise from biotic (insects, microorganisms, animals, competitive species) or abiotic (heat, drought, salinity, heavy metals, flood) stresses. Hence, there is a need to enable accelerated adaptation of plants in coping and thriving under various stress factors. However, plants can accomplish this coping mechanism through diverse strategies such as the regulation of hormones, stress gene expression, toxic metal uptake regulation, activation of plant enzymes, and avoiding drought stress by shortening the plant life cycle [133]. Advances in agricultural nanotechnology suggest that nanoparticles can improve crop production under stressed conditions. Table 2 presents recent experiments applying nanomaterials in combating various environmental stressors.

While salt stress limits crop production in cultivated lands globally, the application of silicon oxide has reportedly shown increased plant fresh weight and dry weight and improved seed growth and chlorophyll content in squash plants and tomatoes under salt stress [141]. Similarly, foliar application of iron sulfate nanoparticles showed that sunflower cultivars positively tolerated salt stress. The results showed improved shoot dry weight, leaf area, net carbon dioxide assimilation rate and chlorophyll content and increased iron content [142]. UV-B stress in plants can also be effectively managed using silicon

NPs [143]. Furthermore, nanoparticles, via foliar application, are reported to be effective in the detoxification of rice plants by regulating cadmium accumulation [144]. Banerjee et al. [145] examined the ameliorative efficacy of SiNPs in molecular damage and yield loss in IR-64 plants irrigated with fluoride-polluted water throughout their life cycle. The results showed improved overall growth of fluoride-stressed plants (Figure 4). By effectively reducing fluoride uptake and bioaccumulation in mature tissues, nano-Si-priming of IR-64 seedlings produced significant levels of fluoride tolerance. The agronomic characteristics and yield of SiNP-treated and stressed seedlings were significantly enhanced, and fluoride bioaccumulation decreased in the grains. Other studies also showed the efficacy of silicon nanoparticles against lead and cadmium accumulation in wheat and rice [146,147].

Table 2. Application of nanomaterials in combating environmental stressors.

Nanomaterial	Mode of Application	Findings	References
Chitosan/Silver/Manganese-Magnesium ferrite Nanocomposite	Foliar and Root Application	Improved the growth and biomass of cabbage under cadmium stress	[134]
Copper Oxide (CuO)	Root Application	Inhibited arsenic bioaccumulation in rice plant	[135]
Selenium Oxide (SeO) and Zinc Oxide (ZnO)	Seed Priming	Elevated seed germination and early seedling growth upon salt stress	[136]
Cerium Oxide (CeO)	Foliar Application	Alleviated salinity stress by improving growth parameters and antioxidant defense system	[137]
Gold Nanoparticles (Au)	Foliar Application	Improved salt tolerance in wheat plant	[138]
Titanium Oxide (TiO_2)	Seedlings	Improved the adaptability of plants under UV-B stress	[139]
Biosynthesized Ferric Oxide (Fe_2O_2)	Foliar Application	Optimum survival rate in wheat plants exposed to drought stress	[140]

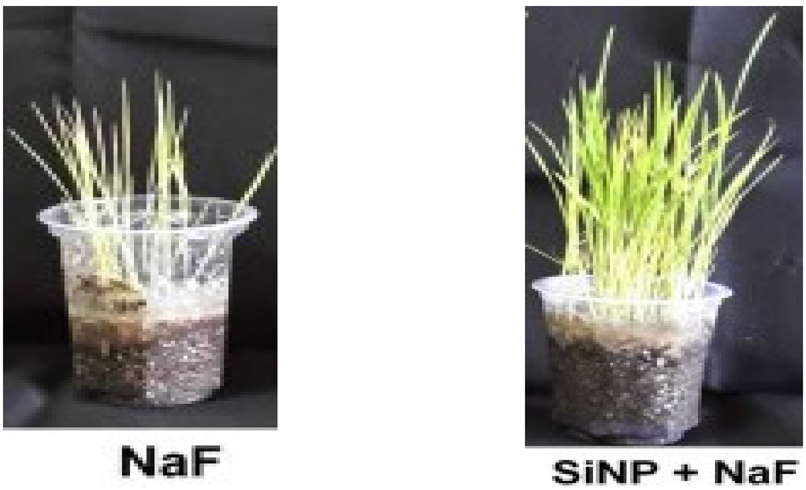

Figure 4. Comparison between a stressed and nanoparticle-managed plant [145].

Furthermore, nanomaterials have shown the potential to regulate stress gene expression. For instance, a microarray analysis after the application of silver nanoparticles in Arabidopsis showed that some genes were up-regulated or down-regulated [148]. Some up-regulated genes were associated with their response to metals and oxidative stress. In contrast, the down-regulated genes were related to their response to pathogens and hormonal stimuli, including systemic acquired resistance and gene regulated by auxin, which is involved in organ size and growth [148].

4. Challenges of Nanotoxicity

Recent advances in technology have postulated that nanomaterials have the potential to revolutionize nutrition, crop production, food packaging, and food availability. Issues associated with latent toxicological profiles of nanomaterials are poorly understood, and hence, so too is the resistance to global acceptance of its applications. The toxicity of NMs is dependent on several factors, such as particle size, surface-area-to-mass ratio, structure, and solubility [149]. Due to their small size and high surface-area-to-mass ratio, NPs can enter cells and cellular organelles, interfering with their normal biological functioning. Their large surface area may boost the production of reactive oxygen species such as superoxide anion and hydroxyl radicals, resulting in oxidative stress. For instance, positively and negatively charged nano-diamonds of different ranges were tested on the intestines of *Daphnia magna*. The results showed that the nano-diamonds with the higher range (15 nm) induced more reactive oxygen species than the lower range (5 nm) [150]. Continued ROS production in a cell may also lead to gene deletions or mutations that could cause cell carcinogenicity, which promotes the proliferation of tumors and cancer [149].

In nanotoxicology, in vitro and in vivo assessment are vital tools in toxicity testing. In vitro assessments have lowered the number of animal studies required for toxicity testing, reducing ethical concerns. Genotoxic and cytotoxic effects of nanomaterials have been examined in primary human epidermal cells using the comet assay [151]. Results showed increased DNA damage in cells exposed to ZnO NPs for 6 h, compared to the control group. The in vitro micronucleus assay and the mycoplasma backward mutation assay have also been used to investigate the cytotoxic effects of AgNPs on strains of *Salmonella typhimurium* [152]. Their reports showed no mutations in any of the test strains. This could be a result of low concentrations of NPs used. In vivo experiments, which usually use rats or mice as model organisms, provide data that enable reports that are not accessible from in vitro studies. An in vivo study was conducted on experimental mouse models to highlight the probable toxicological impact of NPs on their brains. Upon intravenous injection, silica-coated magnetic nanoparticles were found in the animal's brain [153]. A recent in vivo study reported the cytotoxicity of Se nanorods and spherical NPs in female mice. Their findings revealed an accumulation of NPs in the kidney, resulting in oxidative stress and tissue damage [154]. The toxicity of nanomaterials cannot be overlooked as it can potentially impact all organisms, and ultimately humans.

5. Issues of Risk and Regulatory Policies on Nano Crop Farming

5.1. Risk Assessment and Management in the Nano-Agricultural Sector

Assessing the risk associated with using nano-enabled products on human and environmental health is an uphill task because of the varying facets of application, such as different nano-materials used, different nano-formulations, and several exposure dosages and concentrations [155]. Hence, the properties of the active ingredient, concentrations, and the nano-substance should be the focus in identifying associated hazards and risks. The application of engineered nanoparticles as biofertilizers, pesticides, or bioremediation should be monitored and viewed according to their lifespan and persistence in the environment, from field application to residue disposal [156]. However, concerns regarding the fate and transportation of these nanomaterials into the environment are yet to be addressed (Figure 5). These issues certainly need to be considered because nanomaterials' interaction with environmental factors may alter their physicochemical characterization and, inherently, the toxicological profile [155,157]. This reiterates the necessity and importance of characterization—evaluating the composition, chemical form, shape, size, surface area, and functionalization—following the synthesis of nanomaterials. As much as those engaged in synthesizing nanomaterials and their incorporation into agricultural products receive the greatest exposure, contamination of water systems and residual presence in food products may typify other sources of exposure for the general populace. Risk assessment enables tangible forecasts of identified and given risks, allowing their adequate management [158].

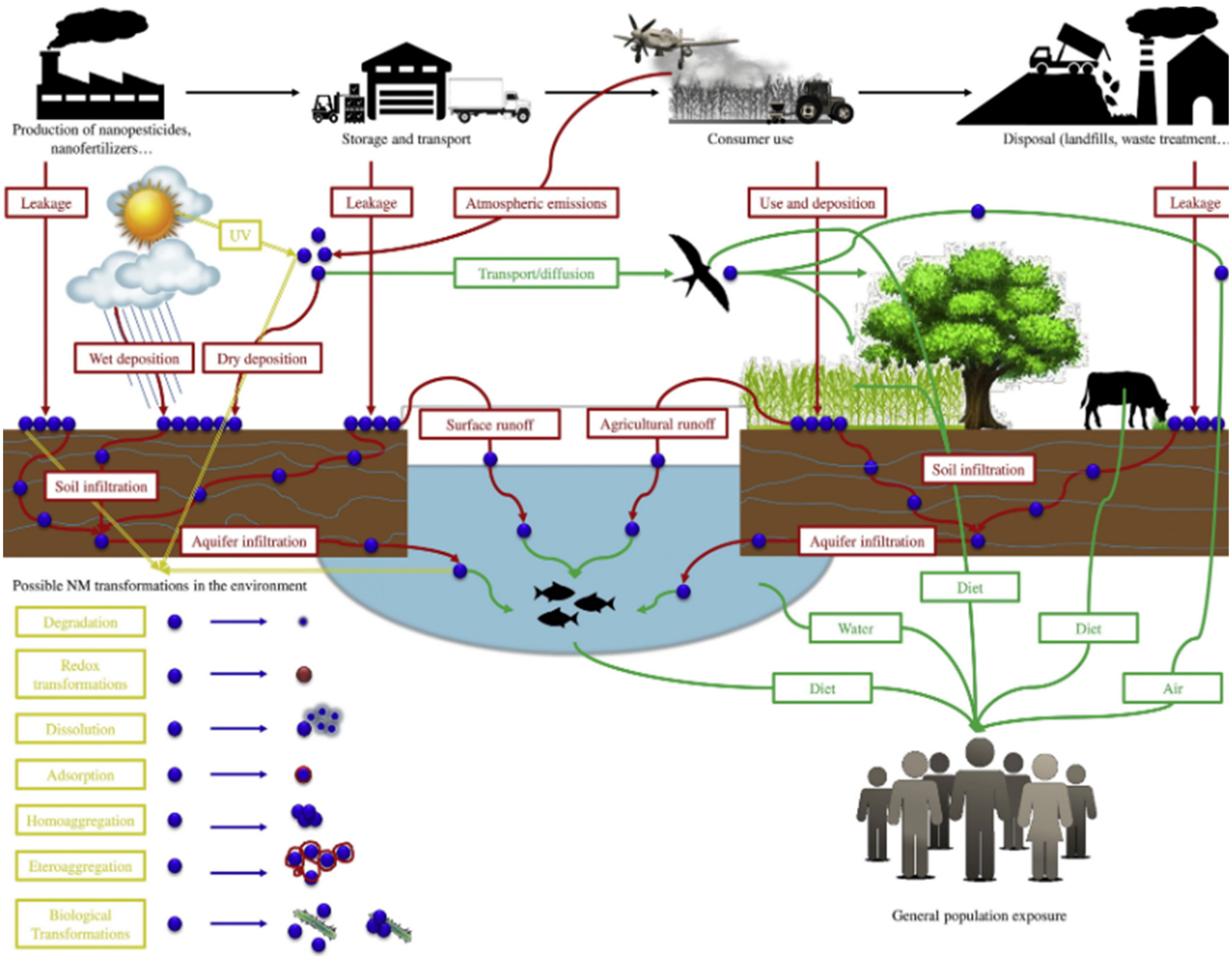

Figure 5. The life cycle of nano-enabled products in agriculture [155].

However, there are still doubts and misgivings regarding exposures and risks in the emerging nanotechnological applications in crop farming, making it crucial to embrace an innovative management strategy before the intentional and direct application of nanomaterials in the environment. This implies that dynamic, continuously evaluated, improved, and verified strategies will be employed in nano-risk management [159]. A management plan that focuses on elimination strategies or alternative exposures should be adopted to address nano-related risks in agricultural practices. In addition, risk reduction via the utilization of administrative structures at all stages of the life cycle of nanomaterials is down to personal protective equipment [155]. Furthermore, the principles of well-established green chemistry can be adopted to produce innovative and safe nanomaterials, thus avoiding reliance on procedures that might lead to environmental contaminants and health risks for the populace [160]. The decision to protect human health and the environment can have an impact and reduce cost when applied early in creating the design and development of a product. This concept has been embraced by green engineering [161]. Hence, the advent of green nanotechnology focuses on the full life cycle that can better equip users to reduce the generation of new hazards through inadvertent consequences.

5.2. Regulatory Aspects and Policies

The potential of nanotechnology applications in various areas for human well-being and development could make life better and easier [162]. This novel and state-of-the-art technology, however, has some demerits. There are existing concerns regarding the possible toxicological impacts of engineered nanomaterials on the environment and, more importantly, public health [163,164]. In as much as the use of nanomaterials is still emerging, nanotechnology could serve to improve and transform many technologies in addition to several industrial sectors. However, the absence of adequate disposal techniques has led to a constant increase in the level of nanomaterials in the environment. Ecological authorities and scientists need to theorize about the influence of nanomaterials, proffering strategies and regulations for the utilization and disposal of nanomaterials to avoid complications associated with their use. Several studies have also been carried out on the exposure limits of nanomaterials [165,166]. In addition, in the USA, manufacturers are mandated to make detailed information on nanomaterials available to the United States Environmental Protection Agency (USEPA) for assessment to ensure that these products do not result in any danger and/or environmental hazards. Presently, the European Union (EU) legislation distinctly reiterates that nanomaterials are to be included in various regulations related to products and consumers [58]. In addition, voluntary structures for data submission on nanomaterials in European nations are serving to collect data regarding awareness and toxicity levels in production and market distribution [167]. Therefore, carrying out an appropriate life-cycle evaluation, in addition to the risk assessment evaluation, is vital for nanomaterials before large-scale application [168].

6. Conclusion and Future Prospects

The COVID-19 pandemic negatively impacted every facet of life, including food supply, safety, and security. Despite various measures put in place to curb the spread of the disease, societies improvised and developed progressive ways to continue living. Although the virus spread is slowing down, the ripple effects of the stringent measures taken to curb its spread have continued, especially in areas of crop production, supply chains, and the availability of affordable food. Efforts in many countries to increase and sustain food demand and supply, food safety, food security, and trade have been inadequate.

Nanotechnology, which had been identified for useful applications in all fields of life, has continued to present high potential in the fight against diseases [169] and also to improve crop production. The usefulness of nanotechnology as a tool for modern agricultural development and crop farming is a promising driver of the economy in coming years for sustainable and viable agriculture. While nanotechnological applications are currently being utilized in medicine to combat COVID-19, there is still a lack of consensus regarding their acceptance in crop production due to the dearth of safety standards that can monitor nanomaterials. In as much as the potential of nanotechnology to improve and increase crop production exists, field applications that can engineer increased crop production are slow due to regulatory and policy-making issues [32]. In the European Union, the regulatory authority regularly scrutinizes the usage of nanomaterials in the agri-food sector, addressing safety standards and risk management issues [170]. For instance, the European Commission Food Law Regulation ensures that nano-based foods have pre-market approval and provides guidelines for the production and distribution of food. In addition, the international standard organization has certain standards regarding the manufacture and toxicity assessment of nano-based products, which are followed by most countries worldwide. With the pressure on regulating agencies by non-state actors and the growing nano-agri sector, new regulatory approaches such as self-regulation, co-regulation, and meta-regulation are receiving wider recognition [32]. There is a need to collaborate with private agencies, industries, academic and research institutions, stakeholders, government bodies, and the public to weigh up the positive and negative effects of nanotechnology and its products in crop production.

However, future research could be focused on but not limited to the following:

(i) Collaborative efforts of researchers to strengthen controlled green synthesis of nanomaterials, which will be vital for the development of stable, cheap, efficient, multifunctional, and eco-friendly nanomaterials;

(ii) Further research on the synthesis, characterization, and application of bio-synthesized nanomaterials for their wider field application in plants of high economic importance;

(iii) The need to understand nanoparticles' mechanism of interaction with plant systems, their behavior, and persistence in agricultural soils;
(iv) Exploration of more field applications, useful for large-scale implementation of nano-based techniques.

Agriculture is one of the major sources of food for humans, yet this sector was one of the most impacted by the COVID-19 pandemic, and as such the assistance of prominent technology such as nanotechnology could have latent and notable advantages. With the increasing global population and climate change that has affected land use, COVID-19 further aggravated food insecurity, malnutrition and hunger because it triggered stringent measures that affected crop production and supply. Nanotechnology has found many applications in agricultural activities, including the replacement and/or more effective use of agrochemicals, stress management agents, or even environmental remediation agents [12]. Modern nanotechnological applications have the potential to solve many problems related to conventional agricultural practices such as poor control of micronutrient release, poor amount of mineral micronutrients available to plants, high rate of chemical and fertilizer run-offs, poor nutrient-use efficiency of plants, and so on [12]. Since there had been shortage of food supply and increased demand, nanotechnological applications are emerging in food preservation and packaging to maintain the freshness of the limited supply. Although the fate, behavior, and impact of nanomaterials on the environment are yet to be firmly understood and ascertained by environmental scientists and researchers, the emergence of artificial intelligence and machine learning being integrated with nano-precision farming is also progressing to monitor the safety of nanomaterials in food products, even though it is still in its infancy [34]. Nanomaterial application may enhance agronomic parameters and yield of crops, but various plant species may respond differently [12]. Hence, before commercial use, rigorous investigations into the assessment, evaluation, and optimization of the nanomaterials for different plant species are required.

Since the interaction of nanoparticles with the plant body is strongly affected by plant physiology, the results from species to species is significantly different [171]. In addition, farmers are unwilling to utilize this technology as an alternative strategy in the fields because of the low-cost benefit economics of nanomaterials production [155]. Due to high-cost input in some laboratory experiments that have been restricted to few plants in growth chambers or hydroponics, the interesting findings are seldom reproduced in the field. In conclusion, the importance and beneficial applications of nanotechnology have been stated, allaying consumers' concerns regarding the safety of this progressing technology. Hence, adequate understanding, more funding, and wider field applications of nanotechnological advances are necessary to enhance its development.

Author Contributions: Conceptualization, F.O.A., O.I.A. and G.A.D.; Writing–original draft preparation, F.O.A., O.I.A. and G.A.D.; Writing–review and editing, F.O.A., O.I.A., E.F.A. and G.A.D.; Visualization, F.O.A. and O.I.A.; Supervision, O.I.A., E.F.A. and G.A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data that support these findings available within this article.

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

References

1. Su, S.; Wong, G.; Shi, W.; Liu, J.; Lai, A.C.K.; Zhou, J.; Liu, W.; Bi, Y.; Gao, G.F. Epidemiology, genetic recombination, and pathogenesis of coronaviruses. *Trends Microbiol.* **2016**, *6*, 490–502. [CrossRef] [PubMed]
2. Wang, N.; Shi, X.; Jiang, L.; Zhang, S.; Wang, D.; Tong, P.; Guo, D.; Fu, L.; Cui, Y.; Liu, X.; et al. Structure of MERS-CoV spike receptor-binding domain complexed with human receptor DPP4. *Cell Res.* **2013**, *23*, 986–993. [CrossRef]
3. Tabish, S.A. COVID-19 Pandemic: The crisis and the longer-term perspectives. *J. Cardiol.* **2020**, *13*, 41–44. [CrossRef]

4. Du, T.A. Outbreak of a novel coronavirus. *Nat. Rev. Microbiol.* **2020**, *18*, 123.
5. World Health Organization (WHO). WHO Announces COVID-19 Outbreak a Pandemic. Europe: World Health Organization. 2020. Available online: http://www.euro.who.int/en/health-topics/health-emergencies/coronavirus-covid-19/news/news/2020/3/who-announces-covid-19-outbreak-a-pandemic (accessed on 16 September 2022).
6. World Health Organization (WHO). Coronavirus Disease (COVID-19) Outbreak Situation. Geneva: World Health Organization. 2020. Available online: https://www.who.int/emergencies/diseases/novel-coronavirus-2019 (accessed on 16 September 2022).
7. Aba, S.C.; Baiyeri, K.P. Application of biological and digital technologies in resolving the negative effects of COVID-19 pandemic on crop production in Nigeria. *J. Trop. Agric. Food Environ. Ext.* **2021**, *20*, 46–51. [CrossRef]
8. Mirian, O.; Danjuma, Y.; Amaonyeze, N. Impact of corona virus disease-2019 (COVID-19) pandemic on social lives and interactions of Nigerian citizens. *Arch. Med.* **2021**, *13*, 15.
9. Andam, K.; Edeh, H.; Oboh, V.; Pauw, K.; Thurlow, J. Impacts of COVID-19 on food systems and poverty in Nigeria. *Adv. Food Secur. Sustain.* **2020**, *5*, 5–145.
10. FAO; IFAD; UNICEF; WFP; WHO. *The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets*; FAO: Rome, Italy, 2020. [CrossRef]
11. Ashraf, S.A.; Siddiqui, A.J.; Elkhalifa, A.E.O.; Khan, M.I.; Patel, M.; Alreshidi, M.; Moin, A.; Singh, R.; Snoussi, M.; Adnan, M. Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment. *Sci. Total Environ.* **2021**, *768*, 144990. [CrossRef]
12. Usman, M.; Farooq, M.; Wakeel, A.; Nawaz, A.; Cheema, S.A.; Rehman, H.; Ashraf, I.; Sanaullah, M. Nanotechnology in agriculture: Current status, challenges and future opportunities. *Sci. Total Environ.* **2020**, *721*, 137778. [CrossRef]
13. Hamad, H.T.; Al-Sharify, Z.T.; Al-Najjar, S.Z.; Gadooa, Z.A. A review on nanotechnology and its applications on fluid flow in agriculture and water recourses. *Mater. Sci. Eng.* **2020**, *870*, 012038. [CrossRef]
14. Paliwal, P.; Sargolzaei, S.; Bhardwaj, S.K.; Bhardwaj, V.; Dixit, C.; Kaushik, A. Grand Challenges in Bio-Nanotechnology to Manage the COVID-19 Pandemic. *Front. Nanotechnol.* **2020**, *2*, 2673–3013. [CrossRef]
15. Hofmann, T.; Lowry, G.V.; Ghoshal, S.; Tufenkji, N.; Brambilla, D.; Dutcher, J.R.; Gilbertson, L.M.; Giraldo, J.P.; Kinsella, J.M.; Landry, M.P.; et al. Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture. *Nat. Food* **2020**, *1*, 416–425. [CrossRef]
16. He, X.; Deng, H.; Hwang, H. The current application of nanotechnology in food and agriculture. *J. Food Drug Anal.* **2019**, *27*, 1–21. [CrossRef] [PubMed]
17. Bai, R.G.; Sabouni, R.; Husseini, G. Green nanotechnology—A road map to safer nanomaterials. In *Applications of Nanomaterials*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 133–159. [CrossRef]
18. Saratale, R.G.; Karuppusamy, I.; Saratale, G.D.; Pugazhendhi, A.; Kumar, G.; Park, Y.; Ghodake, G.S.; Bharagava, R.N.; Banu, J.R.; Shin, H.S. A comprehensive review on green nanomaterials using biological systems: Recent perception and their future applications. *Colloids Surf. B Biointerfaces* **2018**, *170*, 20–35. [CrossRef] [PubMed]
19. Campos, J.; Estefânia, V.R.; Proença, P.L.F.; Oliveira, J.L.; Pereira, A.E.S.; de Morais Ribeiro, L.N.; Fernandes, F.O.; Gonçalves, K.C.; Polanczyk, R.A.; Pasquoto-Stigliani, T.; et al. Carvacrol and linalool co-loaded in β-cyclodextrin-grafted chitosan nanoparticles as sustainable biopesticide aiming pest control. *Sci. Rep. Nat.* **2018**, *8*, 1–14. [CrossRef] [PubMed]
20. Oliveira, J.L.; de Campos, E.V.R.; Pereira, A.E.S.; Pasquoto, T.; Lima, R.; Grillo, R.; de Andrade, D.J.; de Santos, F.A.; dos Fraceto, L.F. Zein nanoparticles as eco-friendly carrier systems for botanical repellents aiming sustainable agriculture. *J. Agric. Food Chem.* **2018**, *66*, 1330–1340. [CrossRef]
21. Pascoli, M.; Lopes-Oliveira, P.J.; Fraceto, L.F.; Seabra, A.B.; Oliveira, H.C. State of the art of polymeric nanoparticles as carrier systems with agricultural applications: A mini review. *Energy Ecol. Environ.* **2018**, *3*, 137–148. [CrossRef]
22. Shang, Y.; Hasan, M.d.K.; Ahammed, G.J.; Li, M.; Yin, H.; Zhou, J. Applications of Nanotechnology in Plant Growth and Crop Protection: A Review. *Molecules* **2019**, *24*, 14. [CrossRef]
23. Harismah, K.; Mirzaei, M. COVID-19: A serious warning for emergency health innovation. *Adv. J. Sci. Eng.* **2020**, *1*, 32–33.
24. Ozkendir, O.M.; Askar, M.; Kocer, N.E. Influence of the Epidemic COVID-19: An Outlook on Health, Business and Scientific Studies. *Lab-Silico* **2020**, *1*, 26–30.
25. Sportelli, M.C.; Izzi, M.; Kukushkina, E.A.; Hossain, S.I.; Picca, R.A.; Ditaranto, N.; Cioffi, N. Can nanotechnology and materials science help the fight against SARS-CoV-2. *Nanomaterials* **2020**, *10*, 802. [CrossRef] [PubMed]
26. HLPE. *High Level Panel of Experts on Food Security and Nutrition. Impacts of COVID-19 on Food Security and Nutrition: Developing Effective Policy Responses to Address the Hunger and Malnutrition Pandemic*; HLPE: Rome, Italy, 2020. [CrossRef]
27. Bochtis, D.; Benos, L.; Lampridi, M.; Marinoudi, V.; Pearson, S.; Sorensen, C.G. Agricultural workforce crisis in light of the COVID-19 pandemic. *Sustainability* **2020**, *12*, 8212. [CrossRef]
28. Balana, B.; Oyeyemi, M.; Ogunniyi, A.; Fasoranti, A.; Edeh, H.; Aiki, J.; Andam, K.S. The effects of COVID-19 policies on livelihoods and food security of smallholder farm households in Nigeria: Descriptive results from a phone survey. *Int. Food Policy Res. Inst. (IFPRI) Discuss. Pap.* **2020**, *01979*, 34.
29. Ilesanmi, F.; Ilesanmi, O.; Afolabi, A. The effects of the COVID-19 pandemic on food losses in the agricultural value chains in Africa: The Nigerian case study. *Public Health Pract.* **2021**, *2*, 100087. [CrossRef]

30. Javed, R.; Bilal, M.; Ali, J.S.; Khan, S.; Cheema, M. Nanotechnology: A Tool for the Development of Sustainable Agroindustry. In *Agricultural and Environmental Nanotechnology*; Interdisciplinary Biotechnological Advances; Fernandez-Luqueno, F., Patra, J.K., Eds.; Springer: Singapore, 2023. [CrossRef]
31. WHO/ILO Policy Brief. *Preventing and Mitigating COVID-19 at Work*; WHO: Geneva, Switzerland, 2021.
32. Saritha, G.N.G.; Anju, T.; Kumar, A. Nanotechnology-Big impact: How nanotechnology is changing the future of agriculture? *J. Agric. Food Res.* **2022**, *10*, 100457. [CrossRef]
33. Singh, D.P.; Packirisamy, G. Applications of nanotechnology to combat the problems associated with modern food. *J. Sci. Food Agric.* **2022**, *103*, 479–487. [CrossRef]
34. United States Department of Agriculture—National Institute of Food and Agriculture (USDA-NIFA). Nanotechnology in Agriculture and Food Systems | National Institute of Food and Agriculture. 2022. Available online: https://www.usda.gov/ (accessed on 27 January 2023).
35. Chaudhary, V.; Royal, A.; Chavali, M.; Yadav, S.K. Advancements in research and development to combat COVID-19 using nanotechnology. *Nanotechnol. Environ. Eng.* **2021**, *6*, 1–15. [CrossRef]
36. Elkodous, M.A.; El-Sayyad, G.S.; Nasser, H.A.; Elshamy, A.A.; Morsi, M.; Abdelrahman, I.Y.; Kodous, A.S.; Mosallam, F.M.; Gobara, M.; El-Batal, A.I. Therapeutic and diagnostic potential of nanomaterials for enhanced biomedical applications. *Colloids Surf. B Biointerfaces* **2019**, *180*, 411–428. [CrossRef]
37. Akinsiku, A.A.; Ajanaku, K.O.; Dare, E.O. Green synthesis of pseudo-cubic Ag/Ni bimetallic nanoparticles using *Senna occidentalis* leaf extract. *J. Phys. Conf. Ser.* **2019**, *1299*, 012133. [CrossRef]
38. Alayande, S.O.; Akinsiku, A.A.; Akinsipo, O.B.; Ogunjinmi, E.O.; Dare, E.O. Green synthesized silver nanoparticles and their therapeutic applications. In *Comprehensive Analytical Chemistry*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 94, pp. 585–611. ISSN 0166–0526X. [CrossRef]
39. Hossain, Z.; Yasmeen, F.; Komatsu, S. Nanoparticles: Synthesis, morphophysical effects and proteomic responses of crop plants. *Int. J. Mol. Sci.* **2020**, *21*, 3056. [CrossRef]
40. Ferreira, C.D.; Nunes, I.L. Oil nanoencapsulation: Development, application, and incorporation into the food market. *Nanoscale Res. Lett.* **2019**, *14*, 9. [CrossRef]
41. Jafari, S.M. *An Overview of Nanoencapsulation Techniques and Their Classification—Nanoencapsulation Technologies for the Food and Nutraceutical Industries Amsterdam*; Academic Press: Cambridge, MA, USA, 2017; pp. 1–34.
42. Suganya, V.; Anuradha, V. Microencapsulation and nanoencapsulation: A review. *Int. J. Pharm. Clin. Res.* **2017**, *9*, 233–239. [CrossRef]
43. Patra, J.K.; Das, G.; Fraceto, L.F.; Campos, E.V.R.; Rodriguez-Torres, M.D.P.; Acosta-Torres, L.S.; Diaz-Torres, L.A.; Grillo, R.; Swamy, M.K.; Sharma, S.; et al. Nano based drug delivery systems: Recent developments and future prospects. *J. Nanobiotechnol.* **2018**, *16*, 71. [CrossRef]
44. Wani, T.A.; Masoodi, F.A.; NabiBaba, W.; Ahmad, M.; Rahmanian, N.; Jafari, S.M. Chapter 11—Nanoencapsulation of Agrochemicals, Fertilizers, and Pesticides for Improved Plant Production. *Adv. Phytonanotechnol.* **2019**, 279–298.
45. Robledo, N.; Loópez, L.; Bunger, A.; Tapia, C.; Abugoch, L. Effects of antimicrobial edible coating of thymol nanoemulsion/quinoa protein/ chitosan on the safety, sensorial properties, and quality of refrigerated strawberries (*Fragaria ananassa*) under commercial storage environment. *Food Bioprocess. Technol.* **2018**, *11*, 1566–1574. [CrossRef]
46. Che Marzuki, N.H.; Wahab, R.A.; Abdul Hamid, M. An overview of nanoemulsion: Concepts of development and cosmeceutical applications. *Biotechnol. Biotechnol. Equip.* **2019**, *33*, 779–797. [CrossRef]
47. Feng, J.; Zhang, Q.; Liu, Q.; Zhu, Z.; McClements, D.J.; Jafari, S.M. *Chapter 12—Application of Nanoemulsions in Formulation of Pesticides*; Nanoemulsions, Jafari, S.M., McClements, D.J., Eds.; Academic Press: Cambridge, MA, USA, 2018; pp. 379–413.
48. Ko, F.K.; Wan, Y. *Introduction to Nanofiber Materials*; Cambridge University Press: Cambridge, UK, 2014; pp. 1–9.
49. Xu, N.; Li, Z.; Huangfu, X.; Cheng, X.; Christodoulatos, C.; Qian, J.; Chen, M.; Chen, J.; Su, C.; Wang, D. Facilitated transport of nTiO_2-kaolin aggregates by bacteria and phosphate in water-saturated quartz sand. *Sci. Total Environ.* **2020**, *713*, 136589. [CrossRef]
50. Anzar, N.; Hasan, R.; Tyagi, M.; Yadav, N.; Narang, J. Carbon nanotube-A review on Synthesis, Properties and plethora of applications in the field of biomedical science. *Sens. Int.* **2020**, *1*, 100003. [CrossRef]
51. Lahiani, M.; Nima, Z.; Villagarcia, H.; Biris, A.S.; Khodakovskaya, M. Assessment of effects of the long-term exposure of agricultural crops to carbon nanotubes. *J. Agric. Food Chem.* **2018**, *66*, 6654–6662. [CrossRef]
52. Patel, D.K.; Kim, H.B.; Dutta, S.D.; Ganguly, K.; Lim, K.T. Carbon nanotubes-based nanomaterials and their agricultural and biotechnological applications. *Materials* **2020**, *13*, 1679. [CrossRef]
53. Lahiani, M.H.; Chen, J.; Irin, F.; Puretzky, A.A.; Green, M.J.; Khodakovskaya, M.V. Interaction of carbon nanohorns with plants: Uptake and biological effects. *Carbon* **2015**, *81*, 607–619. [CrossRef]
54. Sanvicens, N.; Pastells, C.; Pascual, N.; Marco, M.P. Nanoparticle-based biosensors for detection of pathogenic bacteria. *TrAC Trends Anal. Chem.* **2009**, *28*, 1243–1252. [CrossRef]
55. Singh, A.; Tiwari, S.; Pandney, J.; Lata, C.; Singh, I.K. Role of nanoparticles in crop improvement and abiotic stress management. *J. Biotechnol.* **2021**, *337*, 57–70. [CrossRef]
56. Tirani, M.M.; Haghjou, M.M.; Ismaili, A. Hydroponic grown tobacco plants respond to zinc oxide nanoparticles and bulk exposures by morphological, physiological and anatomical adjustments. *Funct. Plant Biol.* **2019**, *46*, 360–375. [CrossRef]

57. Acharya, A.; Pal, P.K. Agriculture nanotechnology: Translating research outcome to field applications by influencing environmental sustainability. *NanoImpact* **2020**, *19*, 100232. [CrossRef]
58. Duhan, J.S.; Kumar, R.; Kumar, N.; Kaur, P.; Nehra, K.; Duhan, S. Nanotechnology: The new perspective in precision agriculture. *Biotechnol. Rep.* **2017**, *125*, 11–23. [CrossRef]
59. Zhang, P.; Guo, Z.; Ullah, S.; Melagraki, G.; Afantitis, A.; Lynch, I. Nanotechnology and artificial intelligence to enable sustainable and precision agriculture. *Nat. Plants* **2021**, *7*, 864–876. [CrossRef]
60. Day, W. Engineering precision into variable biological systems. *Ann. Appl. Biol.* **2005**, *146*, 155–162. [CrossRef]
61. Dong, J.; Liu, X.; Chen, Y.; Yang, W.; Du, X. User-safe and efficient chitosan-gated porous carbon nanopesticides and nanoherbicides. *J. Colloid Interface Sci.* **2021**, *594*, 20–34. [CrossRef]
62. Haq, I.U.; Ijaz, S. Use of Metallic Nanoparticles and Nanoformulations as Nanofungicides for Sustainable Disease Management in Plants. In *Nanobiotechnology in Bioformulations*; Prasad, R., Kumar, V., Kumar, M., Choudhary, D., Eds.; Springer: Cham, Switzerland, 2019; pp. 289–316.
63. Shahzad, K.; Manzoor, F. Nanoformulations and their mode of action in insects: A review of biological interactions. *Drug Chem. Toxicol.* **2019**, *44*, 1–11. [CrossRef]
64. Zheng, Q.; Wang, R.; Qin, D.; Yang, L.; Lin, S.; Cheng, D.; Huang, S.; Zhang, Z. Insecticidal efficacy and mechanism of nanoparticles synthesized from chitosan and carboxymethyl chitosan against *Solenopsis invicta* (*Hymenoptera*: Formicidae). *Carbohydr. Polym.* **2021**, *260*, 117839. [CrossRef]
65. Jameel, M.; Shoeb, M.; Khan, M.T.; Ullah, R.; Mobin, M.; Farooqi, M.K.; Adnan, S.M. Enhanced Insecticidal Activity of Thiamethoxam by Zinc Oxide Nanoparticles: A Novel Nanotechnology Approach for Pest Control. *ACS Omega* **2020**, *5*, 1607–1615. [CrossRef] [PubMed]
66. Ayoub, H.A.; Khairy, M.; Rashwan, F.A.; Abdel-Hafez, H.F. Synthesis and characterization of silica nanostructures for cotton leaf worm control. *J. Nanostructured Chem.* **2017**, *7*, 91–100. [CrossRef]
67. Elnaggar, M.; Abdelsalam, N.; Fouda, M.; Mackled, M.; Al-Jaddadi, M.; Ali, H.; Siddiqui, M.H.; Kandil, E. Soil Application of Nano Silica on Maize Yield and Its Insecticidal Activity Against Some Stored Insects After the Post-Harvest. *Nanomaterials* **2020**, *10*, 739. [CrossRef] [PubMed]
68. Wang, Z.; Zhu, W.; Chen, F.; Yue, L.; Ding, Y.; Xu, H.; Rasmann, S.; Xiao, Z. Nanosilicon enhances maize resistance against oriental armyworm (*Mythimna separata*) by activating the biosynthesis of chemical defenses. *Sci. Total Environ.* **2021**, *778*, 146378. [CrossRef] [PubMed]
69. El-Ashry, R.M.; El-Saddony, M.T.; El-Sobki, A.E.A.; El-Tahan, A.M.; Al-Otaibi, S.; El-Shehawi, A.M.; Saad, A.M.; Elshaer, N. Biological Silicon Nanoparticles maximize the efficiencies of nematicides against biotic stress induced by *Meloidogyne incognita* in eggplant. *Saudi J. Biol. Sci.* **2022**, *29*, 920–932. [CrossRef] [PubMed]
70. Pereira, A.E.S.; Grillo, R.; Mello, N.F.S.; Rosa, A.H.; Fraceto, L.F. Application of poly(epsilon-caprolactone) nanoparticles containing atrazine herbicide as an alternative technique to control weeds and reduce damage to the environment. *J. Hazard. Mater.* **2014**, *268*, 207–215. [CrossRef] [PubMed]
71. Grillo, R.; Pereira, A.E.; Nishisaka, C.S.; de Lima, R.; Oehlke, K.; Greiner, R.; Fraceto, L.F. Chitosan/tripolyphosphate nanoparticles loaded with paraquat herbicide: An environmentally safer alternative for weed control. *J. Hazard. Mater.* **2014**, *8*, 163–171. [CrossRef]
72. de Sousa, B.T.; Pereira, A.E.S.; Fraceto, L.F.; Oliveira, H.C.; Dalazen, G. Post-emergence herbicidal activity of nanoatrazine against Alternanthera tenella Colla plants compared to other weed species. *Heliyon* **2022**, *8*, e09902. [CrossRef]
73. Ahmad, H.; Venugopal, K.; Rajagopal, K.; De Britto, S.; Nandini, B.; Pushpalatha HGKonappa, N.; Udayashankar, A.C.; Geetha, N.; Jogaiah, S. Green Synthesis and Characterization of Zinc Oxide Nanoparticles Using Eucalyptus globules and Their Fungicidal Ability Against Pathogenic Fungi of Apple Orchards. *Biomolecules* **2020**, *10*, 425. [CrossRef]
74. Chen, J.; Wu, L.; Lu, M.; Lu, S.; Li, Z.; Ding, W. Comparative study on the fungicidal activity of metallic MgO nanoparticles and macroscale MgO against Soil-borne fungal phytopathogens. *Front. Microbiol.* **2020**, *11*, 365. [CrossRef] [PubMed]
75. Irshad, M.A.; Nawaz, R.; Zia ur Rehman, M.; Imran, M.; Ahmad, J.; Ahmad, S.; Inam, A.; Razzaq, A.; Rizwan, M.; Ali, S. Synthesis and characterization of titanium dioxide nanoparticles by chemical and green methods and their antifungal activities against wheat rust. *Chemosphere* **2020**, *258*, 127352. [CrossRef] [PubMed]
76. Oussou-Azo, A.; Nakama, T.; Nakamura, M.; Futagami, T.; Vestergaard, M. Antifungal Potential of Nanostructured Crystalline Copper and Its Oxide Forms. *Nanomaterials* **2020**, *10*, 1003. [CrossRef] [PubMed]
77. Jahangirian, H.; Rafiee-Moghaddam, R.; Jahangirian, N.; Nikpey, B.; Jahangirian, S.; Bassous, N.; Saleh, B.; Kalantari, K.; Webster, T.J. Green Synthesis of Zeolite/$Fe_{(2)}O_{(3)}$ Nanocomposites: Toxicity & Cell Proliferation Assays and Application as a Smart Iron Nanofertilizer. *Int. J. Nanomed.* **2020**, *15*, 1005–1020.
78. Cota-Ruiz, K.; Ye, Y.; Valdes, C.; Deng, C.; Wang, Y.; Hernández-Viezcas, J.A.; Duarte-Gardea, M.; Gardea-Torresdey, J.L. Copper nanowires as nanofertilizers for alfalfa plants: Understanding nano-bio systems interactions from microbial genomics, plant molecular responses and spectroscopic studies. *Sci. Total Environ.* **2020**, *742*, 140572. [CrossRef]
79. Naseem, F.; Zhi, Y.; Farrukh, M.A.; Hussain, F.; Yin, Z. Mesoporous ZnAl2SiO nanofertilizers enable high yield of *Oryza sativa* L. *Sci. Rep.* **2020**, *10*, 10841. [CrossRef]
80. Pérez-de-Luque, A.; Rubiales, D. Nanotechnology for parasitic plant control. *Pest Manag. Sci.* **2009**, *65*, 540–545. [CrossRef]

81. Grillo, R.; dos Santos, N.Z.P.; Maruyama, C.R.; Rosa, A.H.; de Lima, R.; Fraceto, L.F. Poly(γ-caprolactone) nanocapsules as carrier systems for herbicides: Physico-chemical characterization and genotoxicity evaluation. *J. Hazard. Mater.* **2012**, *231–232*, 1–9. [CrossRef]
82. Rani, P.U.; Madhusudhanamurthy, J.; Sreedhar, B. Dynamic adsorption of α-pinene and linalool on silica nanoparticles for enhanced anti-feedant activity against agricultural pests. *J. Pestic. Sci.* **2014**, *87*, 191–200. [CrossRef]
83. Abigail, M.E.A.; Melvin, S.S.; Chidambaram, R. Application of rice husk nano-sorbents containing, 2,4-dichlorophenoxyacetic acid herbicide to control weeds and reduce leaching from soil. *J. Taiwan Inst. Chem. Eng.* **2016**, *63*, 318–326. [CrossRef]
84. Sharma, P.; Sharma, A.; Sharma, M.; Bhalla, N.; Estrela, P.; Jain, A.; Thakur, P.; Thakur, A. Nanomaterial Fungicides: In Vitro and In Vivo Antimycotic Activity of Cobalt and Nickel Nanoferrites on Phytopathogenic Fungi Global Challenges. *Glob. Chall.* **2017**, *1*, 1770071. [CrossRef]
85. Pariona, N.; Mtz-Enriquez, A.I.; Sánchez-Rangel, D.; Carrión, G.; Paraguay-Delgad, F.; Rosas-Saito, G. Green-synthesized copper nanoparticles as a potential antifungal against plant pathogens. *RSC Adv.* **2019**, *9*, 18835. [CrossRef] [PubMed]
86. Le, V.T.; Bach, L.G.; Pham, T.T.; Le, N.T.T.; Ngoc, U.T.P.; Tran, D.H.N.; Nguyen, D.H. Synthesis and antifungal activity of chitosan-silver nanocomposite synergize fungicide against *Phytophthora Capsici*. *J. Macromol. Sci. Part A* **2019**, *56*, 522–528. [CrossRef]
87. Giannousi, K.; Avramidis, I.; Dendrinou-Samara, C. Synthesis, characterization and evaluation of copper based nanoparticles as agrochemicals against *Phytophthora infestans*. *RCS Adv.* **2013**, *3*, 21743–21752. [CrossRef]
88. Salama, D.M.; El-Aziz, M.E.A.; Rizk, F.A.; Elwahed, M.S.A. Applications of nanotechnology on vegetable crops. *Chemosphere* **2021**, *266*, 129026. [CrossRef] [PubMed]
89. Askary, M.; Amirjani, M.R.; Saberi, T. Comparison of the effects of nano-iron fertilizer with iron-chelate on growth parameters and some biochemical properties of *Catharanthus roseus*. *J. Plant Nutr.* **2017**, *40*, 974–982. [CrossRef]
90. Bastani, S.; Hajiboland, R.; Khatamian, M.; Saket-Oskoui, M. Nano iron (Fe) complex is an effective source of Fe for tobacco plants grown under low Fe supply. *J. Soil Sci. Plant Nutr.* **2018**, *18*, 524–541. [CrossRef]
91. Elrys, A.S.; Abdo, A.I.E.; Desoky, E.S.M. Potato tubers contamination with nitrate under the influence of nitrogen fertilizers and spray with molybdenum and salicylic acid. *Environ. Sci. Pollut. Res.* **2018**, *25*, 7076–7089. [CrossRef]
92. Abbasifar, A.; ValizadehKaji, B.; Iravani, M.A. Effect of green synthesized molybdenum nanoparticles on nitrate accumulation and nitrate reductase activity in spinach. *J. Plant Nutr.* **2020**, *43*, 13–27. [CrossRef]
93. Osman, S.A.; Salama, D.M.; Abd El-Aziz, M.E.; Shaaban, E.A.; AbdElwahede, M.S. The influence of MoO3-NPs on agro-morphological criteria, genomic stability of DNA, biochemical assay, and production of common dry bean (*Phaseolus vulgaris* L.). *Plant Physiol. Biochem.* **2020**, *151*, 77–87. [CrossRef]
94. Al-Ubaidy, R.M.; Mohammed, M.M.; Al-Zaidy, A.K. Influence of chemical fertilizers and foliar spraying with humic acid in growth and yield of red cabbage. *Biochem. Cell. Arch.* **2019**, *19*, 1215–1219.
95. Abdulhameed, M.F.; Taha, A.A.; Ismail, R.A. Improvement of cabbage growth and yield by nanofertilizers and nanoparticles. *Environ. Nanotechnol. Monit. Manag.* **2021**, *15*, 100437. [CrossRef]
96. Abdel-Aziz, H.M.M.; Hasaneen, M.N.A.; Omer, A.M. Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Span. J. Agric. Res.* **2016**, *14*, 17. [CrossRef]
97. Mastronardi, E.; Tsae, P.; Zhang, X.; Monreal, C.; DeRosa, M.C. Strategic role of nanotechnology in fertilizers: Potential and limitations. In *Nanotechnologies in Food and Agriculture*; Rai, M., Ribeiro, C., Mattoso, L., Duran, N., Eds.; Springer: Cham, Switzerland, 2015; pp. 25–67.
98. Monreal, C.M.; DeRosa, M.; Mallubhotla, S.C.; Bindraban, P.S.; Dimkpa, C. Nanotechnologies for increasing the crop use efficiency of fertilizer-micronutrients. *Biol. Fertil. Soils* **2016**, *52*, 423–437. [CrossRef]
99. Arduini, F.; Cinti, S.; Scognamiglio, V.; Moscone, D. Nanomaterials in electrochemical biosensors for pesticide detection: Advances and challenges in food analysis. *Microchim. Acta* **2016**, *183*, 2063–2083. [CrossRef]
100. Antonacci, A.; Arduini, F.; Moscone, D.; Palleschi, G.; Scognamiglio, V. Nanostructured (bio)sensors for smart agriculture. *TrAC Trends Anal. Chem.* **2018**, *98*, 95–103. [CrossRef]
101. Tarafdar, J.C.; Sharma, S.; Raliya, R. Nanotechnology: Interdisciplinary science of applications. *Afr. J. Biotechnol.* **2013**, *12*, 219–226.
102. Walia, S.; Acharya, A. Fluorescent cadmium sulfide nanoparticles for selective and sensitive detection of toxic pesticides in aqueous medium. *J. Nanoparticle Res.* **2014**, *16*, 2778. [CrossRef]
103. Dar, A.I.; Walia, S.; Acharya, A. Citric acid-coated gold nanoparticles for visual colorimetric recognition of pesticide dimethoate. *J. Nanoparticle Res.* **2016**, *18*, 233. [CrossRef]
104. Hu, W.; Wan, L.; Jian, Y.; Ren, C.; Jin, K.; Su, X.; Bai, X.; Haick, H.; Yao, M.; Wu, W. Electronic noses: From advanced materials to sensors aided with data processing. *Adv. Mater. Technol.* **2019**, *4*, 1800488. [CrossRef]
105. Gong, X.; Huang, D.; Liu, Y.; Peng, Z.; Zeng, G.; Xu, P.; Cheng, M.; Wang, R.; Wan, J. Remediation of contaminated soils by biotechnology with nanomaterials: Biobehavior, applications, and perspectives. *Crit. Rev. Biotechnol.* **2018**, *38*, 455–468. [CrossRef] [PubMed]
106. Hamid, Y.; Tang, L.; Hussain, B.; Usman, M.; Gurajala, H.K.; Rashid, M.S.; He, Z.; Yang, X. Efficiency of lime, biochar, Fe containing biochar and composite amendments for Cd and Pb immobilization in a co-contaminated alluvial soil. *Environ. Pollut.* **2020**, *257*, 113609. [CrossRef] [PubMed]

107. Robinson, B.H.; Bañuelos, G.; Conesa, H.M.; Evangelou, M.W.H.; Schulin, R. The phytomanagement of trace elements in soil. *Crit. Rev. Plant Sci.* **2009**, *28*, 240–266. [CrossRef]
108. Boente, C.; Sierra, C.; Martínez-Blanco, D.; Menéndez-Aguado, J.M.; Gallego, J.R. Nanoscale zero-valent iron-assisted soil washing for the removal of potentially toxic elements. *J. Hazard. Mater.* **2018**, *350*, 55–65. [CrossRef]
109. Kumar, L.; Ragunathan, V.; Chugh, M.; Bharadvaja, N. Nanomaterials for remediation of contaminants: A review. *Environ. Chem. Lett.* **2021**, *19*, 3139–3163. [CrossRef]
110. Jorfi, S.; Rezaee, A.; Moheb-ali, G.A.; Jaafarzadeh, N.A. Pyrene removal from contaminated soils by modified Fenton oxidation using iron nano particles. *J. Environ. Health Sci. Eng.* **2013**, *11*, 17. [CrossRef]
111. Santos, A.; Firak, D.S.; Emmel, A.; Siedlecki, K.; Lopes, A.; Peralta-Zamora, P. Evaluation of the Fenton process effectiveness in the remediation of soils contaminated by gasoline: Effect of soil physicochemical properties. *Chemosphere* **2018**, *207*, 154–161. [CrossRef]
112. Barbato, R.A.; Reynolds, C.M. 22- Bioremediation of contaminated soils. In *Principles and Application of Soil Microbiology*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 607–631.
113. Le, T.T.; Nguyen, K.H.; Jeon, J.R.; Francis, A.J.; Chang, Y.S. Nano/bio treatment of polychlorinated biphenyls with evaluation of comparative toxicity. *J. Hazard. Mater.* **2015**, *287*, 335–341. [CrossRef]
114. Singh, J.; Lee, B.K. Influence of nano-TiO_2 particles on the bioaccumulation of Cd in soybean plants (*Glycine max*): A possible mechanism for the removal of Cd from the contaminated soil. *J. Environ. Manag.* **2016**, *170*, 88–96. [CrossRef]
115. Liang S-x Jin, Y.; Liu, W.; Li, X.; Shen, S.G.; Ding, L. Feasibility of Pb phytoextraction using nano-materials assisted ryegrass: Results of a one-year field-scale experiment. *J. Environ. Manag.* **2017**, *190*, 170–175. [CrossRef]
116. Anjum, S.; Anjum, I.; Hano, C.; Kousar, S. Advances in nanomaterials as novel elicitors of pharmacologically active plant specialized metabolites: Current status and future outlooks. *RSC Adv.* **2019**, *9*, 40404–40423. [CrossRef]
117. Paramo, L.A.; Feregrino-Perez, A.A.; Guevara, R.; Mendoza, S.; Esquivel, K. Nanoparticles in agroindustry: Applications, toxicity, challenges and trends. *Nanomaterials* **2020**, *10*, 1654. [CrossRef] [PubMed]
118. Kongala, S.I.; Nadendla, S.R.; Mamidala, P. Internalization and induction of defense responses in tobacco by harpinPss conjugated gold nanoparticles as a foliar spray. *Colloid Interface Sci. Commun.* **2021**, *43*, 100438. [CrossRef]
119. Cai, L.; Cai, L.; Jia, H.; Liu, C.; Wang, D.; Suna, X. Foliar exposure of Fe_3O_4 nanoparticles on *Nicotiana benthamina*—Evidence for nanoparticles uptake, plant growth promoter and defense response elicitor against plant virus. *J. Hazard. Mater.* **2020**, *393*, 122415. [CrossRef]
120. Ghanati, F.; Bakhtiarian, S. Effect of Methyl Jasmonate and Silver Nanoparticles on Production of Secondary Metabolites by *Calendula officinalis* L (*Asteraceae*). *Trop. J. Pharm. Res.* **2014**, *13*, 1783–1789. [CrossRef]
121. Salman-Khan, M.; Zaka, M.; Haider Abbasi, B.; Rahman, L.; Shah, A. Seed germination and biochemical profile of *Silybum marianum* exposed to monometallic and bimetallic alloy nanoparticles. *IET Nanobiotechnology* **2016**, *10*, 359–366. [CrossRef] [PubMed]
122. Javed, R.; Yucesan, B.; Zia, M.; Gurel, E. Elicitation of Secondary Metabolites in Callus Cultures of *Stevia rebaudiana* Bertoni Grown Under ZnO and CuO Nanoparticles Stress. *Sugar Technol.* **2018**, *20*, 194–201. [CrossRef]
123. Li, Y.; Gao, J.; Xu, X.; Wu, Y.; Zhuang, J.; Zhang, X.; Zhang, H.; Lei, B.; Zheng, M.; Liu, Y.; et al. Carbon Dots as a Protective Agent Alleviating Abiotic Stress on Rice (*Oryza sativa* L.) through Promoting Nutrition Assimilation and the Defense System. *ACS Appl. Mater. Interfaces* **2020**, *12*, 33575–33585. [CrossRef]
124. Santana, I.; Wu, H.; Hu, P.; Giraldo, J.U. Targeted delivery of nanomaterials with chemical cargoes in plants enabled by a bio-recognition motif. *Nat. Commun.* **2020**, *11*, 2045. [CrossRef]
125. Demirer, G.S.; Zhang, H.; Matos, J.L.; Goh, N.S.; Cunningham, F.J.; Sung, Y.; Chang, R.; Aditham, A.J.; Chio, L.; Cho, M.; et al. High aspect ratio nanomaterials enable delivery of functional genetic material without DNA integration in mature plants. *Nat. Nanotechnol.* **2019**, *14*, 456–464. [CrossRef]
126. Miller, J.B.; Zhang, S.; Kos, P.; Xiong, H.; Zhou, K.; Perelman, S.S.; Zhu, H.; Siegwart, D.J. Non-viral CRISPR/Cas gene editing in vitro and in vivo enabled by synthetic nanoparticle co-delivery of Cas9 mRNA and sgRNA. *Angew. Chem. Int. Ed.* **2017**, *56*, 1059–1063. [CrossRef] [PubMed]
127. Mukarram, M.; Khan, M.M.A.; Corpas, F.J. Silicon nanoparticles elicit an increase in lemongrass (*Cymbopogon flexuosus* (Steud.) Wats) agronomic parameters with a higher essential oil yield. *J. Hazard. Mater.* **2021**, *412*, 125254. [CrossRef] [PubMed]
128. Cheng, B.; Chen, F.; Wang, C.; Liu, X.; Yue, L.; Cao, X.; Wang, Z.; Xing, B. The molecular mechanisms of silica nanomaterials enhancing the rice (*Oryza sativa* L.) resistance to planthoppers. *Sci. Total Environ.* **2021**, *767*, 144967. [CrossRef] [PubMed]
129. Gatadi, S.; Madhavi, Y.V.; Nanduri, S. Nanoparticle drug conjugates treating microbial and viral infections: A review. *J. Mol. Struct.* **2021**, *1228*, 129750. [CrossRef]
130. Kapoor, P.; Dhaka, R.K.; Sihag, P.; Mehla, S.; Sagwal, V.; Singh, Y.; Langaya, S.; Balyan, P.; Singh, K.P.; Xing, B.; et al. Nanotechnology-enabled biofortification strategies for micronutrients enrichment of food crops: Current understanding and future scope. *NanoImpact* **2022**, *26*, 100407. [CrossRef]
131. Khan, A.; Singh, J.; Upadhayay, V.K.; Singh, A.V.; Shah, S. Microbial biofortification: A Green technology through plant growth promoting microorganisms. In *Sustainable Green Technologies for Environmental Management*; Springer: New York, NY, USA, 2019; pp. 255–269.
132. Roychoudhury, A. Silicon-nanoparticles in crop improvement and agriculture. *Int. J. Adv. Res. Biotechnol. Nanotechnol.* **2020**, *3*, 54.

133. Ahmadian, K.; Jalilian, J.; Pirzad, A. Nano-fertilizers improved drought tolerance in wheat under deficit irrigation. *Agric. Water Manag.* **2021**, *244*, 106544. [CrossRef]
134. Abdel-Maksoud, M.I.A.; Bekhit, M.; El-Sherif, D.M.; Sofy, A.R.; Sofy, M. Gamma radiation-induced synthesis of a novel chitosan/silver/Mn-Mg ferrite nanocomposite and its impact on cadmium accumulation and translocation in *brassica* plant growth. *Int. J. Biol. Macromol.* **2022**, *194*, 306–316. [CrossRef]
135. Liu, J.; Li, J.; Wolfe, K.; Perrotta, B.; Cobb, G.P. Mobility of arsenic in the growth media of rice plants (*Oryza sativa* subsp. japonica. 'Koshihikari') with exposure to copper oxide 3 nanoparticles in a life-cycle greenhouse study. *Sci. Total Environ.* **2021**, *774*, 145620. [CrossRef]
136. El-Badri, A.M.; Batool, M.; Wang, C.; Hashem, A.M.; Tabl, K.M.; Nishawy, E.; Kuai, J.; Zhou, G.; Wang, B. Selenium and zinc oxide nanoparticles modulate the molecular and morpho-physiological process during seed germination of *Brassica napus* under salt stress. *Ecotoxicol. Environ. Saf.* **2021**, *225*, 112695. [CrossRef]
137. Mohammadi, M.H.Z.; Panahirad, S.; Navai, A.; Bahrami, M.K.; Kulak, M.; Gohari, G. Cerium oxide nanoparticles improve growth parameters and antioxidant defense system in Moldavian Balm (*Dracocephalum moldavica*) under salinity stress. *Plant Stress* **2021**, *1*, 100006. [CrossRef]
138. Wahid, I.; Rani, P.; Kumari, S.; Ahmad, R.; Hussain, S.J.; Alamri, S.; Tripathy, N.; Khan, M.I.R. Biosynthesized gold nanoparticles maintained nitrogen metabolism, nitric oxide synthesis, ions balance and stabilizes the defense systems to improve salt stress tolerance in wheat. *Chemosphere* **2022**, *287*, 132142. [CrossRef] [PubMed]
139. Wang, J.; Li, M.; Feng, J.; Yan, X.; Chen, H.; Han, R. Effects of TiO_2-NPs pretreatment on UV-B stress tolerance in *Arabidopsis thaliana*. *Chemosphere* **2021**, *281*, 130109. [CrossRef]
140. Noor, R.; Yasmin, H.; Ilyas, N.; Nosheen, A.; Hassan, M.N.; Mumtaz, S.; Khan, N.; Ahmad, A.; Ahmad, P. Comparative analysis of iron oxide nanoparticles synthesized from ginger (*Zingiber officinale*) and cumin seeds (*Cuminum cyminum*) to induce resistance in wheat against drought stress. *Chemosphere* **2022**, *292*, 133201. [CrossRef] [PubMed]
141. Siddiqui, M.H.; Al-Whaibi, M.H. Role of nano-SiO_2 in germination of tomato (*Lycopersicum esculentum* seeds Mill.). *Saudi J. Biol. Sci.* **2014**, *21*, 13–17. [CrossRef] [PubMed]
142. Torabian, S.; Zahedi, M.; Khoshgoftar, A.H. Effects of foliar spray of nano-particles of $FeSO_4$ on the growth and ion content of sunflower under saline condition. *J. Plant Nutr.* **2017**, *40*, 615–623. [CrossRef]
143. Tripathi, D.K.; Singh, S.; Singh, V.P.; Prasad, S.M.; Dubey, N.K.; Chauhan, D.K. Silicon nanoparticles more effectively alleviated UV-B stress than silicon in wheat (*Triticum aestivum*) seedlings. *Plant Physiol. Biochem.* **2017**, *110*, 70–81. [CrossRef]
144. Wang, S.H.; Wang, F.Y.; Gao, S.C. Foliar application with nano-silicon alleviates Cd toxicity in rice seedlings. *Environ. Sci. Pollut. Res.* **2015**, *22*, 2837–2845. [CrossRef]
145. Banerjee, A.; Singh, A.; Sudarshan, M.; Roychoudhury, A. Silicon nanoparticle-pulsing mitigates fluoride stress in rice by finetuning the ionomic and metabolomics balance and refining agronomic traits. *Chemosphere* **2021**, *262*, 127826. [CrossRef]
146. Ali, S.; Rizwan, M.; Hussain, A.; ur Rehman, M.Z.; Ali, B.; Yousaf, B.; Wijaya, L.; Alyemeni, M.N.; Ahmad, P. Silicon nanoparticles enhanced the growth and reduced the cadmium accumulation in grains of wheat (*Triticum aestivum* L.). *Plant Physiol. Biochem.* **2019**, *140*, 1–8. [CrossRef]
147. Hussain, B.; Lin, Q.; Hamid, Y.; Sanaullah, M.; Di, L.; Khan, M.B.; Yang, X. Foliage application of selenium and silicon nanoparticles alleviates Cd and Pb toxicity in rice (*Oryza sativa* L.). *Sci. Total Environ.* **2020**, *712*, 136497. [CrossRef]
148. Banerjee, J.; Kole, C. Plant Nanotechnology: An overview on concepts, strategies, and tools. In *Plant Nanotechnology*; Kole, C., Kumar, D., Khodakovskaya, M., Eds.; Springer: Cham, Switzerland, 2016; pp. 1–14.
149. Singh, S.; Jaiswal, V.; Singh, J.K.; Semwal, R.; Raina, D. Nanoparticle formulations: A smart era of advanced treatment with nanotoxicological imprints on the human body. *Chem. -Biol. Interact.* **2023**, *373*, 110355. [CrossRef]
150. Domínguez, G.A.; Torelli, M.D.; Buchman, J.T.; Haynes, C.L.; Hamers, R.J.; Klaper, R.D. Size dependent oxidative stress response of the gut of Daphnia magna to functionalized nanodiamond particles. *Environ. Res.* **2018**, *167*, 267–275. [CrossRef] [PubMed]
151. Sharma, V.; Singh, S.K.; Anderson, D.; Tobin, D.J.; Dhawan, A. Zinc oxide nanoparticle induced genotoxicity in primary human epidermal keratinocytes. *J. Nanosci. Nanotechnol.* **2011**, *11*, 3782–3788. [CrossRef] [PubMed]
152. Li, Y.; Chen, D.H.; Yan, J.; Chen, Y.; Mittelstaedt, R.A.; Zhang, Y.; Biris, A.S.; Heflich, R.H.; Chen, T. Genotoxicity of silver nanoparticles evaluated using the ames test and in vitro micronucleus assay. *Mutat. Res.* **2012**, *745*, 4–10. [CrossRef] [PubMed]
153. Kim, J.S.; Yoon, T.J.; Yu, K.N.; Kim, B.G.; Park, S.J.; Kim, H.W.; Lee, J.K.; Cho, M.H. Toxicity and tissue distribution of magnetic nanoparticles in mice. *Toxicol. Sci.* **2006**, *89*, 338–347. [CrossRef]
154. Stepankova, H.; Michalkova, H.; Splichal, Z.; Richtera, L.; Svec, P.; Vaculovic, T.; Pribyl, J.; Kormunda, M.; Rex, S.; Adam, V.; et al. Unveiling the nanotoxicological aspects of Se nanomaterials differing in size and morphology. *Bioact. Mater.* **2023**, *20*, 489–500. [CrossRef]
155. Iavicoli, I.; Leso, V.; Beezhold, D.H.; Shvedova, A.A. Nanotechnology in agriculture: Opportunities, toxicological implications and occupational risks. *Toxicol. Appl. Pharamacology* **2017**, *329*, 96–111. [CrossRef]
156. Shatkin, J.A.; Kim, B. Cellulose nanomaterials: Life cycle risk assessment and environmental health and safety roadmap. *Environ. Sci. Nano* **2015**, *2*, 497–499. [CrossRef]
157. Handy, R.D.; Shaw, B.J. Toxic effects of nanoparticles and nanomaterials: Implications for public health, risk assessment and the public perception of nanotechnology. *Health Risk Soc.* **2007**, *9*, 125–144. [CrossRef]

158. Savolainen, K.; Alenius, H.; Norppa, H.; Pylkkänen, L.; Tuomi, T.; Kasper, G. Risk assessment of engineered nanomaterials and nanotechnologies—A review. *Toxicology* **2010**, *269*, 92–104. [CrossRef] [PubMed]
159. Iavicoli, I.; Leso, V.; Ricciardi, W.; Hodson, L.L.; Hoover, M.D. Opportunities and challenges of nanotechnology in the green economy. *Environ. Health* **2014**, *7*, 78. [CrossRef] [PubMed]
160. Bergeson, L.L. Sustainable nanomaterials: Emerging governance systems. *ACS Sustain. Chem. Eng.* **2013**, *1*, 724–730. [CrossRef]
161. Pandiyan, G.K.; Prabaharan, T. Implementation of nanotechnology in fuel cells. *Mater. Today Proc.* **2020**, *1*, 368. [CrossRef]
162. Trump, B.D.; Hristozov, D.; Malloy, T.; Linkov, I. Risk associated with engineered nanomaterials: Different tools for different ways to govern. *Nano Today* **2018**, *21*, 9–13. [CrossRef]
163. Kühnel, D.; Nickel, C.; Hellack, B.; van der Zalm, E.; Kussatz, C.; Herrchen, M.; Meisterjahn, B.; Hund-Rinke, K. Closing gaps for environmental risk screening of engineered nanomaterials. *NanoImpact* **2019**, *15*, 100173. [CrossRef]
164. Rodríguez-Ibarra, C.; Déciga-Alcaraz, A.; Ispanixtlahuatl-Meráz, O.; Medina-Reyes, E.I.; Delgado-Buenrostro, N.L.; Chirino, Y.I. International landscape of limits and recommendations for occupational exposure to engineered nanomaterials. *Toxicol. Lett.* **2020**, *322*, 111–119. [CrossRef]
165. Johnston, L.J.; Gonzalez-Rojano, N.; Wilkinson, K.J.; Xing, B. Key challenges for evaluation of the safety of engineered nanomaterials. *NanoImpact* **2020**, *18*, 100219. [CrossRef]
166. Hermann, A.; Diesner, M.O.; Abel, J.; Hawthorne, C.; Greßmann, A. *Assessment of Impacts of a European Register of Products Containing Nanomaterials*; Federal Environment Agency: Dessau-Roßlau, Germany, 2014; p. 142.
167. Salieri, B.; Turner, D.A.; Nowack, B.; Hischier, R. Life cycle assessment of manufactured nanomaterials: Where are we? *NanoImpact* **2018**, *10*, 108–120. [CrossRef]
168. Tripathi, M.; Yadav, S.N.; Prasad, N.; Kumar, A. Nanotechnology: An Aid to Human Welfare in COVID-19 Pandemic Era. *Virol. Immunol. J.* **2020**, *4*, 000252.
169. Mitter, N.; Hussey, K. Moving policy and regulation forward for nanotechnology applications in agriculture. *Nat. Nanotechnol.* **2019**, *14*, 508–510. [CrossRef] [PubMed]
170. Kah, M.; Tufenkji, N.; White, J.C. Nano-enabled strategies to enhance crop nutrition and protection. *Nat. Nanotechnol.* **2019**, *14*, 532–540. [CrossRef] [PubMed]
171. Siddiqui, M.H.; Al-Whaibi, M.H.; Firoz, M.; Al-Khaishany, M.Y. Role of nanoparticles in plants. In *Nanotechnology and Plant Sciences*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 19–35.