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Review

Advances in Nanotechnology for Sustainable Agriculture: A Review of Climate Change Mitigation

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Abstract: Currently, one of the main challenges is the mitigation of the effects of climate change on the agricultural sector. Conventional agriculture, with the intensive use of herbicides and pesticides to control weeds and pests, and the improper use of mineral fertilizers, contributes to climate change by causing increased greenhouse gases and groundwater pollution. Therefore, more innovative technologies must be used to overcome these problems. One possible solution is nanotechnology, which has the potential to revolutionize the conventional agricultural system. Active nanoparticles can be used both as a direct source of micronutrients and as a delivery platform for bioactive agrochemicals to improve crop growth, yield, and quality. The use of nanoparticle formulations, including nano-pesticides, nano-herbicides, nano-fertilizers, and nano-emulsions, has been extensively studied to improve crop health and shelf-life of agricultural products. Comprehensive knowledge of the interactions between plants and nanoparticles opens up new opportunities to improve cropping practices through the enhancement of properties such as disease resistance, crop yield, and nutrient use. The main objective of this review is to analyze the main effects of climate change on conventional agricultural practices, such as the use of pesticides, herbicides, and fertilizers. It also focuses on how the introduction of nanoparticles into conventional practices can improve the efficiency of chemical pest control and crop nutrition. Finally, this review examines in depth the last 10 years (2014–2024) of scientific literature regarding the use of nanoparticles in agriculture to mitigate the effects of climate change.

Keywords: climate change; agricultural management; nanomaterials; crop physiology; crop establishment; biotic stress; abiotic stress

1. Introduction

Nowadays, agriculture is facing new challenges that are brought about by climate change, and the world population steadily needs safe food and high yields to feed all the people [1]. Although the agricultural sector is one of the first sectors to be affected by climate change, it is also one of the biggest contributors to this phenomenon. It is therefore necessary to modify the entire production process of the agricultural sector so that it can adapt to the inevitable climate change. According to the European Union, through the Farm to Fork Strategy, chemical fertilization must be reduced by 20% [2]; consequently, new innovative technologies must be applied in agriculture. Climate change affects some parameters (e.g., temperature, area of cultivation, and rain patterns) that influence the growth of the main crop for human sustainability (Figure 1). Table 1 summarizes the main nanoparticles used as nano-fertilizers and their effects on plants.

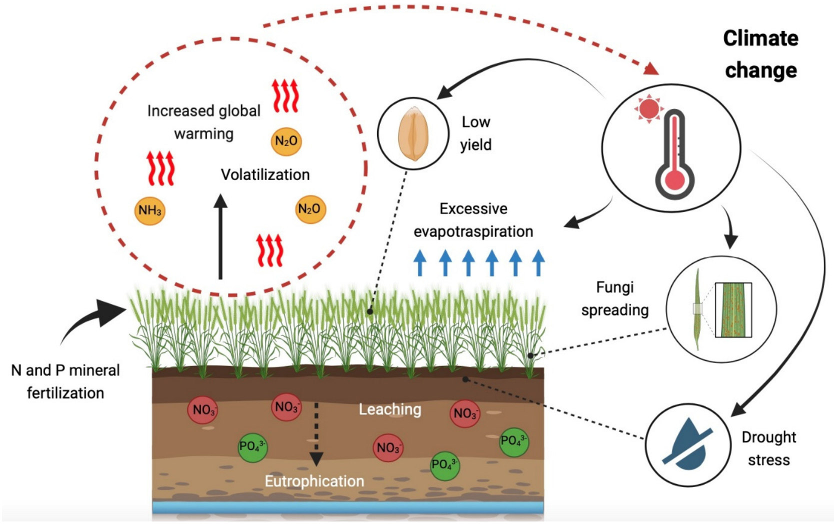

Figure 1. The main impacts of agricultural practices on climate change and, conversely, the effects of climate change on the agricultural system.

Global warming can put crops under severe stressed conditions, and, consequently, this leads to a significant decrease in crop yield. The "Paris Agreement" stipulated in 2015 proposed not to exceed the global average temperature by 2 °C. The risks related to breaching this threshold are demonstrated by [16] who studied the reduction in yields of some crops, specifically up to −14% for maize (*Zea mays*) and −20% for soybean (*Glycine max*). In contrast to winter crops such as wheat (*Triticum aestivum*), Moriondo et al. [17] showed that sunflower (*Helianthus annuus*) is more affected by heat stress. A key factor that determines the geographic areas in which crops can be grown and influences their growth rate, development, and yield is temperature [18]. Each crop is characterized by optimum temperature ranges for each phase of the growth cycle. Therefore, temperature fluctuations during the anthesis phase can cause a reduction in yield and disturb crop development [19]. According to the Intergovernmental Panel on Climate Change [20], temperature change in tropical areas has generally harmed food production. However, the increase in maximum temperatures caused by climate change is beneficial for agricultural production in northern locations due to a longer growing season [21,22]. However, the negative effects of high temperatures are associated with and aggravated by other environmental factors, such as the frequency of precipitation, the presence of strong winds, and the duration and intensity of sunlight. The consequent increase in temperature is correlated with an increase in water demand from the atmosphere, which leads to a consequent reduction in the availability of water to crops and thus a loss of crop yields [23]. On the other hand, the increase in temperature leads to indirect effects, such as an increase in the frequency of heat waves, an impact on the presence of pests, and the development of weeds and crop diseases [24]. Climate change can lead to the adaptation of invasive species, pathogens, and pests to agroecosystems different from their original ones [25]. Another factor that has a severe impact on crop development is water availability. Climate change affects soil moisture storage, precipitation patterns, evaporation, and runoff [26].

Table 1. Main nanoparticles used as nano-fertilizers and their effects on plants.

Botanical Family	Plant Involved	Nanoparticle	Function	References
Asteraceae	*Helianthus annuus*	Si NPs	Head diameter and grain yield enhanced and greater content of oleic acid and linoleic acid compared to the control	[3]
		ZnO NPs		
	Lactuca sativa	ZnO NPs	Biomass, chlorophyll, phenolics, flavonoids, and vitamin C increase	[4]
Brassicaceae	*Brassica napus*	CeO_2 NPs	Higher biomass and reduced stress conditions in a salinity-affected environment	[5]
Cucurbitaceae	*Cucumis sativus*	CeO_2 NPs	Root biomass, vitamin C, and soluble sugar content enhanced, with biotransformation of the rhizosphere	[6]
Fabaceae	*Glycine max*	FeNPs	Number of root nodules boosted and nitrogen-fixing activity increased	[7]
		GeNPs		
		CoNPs		
	Medicago sativa	TiO_2	Stomata opening, antioxidant system, plant height, and fresh weight increased	[8]
Poaceae	*Oryza sativa*	ZnO NPs	Shoot length, root length, and amylase activity improved under cadmium stress	[9]
	Triticum aestivum	CuO NPs	Plant height, spike length, and grain and straw yield increased, pigments content enhanced, and stress due to cadmium reduced	[10]
		CeO_2 NPs	Plant conditions improved under cadmium toxicity	[11]
		Fe NPs	Plant growth enhanced and pigment content and micronutrients uptake increased under salinity stress	[12]
Rosaceae	*Fragaria ananassa*	CeO_2 NPs	Yield increase, greater pollen grain numbers and pollen tube elongation, and total phenols, vitamin C, and soluble sugar content enhanced	[13]
Solanaceae	*Solanum lycopersicum*	AgNPs	Resistance to abiotic stress enhanced and stress parameters reduced	[14]
		ZnO NPs	Foliar spray increases crop growth and zinc uptake	[15]

Changes in rainfall patterns are of high relevance because more than 80% of the world's crop production is supplied by rainfall. An increase in the frequency of drought events increases the probability of desertification occurrence ([27]. The main consequences of global warming that may affect plant tolerance and defense include heat stress and drought stress [28]. Corn (*Z. mays*), pea-barley (*Lathyrus oleraceus*), and wheat (*T. aestivum*) yield loss are limited under this condition [29]. Considering this, new strategies and sustainable practices must be adopted. For example, chitosan, which is obtained from arthropods or insects, and microbe-based biofertilizers can improve thermal tolerance by increasing plant's immunity, antioxidants, and hormone production and boosting nitrogen fixation, phosphorus dissolution in soil, crop biomass, and the photosynthesis rate; all of these considerations lead to better crop productivity and a greater yield [30,31]. An innovative technology that can help in achieving this goal is represented by nanoparticles. The use of nanoparticles (NPs) could be a solution to alleviating situations and stresses caused by climate change. In fact, NPs are widely used in the agrifood chain, and they can improve nutrient uptake in plants, enhance plant defense against biotic and abiotic stress, and favor shelf-life products avoiding toxin presence [32]. Nanomaterials can be classified into naturally occurring, incidental, bioinspired, and engineered nanomaterials by function of their origin [33]. Indeed, their use has a promising impact on morphological, biochemical, and physiological crop traits [34], they allow a precise herbicide dose application [35], and they guarantee better food conservability [36].

A check of the existing recent (from 2020 to 2024) literature shows that the most cited reviews dealing with the topic of using nanomaterials in agriculture are particularly specific to the agrifood sector [37] (263 citations), nanopriming [38] (52 citations), titanium- and zinc-based nanomaterials under (a)biotic stresses [39] (30 citations), waste-derived nanobiochar [40] (20 citations), soil microbial communities [41] (15 citations), and mitigation of heavy metal toxicity as nano-enabled agrochemicals [42] (8 citations)

This review aims to assess and summarize the benefits and negative effects of the use of synthetic nanoparticles (nano-fertilizers, nano-pesticides, nano-herbicides, and nano-emulsions) for reducing the influence of climate changes on agricultural chemical inputs, for the control of crop pests and pathogens, and for food health and security. Furthermore, the following review reports the three areas where NPs are mainly employed: fertilization, weed management, and food quality.

1.1. Climate Change on Fertilization

Conventional agriculture, over several decades, has brought an increase of input within the agroecosystem, such as heavy machines, fossil fuels, and fertilizers, compromising the natural fertility of the soil. During the last century, synthetic fertilizers have dramatically increased crop production per cultivated area. Both the production and application of fertilizers have a heavy impact on emissions. Fertilizers are widely used in supporting agricultural production, and their high nitrogen and phosphorous content can lead to increased emissions of greenhouse gases (GHGs), including nitrous oxide (N_2O) and ammonia (NH_3), which can contribute to global warming. The use of the most important main fertilizers, containing nitrogen (N), phosphorus (P), and potassium (K), has increased considerably over the last 40 years, especially for nitrogenous fertilizers. Furthermore, while the use of phosphate and potash fertilizers has stabilized, especially in the last 20 years, the use of N fertilizers continues to increase [43]. If conventional agriculture is combined with climate change, the situation is even more critical. Indeed, temperatures are increasing, and precipitations have become irregular and abundant. These phenomena, changing soil moisture and soil aeration, can result in nitrogen leaching (NO_3^-) and volatilization (NH_3), contributing to eutrophication [44]. In parallel to nitrogen, climate change creates problems in phosphorous management, affecting overall crop production. P availability, uptake, and translocation are affected by fluctuations in temperature, pH, drought, and CO_2 [45]. In fact, extremely low or high soil temperatures reduce P uptake and translocation. Furthermore, alkaline soil pH affects P concentration and decreases its uptake rate by plants, while an acidic soil pH reduces the activity of soil microorganisms, the transpiration rate, and the uptake and utilization of P fertilizer. Finally, increased CO_2 concentration reduces the uptake of this macro element from the soil by plants [46]. Regarding the connection between excessive fertilizer use and increased CO_2 emissions, Guo et al. [47] showed that China's excessive carbon dioxide emissions are due to the excessive use of chemical fertilizers in agriculture. Since mineral fertilizer application can bring these problems just listed, new technologies are required. Indeed, instead of using a common fertilizer, it is possible to apply a nano-fertilizer, which is more sustainable, requires fewer quantities, and boosts nutrient use efficiency in crops.

1.2. Climate Change on Agrochemicals

It is important to know that 99% of all synthetic chemicals, including pesticides, are derived from fossil fuels [48]. In addition to the production phase, pesticides can also release greenhouse gas emissions after their application. It has been shown that the application of fumigant pesticides can contribute to a significant increase in nitrous oxide production in the soil [49,50]. However, even if pesticide use is one of the origins of climate change, studies show that the effects of climate change are likely to lead to an increase in the use of synthetic pesticides [51]. This is mainly due to a reduction in the ability of crops to resist abiotic stresses, such as drought conditions, that weaken the crops' natural defenses and change their biology, making them more vulnerable to pests [52,53]. In addition, rising temperatures are likely to stimulate the growth of pest insect populations in some regions, and there will be a change in the geographic regions of some insects and their potential winter survival rate [54,55]. Tonnang et al. [56] predicted that the increase in CO_2 and temperatures will lead to an acceleration in the metabolism and consumption of insect pests, leading to a decrease in crop yields. Furthermore, Thomson et al. [57] predicted that the effects of climate change could cause pests to migrate to new areas where their natural enemies are absent or cause a shift in life cycles, reducing the possibility of natural control. Some studies found that certain climatic changes affect different pests in different ways. For example, Pathak et al. [58] demonstrate that smaller pests, such as aphids, mites, or whiteflies, can be washed away during intense precipitation. Moreover, with the increase in periods of prolonged precipitation, plant fungal and bacterial diseases can become more common [59].

Therefore, climate impacts will have a significant influence on which pests become more prevalent for each specific region, crop, and pest. In addition, rising CO_2 and temperatures are likely to increase the pressure of weeds on cultivated crops. Weeds, having a diverse gene pool and greater adaptive capacity, are more likely to be resilient and better adapted to the effects of climate change than cultivated crops [60]. Increased carbon dioxide levels can probably increase the size and height of weed seeds, increasing their wind dispersal [61]. Moreover, Rodenburg et al. [62,63] demonstrated that changes in rainfall patterns alter weed seed production and dispersal. Anwar et al. [64] suggest that weeds will have a greater ability to compete with crops in many regions, leading to decreased yields. Similarly to pathogens, climate change is also capable of introducing weeds into new regions and changing regional species composition, particularly favoring invasive species [65]. Regarding the durability of pesticides, the expected increase in temperatures will cause greater volatilization of the compounds, reducing their efficacy [66]. Bailey [67] reported that increasing soil temperatures cause shorter durations of herbicides for weed control due to faster degradation. Conversely, low soil moisture has been linked to the slower degradation of herbicides. Therefore, climate change will accelerate the degradation of pesticides and reduce their use for a shorter time, and farmers will have to increase pesticide application rates [51,68]. The introduction of the use of nano-herbicides, with lower and more accurate application, can reduce the use of traditional agrochemicals and improve the effectiveness and efficiency of pest defense.

1.3. Climate Change on Postharvest

Climatic factors, such as temperature, precipitation, and atmospheric CO_2 concentration, influence fungal colonization and mycotoxin production [69]. Therefore, fluctuations in these factors may lead to an increase/decrease in the relative risk of mycotoxin contamination during both field and postharvest cultivation. Global warming not only has an impact on host–pathogen interactions but may also favor the emergence of new diseases and changes in fungal biodiversity/microbiome and influence the geographic distribution of crops, pathogenic fungi, and thus the mycotoxins they produce [70,71]. In addition, the changes and alterations in the phenology of host plants [72] and in the distribution and temporal activities of fungal pathogens [73,74] will have both economic and social implications and costs [75,76]. Climate change not only brings problems during crop cultivation, but there are also impacts on the shelf-life of harvested products.

High temperatures can accelerate ripening, resulting in fruits being less turgid and, consequently, less durable over time. The other most common problems in postharvest are fruit water loss, tissue fragility, and surface browning due to mechanical injuries [77]. Moreover, global warming is causing fungal spores to spread, which threaten fruit conservation and product quality by becoming dangerous to human health. Indeed, a study conducted by Thole et al. [78] demonstrated that temperature increases can reduce fruit shelf-life by three to five days while fungal susceptibility is enhanced by 6% to 16%. Moreover, microorganisms can be a risk also for dried fruits; indeed, fungi such as *Aspergillus* spp. can survive the drying process, remaining dormant for a long period. Dried fruits more affected are apricots, vine fruits, figs, mulberries, and prunes. Mycotoxins that are mostly produced by fungi and found in products are aflatoxins (AFs) and ochratoxin A (OTA). These mycotoxins are a global issue because they are heat-stable; hence, they survive heating processes [79]. Hence, it is fundamental to prevent their creation by keeping low seed moisture content (SMC), guaranteeing both food safety and seed nutritional quality. In fact, an experiment conducted by Granado-Rodríguez et al. [80] showed that when placing quinoa (*Chenopodium quinoa*) seed at an SMC between 5% and 12%, the nutritional status is safeguarded. Spores spreading and high moisture levels can be avoided by using new innovative technologies able to reduce water content in the air, and this solution can be found by taking advantage of nanoparticles.

2. Nanoparticles in Agriculture

Nanotechnologies can represent an alternative to synthetic compounds widely used in agriculture, reducing the environmental impact of traditional applications. It is possible to obtain nanoparticles through different kinds of synthesis methods. The most adopted techniques are physical (fracturing), chemical (ultrasonication), or biological (enzyme activity) [81]. There is also a sustainable method called green synthesis, which requires leaves as source feedstock. It is eco-friendly, less expensive, and non-toxic [82]. Nanoparticles (NPs) can be applied at very low concentrations, minimizing the doses and frequency of treatments. NPs are characterized by having small dimensions (range of 1 to 100 nm), with unique surfaces and properties, allowing them to enter and interact with plant cells and tissues compared to the same material in another form [83] (Figure 2). The main challenges to nanomaterial application in agriculture involve topics that are still little known. For example, it is not clear how some of them are absorbed and transported inside the plant, and even more so, it is still under study how nanoparticles are transmitted from plants to humans [84].

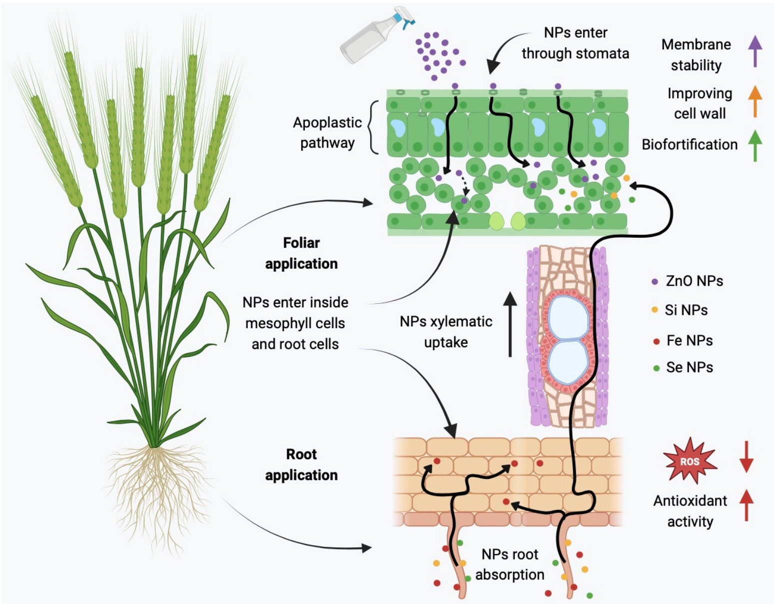

Figure 2. Schematic diagram explaining the different types of interactions between nanoparticles and plant cells and tissues and their main benefits on crops.

Knowledge about nanoparticle translocation mechanisms is limited. A study conducted on wheat and reported by Zhu et al. [85] found out that ZnO NPs can enter the leaf epidermis through stomata. After that, they pass through the apoplastic pathway, and, lastly, a fraction of ZnO NPs dissolves in the apoplast, releasing Zn cations, while the remaining fraction is absorbed by mesophyll cells. Hence, this study demonstrates that stomata play a pivotal role in NPs' mechanism of action. Nanoparticles can be applied also as a root application; in fact, Iannone et al. [86] stated that Fe_3O_4 nanoparticles are absorbed by roots and translocated thanks to the apoplastic pathway in root cells. These NPs are not subjected to aerial part uptake, but they contribute to enhancing antioxidant enzyme activities and improving root defense.

Other nanoparticles, such as silica ones, follow the sap flow using the simplastic and apoplastic pathways, and, finally, they reach the stem and leaves [87]. In addition, trace elements such as selenium, in the form of NPs, are able to be absorbed by the roots and transported to the aerial part, leading to biofortification [88]. The development of nanoparticles with specific functions can be a possible solution to problems related to the development of crops and the reduction in the use of fertilizers and pesticides. Vijayakumar et al. [89] collected the various applications of nanoparticles in agriculture, focusing mainly on their function in stimulating and improving crop growth. In particular, they investigated how applying NPs in the form of nano-fertilizers (NFs) and nano-pesticides (NPs) makes the uptake of nutrients or chemical compounds of pesticides more effective by increasing the production and protection of plants against diseases. It is important to know that the effectiveness and responses of the plant to the presence of nanoparticles depend on their size and concentration. Furthermore, each crop reacts to the presence of NPs in the environment by expressing changes in the morphological and physiological but also biochemical characteristics [90]. Moreover, recent studies have demonstrated that nanoparticles can also influence seed germination, promoting seedling development by increasing cell division and enhancing certain biochemical pathways [91,92]. According to the available published literature, the two main methods of NP application in crops are foliar treatment and root exposure [93]. In the case of in vitro applications, nanoparticles can be added to culture media [94]. In addition to being a solution in nutritional and pathogenic control aspects in field crops, nanoparticles are a useful technology in the conversion of waste material to energy in food preservation [95].

Even though nanoparticles have many beneficial applications, it is necessary to assess all the risks that their use in the agricultural sector may cause in terms of the environment and the food chain [83,96]. According to Bhattacharjee et al. [97], negative impacts on crops are generally found when the application of NPs is elevated and unresponsible. However, the available literature on this topic shows that using reasonable concentrations of nanoparticles, which are appropriate to the treated crop, helps to avoid harmful effects and achieve the desired benefits [98–101].

2.1. Nanoparticles as Nano-Fertilizers and Biofortificators

The two main problems with traditional phosphorus- and nitrogen-based fertilizers are their low nutrient uptake efficiency and rapid transformation into chemical forms that cannot be used by plants, leading to negative impacts on the soil and the environment, with an increase in hazardous greenhouse gas emissions and eutrophication [102]. Therefore, the use of innovative technologies such as nano-fertilizers, which gradually release nutrients, helps to significantly reduce nutrient loss while ensuring environmental safety and plays a significant role in maintaining soil fertility and improving crop yields [103,104].

Nanoparticles can be used as fertilizers by foliar application, leading to yield and growth improvement. Furthermore, their distribution can improve plants' performance in facing pests and diseases. Indeed, nano-fertilizers (1) provide plants with appropriate nutrients via foliar and soil applications, (2) increase the chlorophyll content in leaves (enhancing photosynthesis) [105], (3) are cost-effective resources, (4) have high efficiency [106], (5) play a key role in pollution prevention [107], and (6) enhance the tolerance of plants to cope with environmental stresses (salinity and drought) [108]. The main ones contain zinc (Zn), calcium (Ca), manganese (Mn), silica (Si), and iron (Fe) oxide [109,110] (Figure 3).

Furthermore, with regard to the supply of macronutrients such as nitrogen, phosphorus, and potassium, which is more problematic from an environmental point of view, the use of NFs based on these elements reduces the risks associated with traditional mineral fertilization and allows other important plant growth objectives to be pursued [111,112] (Table 2).

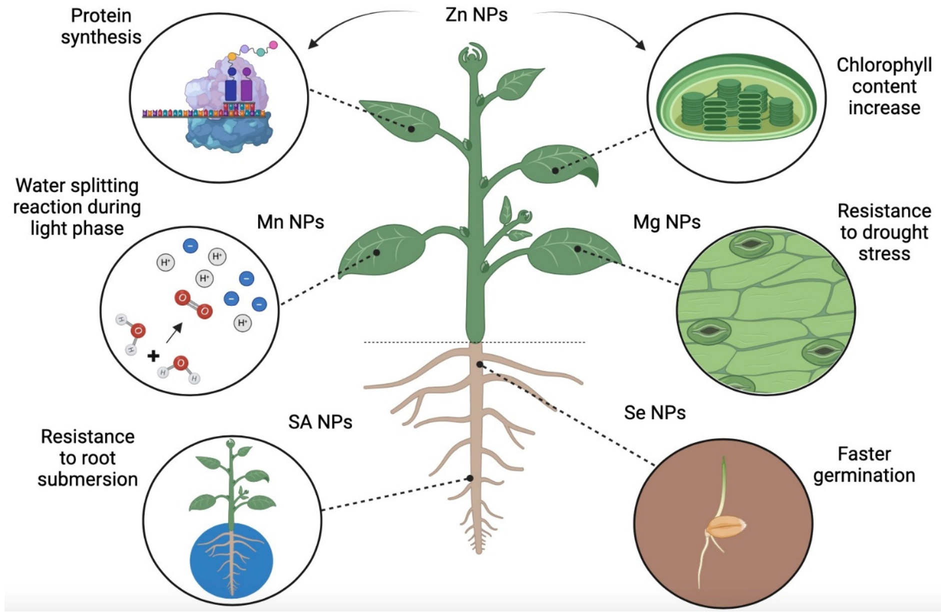

Figure 3. Schematic diagram of the different benefits of applying nanoparticles composed of different chemical elements to plants.

Indeed, nitrogen nano-fertilizers not only improve the efficiency of use but also reduce the leaching of this element, thus reducing eutrophication and greenhouse gas emissions [130]. A study conducted by Sharaf-Eldin et al. [131] stated that nano-nitrogen applied in combination with drip irrigation (75%) and foliar application (25%) can lead to a better yield if compared to common nitrogen fertilizers. On the other hand, zinc is also very important in the soil–plant–human system. Inside plants, it has a pivotal role in metabolism: it is part of many enzymes, it is involved in protein and RNA synthesis, and it contributes to membrane stability by scavenging reactive oxygen species (ROS). Zn deficiency can lead to delayed maturity, reduced grain yield, and even high mortality, and this is most likely to happen in crop species such as rice, wheat, and tomato, which have low tolerance to Zn deficiency [132]. Manganese is another pivotal microelement for plant development; it is involved in ROS detoxification, has a main role in the first part of photosynthesis (water-splitting reaction in PSII), and contributes to lignin biosynthesis. Mn deficiency can lead to a decrease in biomass, in chlorophyll content, and in the number of chloroplasts; it also causes high susceptibility to plant diseases [133].

Silica is mainly found as silicic acid $Si(OH)_4$, and this element can help plants in improving cell wall resistance thanks to silica bodies called phytoliths. It creates a physical barrier against pathogens, and it enhances enzyme activity and endurance against biotic and abiotic stress [134]. Si deficiency may reduce photosynthetic activity and grain yield [135]. Nano-fertilizers can be a promising approach in agriculture because of their effect on plants: their application can reduce the nutrient requirements of plants and nutrient loss by leaching; moreover, they can increase low crop productivity and alleviate abiotic stress [136]. Climate change can induce different kinds of stress inside the plant; for example, drought stress can cause growth slowdown, photosynthesis mitigation, and stomatal closure [137]. This stress can be reduced by using microelements or amino acids such as zinc and proline, which can be sprayed on plants. For example, Hanif et al. [138] demonstrated that proline-coated ZnO (ZnOP) NPs can increase shoot length and dry weight and reduce flavonoid and phenolic concentrations.

Table 2. Main nanoparticles used as nano-herbicides and nano-pesticide and their effects on plants and insects.

Category	Nanoparticle	Plant/Insect Involved	Function	Refs.
Nano-herbicide	ZMCPA	*Phaseolus vulgaris*	Vascular growth destruction and chlorophyll content reduction	[113]
		Sphagneticola trilobata	Leaf, pigment content, and plant height inhibition	[114]
	Ag NP	*Bidens pilosa*	Seed germination and seedling growth arrest	[115]
	Chitosan NP + (clodinofop propargyl or fenoxaprop-P-ethyl)	*Avena fatua* and *Phalaris minor*	Reduced density per m^2 and, consequently, cash crop yield increase	[116]
	Chitosan NP + (mesosulfuron methyl + florasulam + MCPA isooctyl)	*P. minor*, *A. fatua*, *Chenopodium album*, *Lathyrus aphaca*, *Angalis arvensis* and *Melilotus indica*	100% mortality	[117]
	Atrazine NP	*Brassica juncea*	Elevated herbicidal effect	[118]
	2,4-D+biochar nanoformulation	*Brassica* sp. weed	Growth and biomass reduction	[119]
	Encapsulated essential oil	*Rhaphanus sativus*	Germination, root length, and shoot length reduction	[120]
	SiO_2 NP	*Amaranthus retroflexus* and *Taraxacum officinale*		[121]
Nano-pesticide	ZnO NP	*Puto barberi*	Phytophage cuticle dehydration and mortality increase	[122]
		Nezara viridula	Reduced attachment to surfaces by mechanism inhibition	[123]
		Spodoptera litura	100% mortality	[124]
	Si NP	Herbivore insects	NP accumulation and digestion inhibition	[125]
	Fe NP	*Helicoverpa armigera* and *S. litura*	Antifeeding effect	[126]
	Ag NP	Insect larvae	Cell membrane instability	[127]
	Chitosan nanocomplex with siRNA	*S. frugiperda*	Chitin synthesis inhibition	[128]
	Nanochitin with Omethoate, Imidacloprid, and Acetamiprid	*Rhopalosiphum padi*	Mortality increase	[9]
	Pyrethrum extract NP	*Apis mellifera*	Low concentrations (1 ng μL^{-1}) do not affect behavior and health	[129]

Zinc-oxide nanoparticles (ZnO-NP) also lead to a good response in uptaking nutrients. Application on seeds can enhance phosphorus uptake and chlorophyll and pigment content, while if applied through foliar spray to maize (*Z. mays*) plants, it can enhance growth even by 11% [41]. Hence, nano-fertilizers also bring biofortification to crop physiology. A study conducted by Palacio-Márquez et al. [139] showed that Zn can also be applied as zinc nitrate complexed with chitosan, which can favor biomass accumulation and production, photosynthetic activity, and total chlorophyll, amino acid, and carotenoid increase; conversely, ZnO can accelerate plant maturation anticipating the harvest in green bean (*Phaseolus vulgaris*).

Also, magnesium (Mg) can be used as a nanomaterial able to mitigate drought stress, and it can be applied as MgO and $MgCO_3$. According to Silva et al. [140], this nanoparticle treatment can lead to chlorophyll *a*, *b* and carotenoid accumulation in lettuce (*Lactuca sativa*). Another important compound that can prevent abiotic stress is salicylic acid (SA). In fact, due to climate change and abundant precipitation, plants can live in anoxia periods. An experiment reported by Errázuriz-Montanares et al. [141] found that root submersion stress in cherries (*Fragaria ananassa*) can be alleviated by applying SA on the leaf, and this application at preharvest and postharvest can result in improving stomatal conductance and transpiration, implying a better leaf gas exchange response and, consequently, an improved physiological situation. Also, selenium (Se) can be used as a nanopriming agent. Setty et al. [142] reported that soaking rice (*Oryza sativa*) seeds with different concentrations of Se nanoparticles (SeNPs) can lead to faster germination and imbibition. SeNPs can allow a quick water flow inside the cell; moreover, these nanomaterials enhance alpha-amylase activity, bringing higher starch consumption and faster seedling growth.

Cerium oxide (CeO_2) is a rare earth element. It shows interesting results in the most cultivated crops, and it has been demonstrated that its application at low concentrations has a positive effect on many crop species. The following studies come into disagreement since in the first case, cerium caused phytotoxicity, while in the second one, there were many improvements. A study conducted in the Mediterranean region showed unexpected results: in a seed trial, CeO_2 reduced total root length, while in a barley (*Hordeum vulgare*) life cycle study, it negatively affected potassium and sulfur uptake [143]. On the other hand, another experiment performed by Rico et al. [144] on wheat (*T. aestivum*) reported that CeO_2 can improve plant growth, shoot biomass, and grain yield. These studies indicate that, sometimes, the effectiveness of an application may depend on the species and nanomaterial nature.

Research that concerns wheat resistance to salt stress tested many nanoparticles based on zinc, aluminum, copper, and iron. One study showed that each element gives an effect on a specific parameter: Fe_3O_4 accelerated germination parameters, the shoot length was increased by ZnONPs, and CuO increased chlorophyll *a*, *b* and carotenoid content [145]. However, the application of incorrect quantities of nano-fertilizers may cause negative effects due to nutrient toxicity [146]. Before using this technology on a large scale, it is important to know the effects of nano-fertilizer degradation on crop growth and soil fertility. For these reasons, it is important to know how the structure (size, solubility, and type of material) and composition of NFs interact with climatic conditions (drought phenomena, heat waves, and flooding) and soil parameters (ionic strength, organic matter content, pH, electrical conductivity, and phosphate concentration) [147,148]. Read et al. [149] showed that when the soil pH is acidic, ZnO NPs change into ions very rapidly, whereas when the pH is alkaline, the NPs tend to be bounded. Shah et al. [150] demonstrated that ZnO and CuO did not play a significant role in the shifting of the microbial community structure. Instead, silver nanoparticles were the cause of the changes in the microbial community. Although Asadishad et al. [151] found that nanoparticles of CuO, ZnO, and Ag are toxic to soil microbes at concentrations between 1 and 100 mg/kg, nanoparticles of titanium oxide (TiO) are not toxic at these levels. One of the most important aspects to consider is the dose of nano-fertilizer in each application. Indeed, improper doses, whether higher or lower, can cause toxic effects on crop health and production [152] and soil [153]. For example, Chai et al. [154] demonstrated that the application of nano-fertilizers based on ZnO, TiO_2, and CeO_2 can cause the inhibition of and reduction in enzyme activity and abundance of functional bacteria. Furthermore, Morales-Díaz et al. [155] argued that the use of nano-fertilizers based on ZnO, TiO_2, and Fe_3O_4 causes a reduction in microbial biomass in the soil, reducing soil enzyme activities. Similarly, Jośko et al. [156] showed that high application doses can negatively affect the activity of the dehydrogenase enzyme. Therefore, these studies, by highlighting the critical issues in the application of nano-fertilizers, demonstrate the need to clarify the interaction between the application of NFs and the factors involved in the improvement of crop growth and productivity. Finally, it is important to carry out further studies to identify the optimal dose to eliminate the harmful effects that NFs can cause on crops and soil.

2.2. Nanoparticles as a New Strategy in Weed and Pest Management

In modern agriculture, the use of agrochemicals is typically aimed at protecting cultivated plants from pests (pathogens, harmful insects, and parasitic weeds) that impair their production and productivity. The European Green Deal asks to reduce pesticide application by 50%, including herbicides [157]; hence, innovative and sustainable products must be studied. It is well known that herbicide overuse can lead to greenhouse gas emissions and biodiversity loss and favor herbicide-resistant species [158].

A new strategy in weed management, during this climate change era, can be represented by nano-herbicides (NHs). These new nanotechnologies are seen as a promising finding between agrochemicals. Nano-herbicides can guarantee low toxicological implications and just a few residues in the soil and environment, and since they have a specific target, low quantities are required, and costs are reduced [35] (Table 2). Mainly, NHs are applied as a foliar spray. They enter the stomata, and then they use the xylem or the apoplast transportation to reach the membrane [159]. They are built with eco-friendly materials, and, consequently, their toxic accumulation is avoided in crops and soil [160]. This new kind of application has also been tested on seeds. A herbicide called 2-methyl-4-chlorophenoxyacetic acid (MCPA) has been encapsulated in a zinc-layered hydroxide (ZLH), creating a zinc-layered hydroxide-2-methyl-4-chlorophenoxyacetic acid (ZMCPA). This engineered herbicide reduced the chlorophyll of the plant, destroying vascular growth and causing cells to burst [113].

MCPA is persistent in the soil just for a month, but it may still be able to damage nontarget organisms. Hence, using ZLH as a nanocarrier can be a sustainable solution to avoid environmental risk. This nano-formulation has also been tested on weeds by lowering pigment content, the number of leaves, and plant height [114]. Also, element-based nano-formulations can result in having an herbicidal effect. In fact, silver nanoparticles (Ag NPs) can be obtained from botanical biosynthesis. Ag NPs can alter *Bidens pilosa* development by arresting seed germination and seedling growth [115]. An experiment conducted by Khan et al. [116] tested two nano-herbicides wrapped by a chitosan matrix, and the study reported that both clodinofop propargyl and fenoxaprop-P-ethyl can be used to reduce *Avena fatua* and *Phalaris minor* growth in a wheat (*T. aestivum*) field. The same author filled chitosan nanoparticles with mesosulfuron methyl + florasulam + MCPA isooctyl, and this nano-herbicide applied at the recommended dose of normal herbicides showed a mortality of 100%. Consequently, at this treatment plant height, chlorophyll content and fresh and dry biomass were not reported [117]. It is important to study this new nanotechnology to assess its potential phytotoxicity. Indeed, research conducted by Abigail [119] used biochar (BC) as a nano-sorbent, creating a nano-formulation with 2,4-dichlorophenoxyacetic acid (2,4-D). This experiment showed that 2,4-D+BC affected weed growth without reducing maize (*Z. mays*) biomass. NPs can be useful also for insect reduction. Due to climate change, these pests are spreading, and they are causing damage to crop production. Furthermore, because of the temperature increase, new habitats are becoming available for allochthonous species, putting crop production at risk [161]. Hence, new strategies, such as nanoparticles, must be studied to face these problems brought about by climate change. Indeed, some preliminary studies conducted in vitro on mealybug (*Puto barberi*), which causes damage to plant roots, have already reported that a ZnO-NPs 300 ppm suspension can bring a 55% mortality. In fact, this type of NP has the ability to dehydrate the phytophage cuticle [122].

ZnO-NPs have also been shown to be promising by Rebora et al. [123]. In fact, zinc nanoparticles have the property of binding to attachment structures (Pulvilli, hairy pads, and claws). In this way, NPs inhibit the attachment mechanism to surfaces in Hemiptera insects such as *Nezara viridula*. Another inhibition technique is represented by silicon NPs. In fact, if insects feed on plants treated with SiNPs, this can result in nanoparticle accumulation inside the gastrointestinal tract, and digestion is avoided [125]. Furthermore, iron nanoparticles (FeNPs) obtained from *Trigonella foenum-graecum* extract can increase *Helicoverpa armigera* and *Spodoptera litura* mortality by having an antifeedant effect [126]. *S. litura* larvae have also shown a 100% mortality at ZnO-NPs application, as these NPs make insects unable to develop a physiological defense [124]. A larvicidal effect has also been reported by Shahid et al. [127]. Silver nanoparticles, AgNPs, are able to penetrate through the cuticle, and then they bind themselves with phosphorous and sulfur proteins, causing cell membrane instability.

Hence, these new nanotechnologies are important because they can (i) reduce synthetic pesticide application and consequently mitigate climate change and (ii) they represent an eco-friendly and cost-effective solution for the environment and for farmers [127]. Due to the long-term release of the active ingredient being one of the main purposes for which nano-formulates are developed, it is important to understand their capacity and degradation rate in the environment. The incorrect use of this nanotechnology can affect living organisms negatively, as they are characterized by their very small size and can accumulate in the food chain and be transported by air, causing damage to human and animal health. Indeed, the inappropriate use of nanoparticles can lead to their bioaccumulation in living organisms, even beneficial insects. Rapid growth in the use of nanoparticles in agriculture can create serious toxic potential risks in living organisms [162], which can be prolonged over time [163]. The excessive application of nanomaterials can lead to their accumulation in the ecosystem (water bodies, soil biota, and living organisms), bringing biodiversity damage [164]. Moreover, it has been reported that nanomaterials cause toxicity in a dose-dependent manner [165]. In addition, nano-herbicides can block the flow in the vascular bundle of plants and reduce pollination. Moreover, they have negative impacts on soil microbial communities and some algae [166]. Despite the reduction in the amount of active ingredients used in nano-formulations, Kah et al. [167], through a study, suggested that these applications could also be toxic to nontarget organisms. However, nano-pesticides, like conventional ones, can also be subject to leaching following rainfall events, causing negative environmental effects [168]. Despite this, Gao et al. [169] reported that nano-formulations cause, unlike conventional pesticides, less environmental pollution due to lower application rates and reduced losses. Therefore, investigation is required on the ability of these nanoparticles to produce toxic effects through their bioaccumulation in the soil and their translocation in different environmental sectors up to the food chain [170,171].

2.3. Nanoparticles, Pre- and Postharvest Preservation, Food Quality, and Packaging

Climate change exposes food factories to many challenges, such as food production and its conservation. Due to global warming, numerous pathogens, such as fungi, proliferate and produce toxins that threaten food production. Nanoparticles called nano-emulsions (NEs) can be used in the food industry to deal with food quality and packaging but also as carriers able to incorporate healthy compounds inside the finished product. Moreover, NEs improve texture, nutrient quality, taste, and resistance against unwanted microorganisms [36]. Nano-emulsions can be used in food packaging with coatings and films, extending the shelf-life of products. Furthermore, they can be used singularly as edible envelopes capable of bringing flavorings, colorings, useful enzymes, and antioxidants [172].

Crop storage and processing can be altered because of mycotoxins, one of which, produced by *Aspergillus* spp., is called aflatoxin: this compound is carcinogenic and teratogenic, and it is dangerous for human and animal health. Moreover, it reduces cereal quality production. It has been reported by Loi et al. [173] that it is possible to use nanomaterials called magnetic nanoparticles, which are able, thanks to their metal nature, to bind mycotoxins and spoil them. Climate change challenges are represented also by fruit and vegetable postharvest durability over time; hence, new conservation strategies must be found. In this way, it would be possible to reduce postharvest losses. A study reported by Hussain et al. [174] stated that it is impossible to improve fruits' and vegetables' shelf-life through a new process called a desiccant air-conditioning (DAC) system. This new kind of storage can solve problems brought about by climate change, such as high transpiration and respiration postharvest. DAC consists of two phases. The first one, which is called dehumidification, uses nanoparticles as a silica gel that can absorb air moisture. The second phase, regeneration, restores starting conditions. Mariadoss et al. [175] showed that the synthesis, through aqueous extraction of *Punica granatum* peel, of zinc oxide nanoparticles can be effective as antibacterial agents against standard strains of *Staphylococcus aureus* and *Escherichia coli* [176]. Additionally, nanoparticle application can bring alleviation from toxicity present in the soil, which could interfere with plant growth and production, both in quantity and quality, creating a threat to consumers.

An example of phytotoxicity in the soil is brought by a heavy metal, cadmium (Cd), the excessive uptake and accumulation of which are becoming very common in plant tissues, the environment, and crop fields. The combined foliar application of chitosan and putrescine as nanoparticles (CTS-Put NPs) can increase chlorophyll and carotenoid content in grapevine (*Vitis vinifera*). They improve chlorophyll fluorescence parameters and reduce Cd content in leaves and roots [177]. Another toxic element is arsenic (As), which is naturally found in the soil. Firstly, it reduces root growth-damaging cell membranes, lowering nitrogen and sulfur assimilation and decreasing plant transpiration and biomass. In plants such as soybean (*G. max*), As exposure reduces the number of nitrogen-fixing root nodules, but this stress can be neutralized thanks to magnesium oxide nanoparticles (MgO-NPs), which can improve plant height, dry weight, the net photosynthesis rate, and stomatal conductance in stressed plants [178,179]. Another element that can interfere with plant growth is aluminum (Al) Its high presence can stop element uptake (phosphorus, calcium, potassium, and magnesium) by restricting roots. Carbon loaded with tungsten oxide has proven to remove Al^{3+} from soil [180]. Despite the many advantages of this nanotechnology, however, it is important to understand the importance of the stability of the nano-emulsion formulation used. These are influenced by parameters such as temperature and pH, which can affect the solubilization of the applied substances [181]. In addition, characteristics such as input availability, kinetics, acceptability, and polarity are also relevant aspects to be taken into consideration when developing NEs. Being that surfactants/surfactants are present in the formulation of NEs, in addition to nanoparticles, it is important to understand their fate in the environment and in the food chain [182].

In a review, Loira et al. [183] recommended delaying the use of these new technologies in the food industry because these issues are not fully understood. Smolkova et al. [184] discussed the effects that bioaccumulation of nanoparticles can cause at the epigenetic level. Gaillet and Rouanet [185] suggested that Ag NPs can cause inflammation in the intestinal tract. Negative effects have also been observed in NPs based on CuO [186] and on ZnO [187]. However, the point remains that the toxicity of a metallic nanomaterial may vary depending on the state of oxidation, binders, solubility, and morphology, as well as environmental and health conditions [188]. Moreover, is important to realize that toxicity is dependent on the dose, exposure time, surface coating characteristic, and especially the size of the nanoparticle [189]. Although the use of nanotechnology at the food level does not yet have legislation [190], the EFSA Scientific Committee [191], published a paper assessing the risks and making suggestions for the use of nano-emulsions in the food sector.

3. A Bibliometric Analysis of Nanoparticles Used in Agriculture to Cope with Climate Change

3.1. Preface

Climate change negatively affects the agricultural system, including global warming [192], changes in rainfall patterns [193], and the spread of weeds and pests [55,194]. In the challenge of climate change mitigation, the use of nanotechnology is key to addressing today's increasingly important issues for environmental sustainability. In particular, the use of nanoparticles appears to be of recent interest in solving various problems related to conventional agriculture and climate change. Using nanoparticles as containers, they can be used in the agricultural sector as a means of transporting fertilizers, agrochemicals, and postharvest food durability products. Among other advantages, it is useful to say that through foliar or root applications, nanoparticles deliver nutrients more effectively and efficiently while reducing the amount of fertilizer. This is also important in the application of pathogen and weed control treatments, where there is less input from agrochemicals and better control. A bibliometric analysis was conducted to review the nanoparticle-related studies in the worldwide literature from 2014 to 2024 to provide information on specific aspects over time, to identify current research trends, to highlight the importance, and to understand the research progress and future studies regarding these nanotechnologies.

3.2. Methodology

The Scopus database was used in this study to collect the set of published articles on the topic of nanoparticle research. The search query (Figure 4) was selected in the Scopus database as TITLE-ABS-KEY ("nanoparticles" AND "climate change" AND "agriculture").

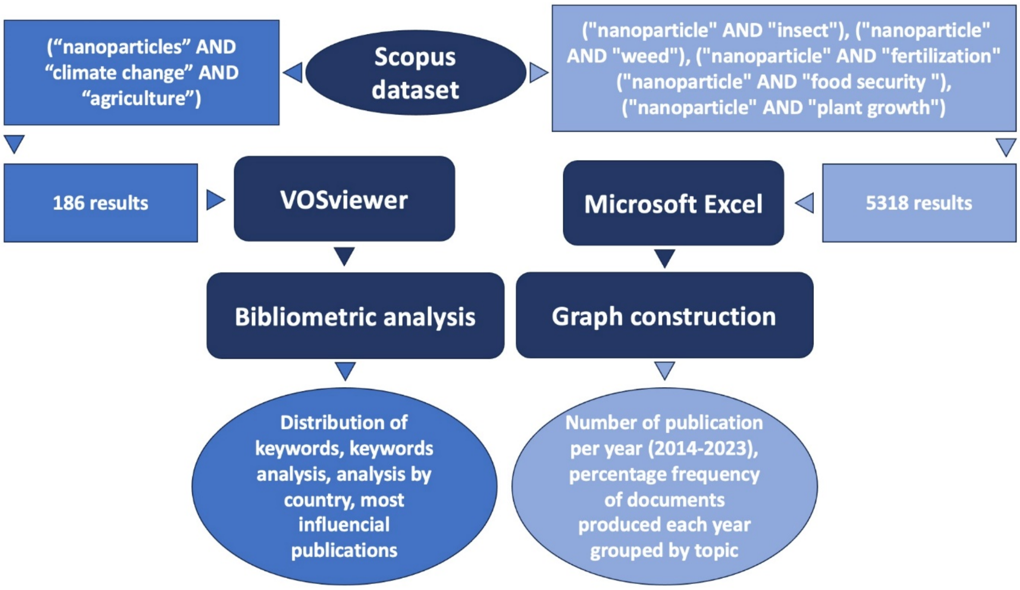

Figure 4. Search steps using Scopus database and analysis software.

The search was carried out in March 2024 and resulted in 186 articles. The table of documents was exported in CSV format, and the database file was then used as the input data for bibliographic analysis. The search retrieved 186 documents, which included studies conducted in 16 different countries from 2014 to 2024. VOS viewer version 1.6.19 (0) [195] was utilized to construct and visualize the different networks used in this work. In addition, an analysis was conducted to observe how the nanoparticle (NP) theme is related to other important topics, such as the presence of insects that, due to climate change, are reproducing very fast, causing enormous damage; the proliferation of weeds that reduce yields; fertilization, which can be improved thanks to NPs; food security, which is becoming increasingly important; and plant growth, which can be helped thanks to micro- and macronutrients in the form of nanoforms. Queries used were TITLE-ABS-KEY ("nanoparticle" AND "insect"), TITLE-ABS-KEY ("nanoparticle" AND "weed"), TITLE-ABS-KEY ("nanoparticle" AND "fertilization"), TITLE-ABS-KEY ("nanoparticle" AND "food security"), and TITLE-ABS-KEY ("nanoparticle" AND "plant growth"). Later, for each query, a bar chart was produced, reporting for each related nanoparticle topic the number of documents published over the years. All documents found in the queries (5318 results) were used to create stacked bar charts that report which are the topics related to NPs mainly studied in the last ten years and their percentage frequency of study.

3.3. Results and Discussion

3.3.1. The Geographical Distribution of Publications and Top Contributing Organizations

Figure 5 represents the geographical distribution of publications, including the keyword "nanoparticles" in Scopus from 2014 to 2024, showing the top countries in the field of NP research in terms of the number of publications. India (76 articles) has the highest publication number in the field, followed by China (22 articles), Egypt (19 articles), the United States (18 articles), Pakistan (17 articles), and Italy (11 articles).

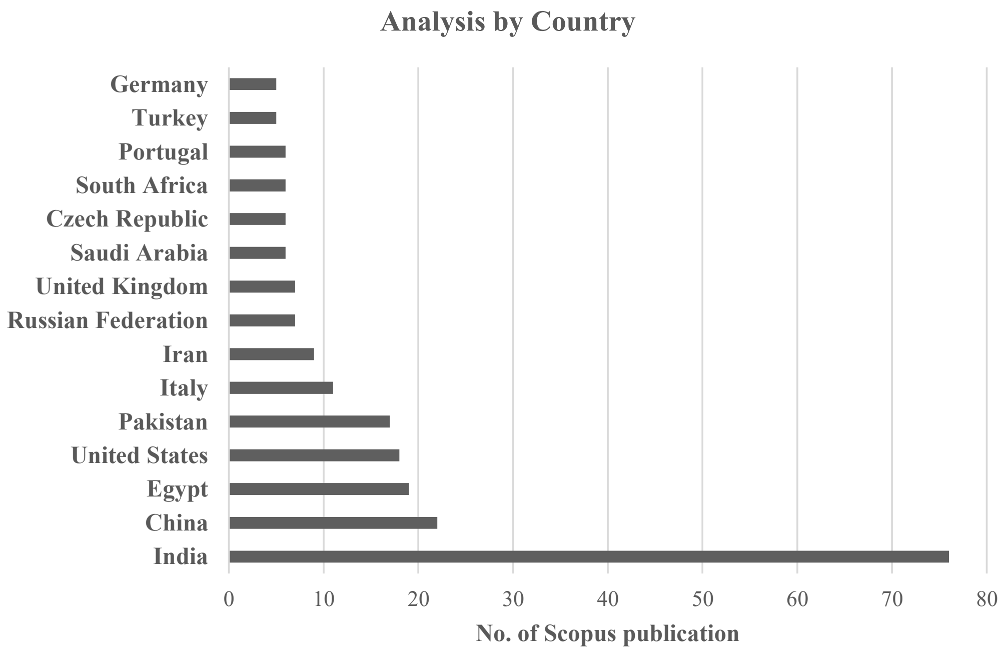

Figure 5. Classification of papers and reviews (no. 186) published from 2014 to 2024 present in the database of Scopus by country (data access until 19 March 2024).

Other countries such as Iran, the Russian Federation, the United Kingdom, and Saudi Arabia have almost fewer than 10 articles. The study of nanotechnology has the potential to open up new horizons in research and development in various disciplines, ranging from healthcare/medicine to electronics, agriculture, water treatment, food processing, and cosmetics. Many of these applications are very relevant to developing countries like India. The development of nanotechnology in this country was conceived and pursued primarily on the premise that this new and emerging technology has the potential to help the population address social challenges such as drinking water supply, healthcare, etc. Therefore, since the early 2000s, the Indian government has played a pioneering role in fostering and promoting nanotechnology research and development in the country [196]. This is the reason why India is the most prolific country in terms of publications on this topic. Instead, the fact that China is one of the most productive countries in nanoparticle research may be because this nation's scientific interest in the development of nanoscience and nanotechnology has been high since its initial stage [197].

3.3.2. Most Influential Publication

Tang et al. [198] is the most cited paper with 338 publications. This article explains how cellulose nanocrystals are important in carbon dioxide production for mitigating climate change. The other studies are mainly related to plant stress [37,199], toxicity [180], and NP uptake [200,201]. Hence, this allows us to confirm what is reported in Figure 6: publications about NPs and insects are decreasing, while food security research is not in the ranking (Table 3) because it is still growing.

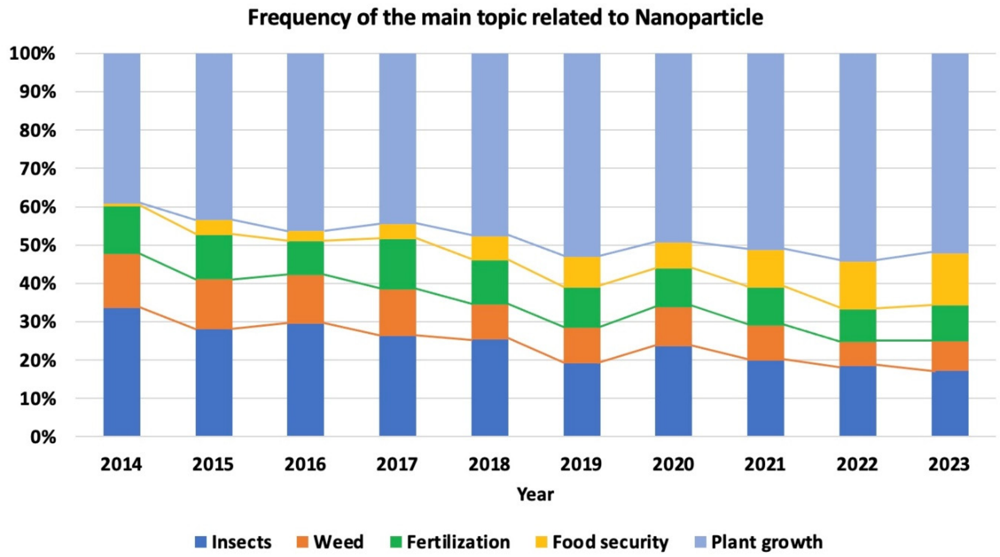

Figure 6. Stacked bar chart shows how the research related to NPs has changed over the years, moving toward certain topics rather than others.

Table 3. Top 10 highly cited papers presenting reviews and articles regarding nanoparticles with a view to focusing on agriculture and climate change.

No.	Authors	Title	Source Title	Cited by
1	[198]	Functionalization of cellulose nanocrystals for advanced applications	Journal of Colloid and Interface Science	338
2	[37]	Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector	Journal of Nanobiotechnology	211
3	[202]	Plant survival under drought stress: Implications, adaptive responses, and integrated rhizosphere management strategy for stress mitigation	Microbiological Research	160
4	[203]	Integrated approach of agri-nanotechnology: Challenges and future trends	Frontiers in Plant Science	160
5	[92]	Nanotechnology potential in seed priming for sustainable agriculture	Nanomaterials	151
6	[200]	Critical review: Role of inorganic nanoparticle properties on their foliar uptake and in planta translocation	Environmental Science and Technology	145
7	[199]	Nanoparticles potentially mediate salt stress tolerance in plants	Plant Physiology and Biochemistry	128
8	[204]	Guiding the design space for nanotechnology to advance sustainable crop production	Nature Nanotechnology	117
9	[180]	Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review	Science of the Total Environment	116
10	[201]	Selenium nanoparticles for stress-resilient fish and livestock	Nanoscale Research Letters	116

3.3.3. Keyword Analysis

According to Scopus, there are almost 896,000 documents found if "nanoparticle" is used as a keyword, but when adding the words "climate change" and "agriculture" in the query, only 186 publications result (only 0.2% of the total). This means that nanoparticles are still seldom studied and applied in the world of agriculture despite the many benefits they can provide. The co-occurrence map, using the keywords of the 186 articles in the Scopus database, revealed the most occurrence index keywords (Figure 7).

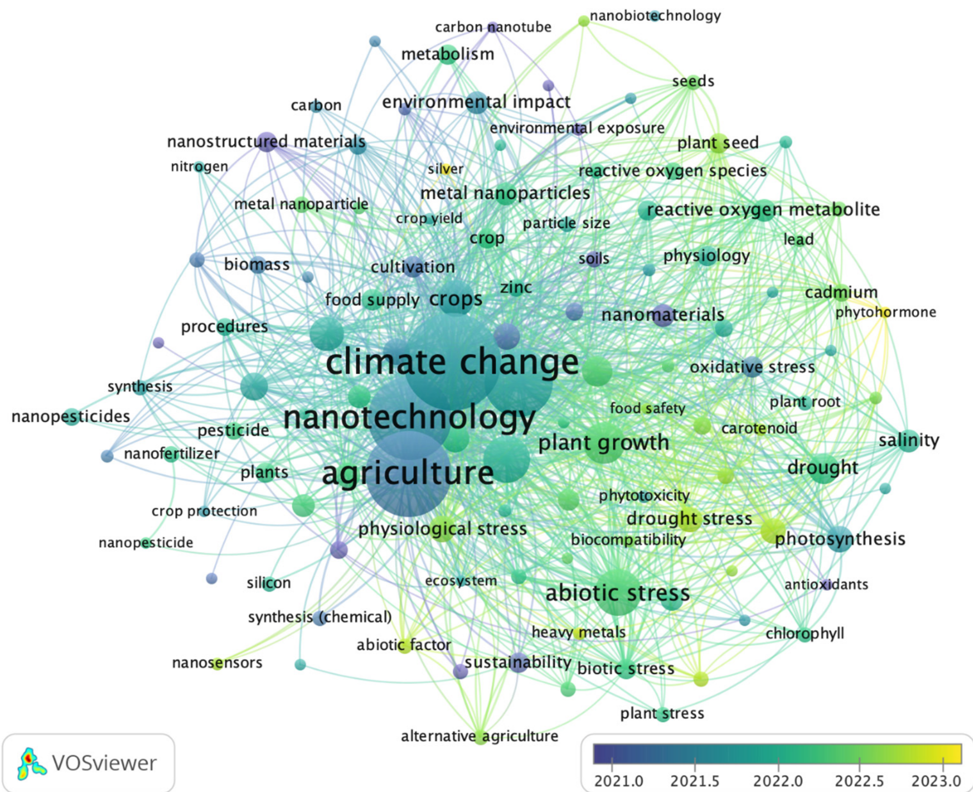

Figure 7. Visualization of keyword co-occurrence network of publications including the keywords "nanoparticles", "climate change", and "agriculture" in Scopus from 2014 to 2024.

The size of the circles is determined by the relevance of the words within the network. The bigger the circles, the bigger the occurrence of the keyword within the addressed data set. It can be seen that together with nanotechnology, agriculture, and climate change, many words are closely associated, the most important of which are plant growth, abiotic stress, and crops. All keywords were ranked from least to most recent. From Figure 7, it can be seen that the keywords 'agriculture', 'climate change', and 'nanotechnology' are present in the articles published between 2021 and 2022. The topics associated with these three keywords are correlated by having a color tending toward yellow, so they are recent in the literature. 'Agriculture', 'climate change', and 'nanotechnology' keywords are very close in the bibliometric analysis, which means that they are strongly related to each other.

Moreover, they are surrounded by big circles, suggesting that they are very important topics. From this bibliometric analysis, it is possible to deduce that 'agriculture', 'climate change', and 'nanotechnology' keywords are linked to plant topics (growth, physiology, biotic and abiotic stress, fertilization, and drought), environmental topics (heavy metals, ecosystem, salinity, lead, and cadmium), and food topics (food safety, yield, and food supply). According to Figure 8, it is possible to notice that nanoparticle-related topics have, over the past 10 years, been increasingly the object of study, as all of the bar charts show a positive trend. The topic that has experienced the greatest surge is food safety. In fact, in 2014, only 1 document had been produced, while in 2023, 160 documents were published (Figure 8D). Furthermore, thanks to Figure 6, it can be seen that over time, the number of insect studies related to NPs has decreased (just over 15 percent), while research related to plant growth (more than 50 percent) and food security (about 10 percent) has increased. With regard to food safety, the fact that studies related to it have increased would indicate an increase in hazards in food preservation.

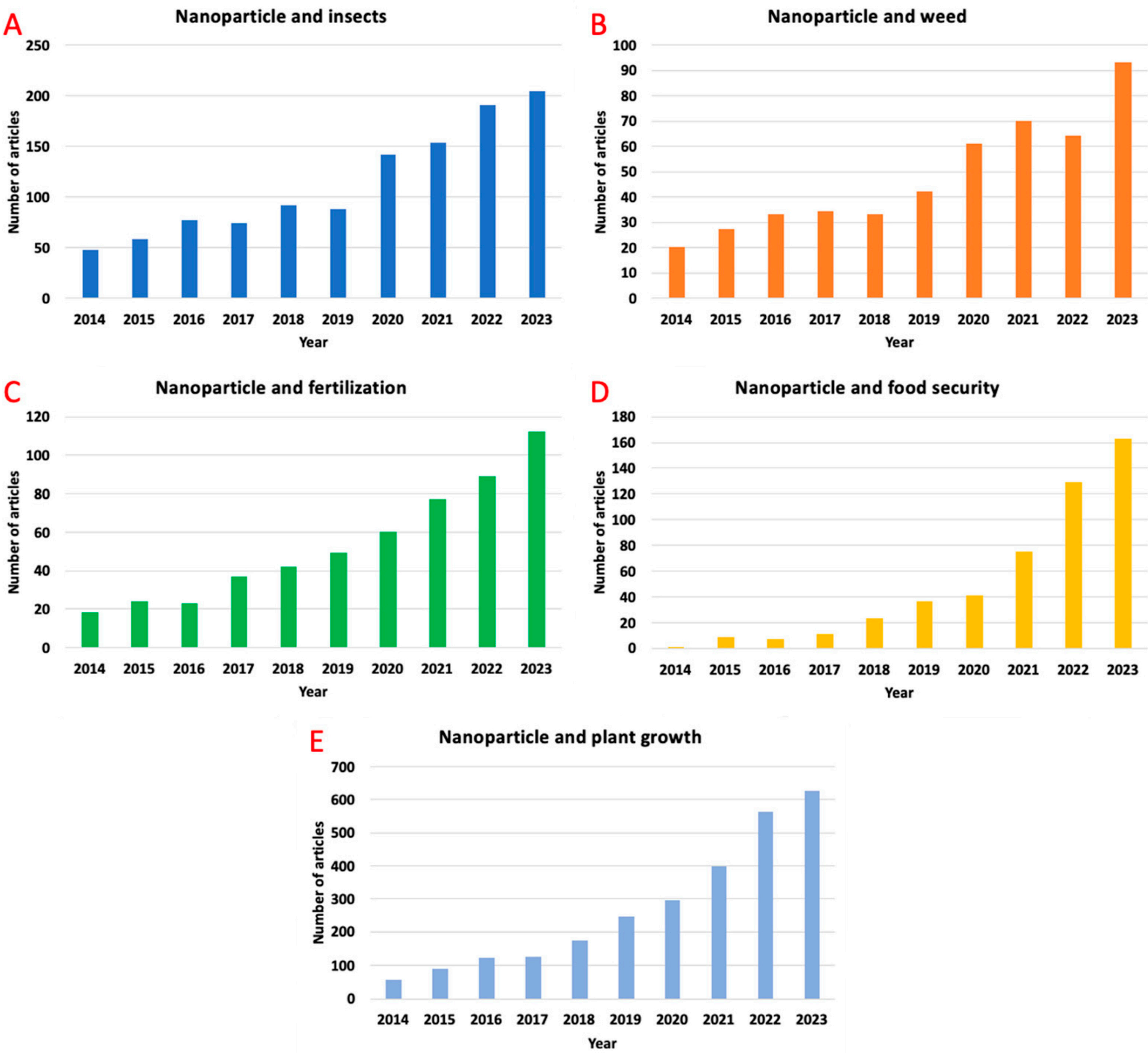

Figure 8. The bar charts report the number of documents published over the years according to main topics related to nanoparticles (insect—(**A**), weed—(**B**), fertilization—(**C**), food security—(**D**), and plant growth—(**E**)).

4. Final Remarks and Future Challenges

Rising temperatures and changing rainfall patterns are some of the main effects of climate change, as these two main factors can bring other several problems such as stressed plants, weed spreading, and spore proliferation during food storage. Moreover, the uncontrolled and excessive use of pesticides and fertilizers in modern agriculture is aggravating this situation. Due to global warming, plants are subjected to new stress; hence, nutrient uptake, plant defense, and biofortification are favored by NPs. All of the studies reported show how microelements are essential for plant development. Through the adoption of nanotechnologies such as nanoparticles, the mitigation of the effects of climate change can be achieved. In fact, through the insertion of macronutrients (N, P, and K) and microelements (Fe, Zn, and Mg) inside the nanoparticle, it is possible to bring nourishment to the plant in a slow and continuous way, avoiding environmental problems, such as the eutrophication of water.

Moreover, the amount of nano-fertilizer required is low, which means a reduction in costs for farmers. Conversely, by inserting agrochemical compounds inside the nanoparticles for the control of insects and weeds, it is possible to carry out a more accurate and effective fight using very small doses of chemical compounds. In this way, it is possible to significantly reduce the release of pollutants in the agroecosystem. Furthermore, nanoparticles are important in increasing the shelf-life of agricultural products in the trade chain and reducing their perishability. In fact, the bibliometric analysis and the search of the main topics related to NPs show that research in food safety is increasing exponentially. Therefore, nanoparticles adapted for agricultural needs, such as nano-fertilizers, nano-pesticides, and nano-emulsions, can be a solution to reducing the negative impacts of the agricultural sector on climate change. It is therefore necessary to continue studying the benefits and possible problems of these technologies, improving their functioning, and developing other nanotechnological solutions.

In conclusion, there is no best nanomaterial that can be used for all conditions, but the objective is always to improve the efficiency of the nanomaterial applied by taking into consideration factors related to the nanomaterial itself (category, method of application, and dose), the environment where it is applied (to mitigate biotic/abiotic stress), and the objective of the application.

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