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Review

Emerging Frontiers in Nanotechnology for Precision Agriculture: Advancements, Hurdles and Prospects

Anurag Yadav [1,*], Kusum Yadav [2], Rumana Ahmad [3] and Kamel A. Abd-Elsalam [4]

1 Department of Microbiology, College of Basic Science and Humanities, Sardarkrushinagar Dantiwada Agricultural University, Sardarkrushinagar, District Banaskantha, Gujarat 385506, India
2 Department of Biochemistry, University of Lucknow, Lucknow 226007, India
3 Department of Biochemistry, Era University, Lucknow 226003, India
4 Plant Pathology Research Institute, Agricultural Research Center, Giza 12619, Egypt
* Correspondence: anuragyadav123@sdau.edu.in

Abstract: This review article provides an extensive overview of the emerging frontiers of nanotechnology in precision agriculture, highlighting recent advancements, hurdles, and prospects. The benefits of nanotechnology in this field include the development of advanced nanomaterials for enhanced seed germination and micronutrient supply, along with the alleviation of biotic and abiotic stress. Further, nanotechnology-based fertilizers and pesticides can be delivered in lower dosages, which reduces environmental impacts and human health hazards. Another significant advantage lies in introducing cutting-edge nanodiagnostic systems and nanobiosensors that monitor soil quality parameters, plant diseases, and stress, all of which are critical for precision agriculture. Additionally, this technology has demonstrated potential in reducing agro-waste, synthesizing high-value products, and using methods and devices for tagging, monitoring, and tracking agroproducts. Alongside these developments, cloud computing and smartphone-based biosensors have emerged as crucial data collection and analysis tools. Finally, this review delves into the economic, legal, social, and risk implications of nanotechnology in agriculture, which must be thoroughly examined for the technology's widespread adoption.

Keywords: nanotechnology; precision agriculture; nanobiosensors; nanofertilizers; agro-waste reduction

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1. Introduction

The farming community regularly focuses on minimizing agricultural input costs to maximize profit. To reach this objective, farmers optimize the crop yield using fertilizers, herbicides, and fungicides [1]. The current scenario has led to a significant tradeoff between higher crop productivity and soil and groundwater health due to the excessive use of agrochemicals. The world has witnessed an unprecedented increase in farmland areas due to population growth over the past few decades [2]. As the farmland area increases, so does the use of agrochemicals, leading to enhanced soil, water, and air pollution. The rising environmental pollution rate is compelling the scientific community to develop advanced farming technologies and methods to save the planet. Given the global awareness of this issue, the farming community is under increasing pressure to reduce agrochemical usage by adopting alternative farming practices [3]. Precision agriculture is a suitable alternative for farmers, which reduces agrochemicals and provides site-specific and targeted remedies according to the crop to increase economic returns. Precision agricultural practices aim to enhance crop productivity while reduce using fertilizers, pesticides, and herbicides. Nanotechnology-based precision agriculture employs computers, global positioning systems (GPS), and remote sensing devices to measure crop-based and environmental parameters [4]. Nanomaterials (NM), the nanotechnology component, possess unique characteristics that distinguish them from their parent materials. These materials typically exhibit significantly higher surface areas, cation exchangeability, and ion absorption capabilities when compared to their bulk counterparts [5,6]. Precision agricultural techniques minimize the use of pesticides, fertilizers, and herbicides by utilizing effective monitoring aids and procedures. This technology involves the controlled release of agrochemicals on targets for efficient nutrient utilization and disease resistance. Such products include nanoscale carriers, nanosensors, nanofertilizers (NFs), nanoherbicides, and nanopesticides. By adopting nanotechnology-based precision agricultural practices, the farming community can reduce agrochemicals while maintaining high crop productivity, protecting soil and water health, and contributing to a cleaner environment. The review explores nanotechnology's potential applications in precision agriculture while examining the advantages of nanoparticles (NPs) in agriculture, particularly fertilizer delivery. It discusses nanotechnology-based nanodiagnostic systems and nanobiosensors for monitoring soil quality, nutrients, humidity, plant diseases, and stress. The review also examines various techniques related to precision agriculture, such as GPS, yield monitoring, and remote sensing. The review identifies issues and concerns related to precision agriculture in the Indian context. Additionally, the review explores the potential of tagging, monitoring, and tracking agroproducts using nanotechnology methods and devices, smartphone-based biosensors in precision agriculture, precision agriculture, and cloud computing, and the economic, legal, social, and risk implications of nanotechnology in agribusiness. The review also aims to emphasize the potential for nanotechnology to enhance the productivity and efficiency of agricultural techniques while addressing issues of food security, environmental sustainability, and socioeconomic development. The implications of this review could be significant in terms of the future development of nanotechnology in precision agriculture. Using NPs to improve seed germination, plant growth, micronutrient supply, and stress alleviation can significantly increase crop yields and reduce production costs. The delivery of bio- and chemical fertilizers through nanotechnology can further reduce the dosage of fertilizers and pesticides required, which can help mitigate environmental concerns related to the excessive use of these chemicals. Employing nanobiosensors in diagnostics and precision agriculture aid in tracking various soil quality parameters, concentrations of pesticides or herbicides, amounts of nutrients, degrees of humidity, and plant stress and disease. This sophisticated technology can guide farmers in making knowledgeable decisions about using fertilizers, pesticides, and other inputs. Using smartphone-based biosensors and cloud computing can further facilitate real-time monitoring and decision-making. The review also highlights the potential of nanotechnology for reducing agro-waste and synthesizing high-value products, which can significantly impact sustainability and profitability in agriculture. However, the review also points out concerns about implementing precision agriculture in developing countries, such as data management, ownership, privacy, infrastructure, and socio-economic conditions. Addressing these concerns will be crucial for successfully adopting precision agriculture in India and other developing countries.

2. Synergies of Precision Agriculture and Nanotechnology for Sustainable Crop Growth

Precision agriculture (PA) is an approach to farming that utilizes advanced technologies that leverage cutting-edge technology and data-driven decision-making tools to increase crop yields and optimize resource management (Figure 1). It aims to reduce waste, improve efficiency, and increase profitability. On the other hand, nanotechnology is a field of science and technology that deals with materials and structures on a nanoscale level. Nanotechnology can revolutionize the field of precision agriculture, offering farmers and growers new tools and techniques for enhancing crop production. Although nanotechnology and precision agriculture differ in their focus, they share some interrelated aspects. Nanotechnology can create new materials and tools that can strengthen precision agriculture practices. For example, nanosensors can monitor soil and plant health in real-time, allowing for more accurate and efficient crop management. NPs can also improve the delivery of nutrients and pesticides to plants, reducing waste and increasing effectiveness.

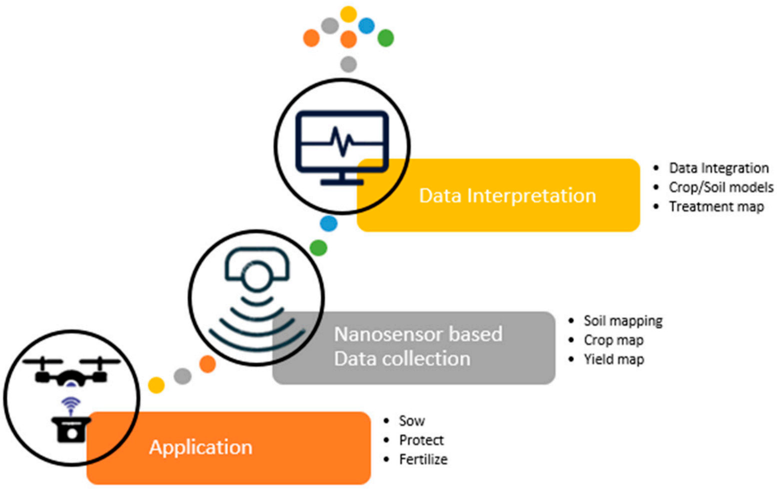

Figure 1. Representation of nanosensor-based precision agriculture in action.

On the other hand, PA uses advanced technologies and data-driven decision-making tools to optimize crop yields and resource management. The intersection between these two fields lies in applying nanotechnology to enhance PA practices. PA enables farmers to assess and manage field variability using remote sensing and global information system (GIS) based technologies, which can create prescription maps for variable-rate application of inputs, thereby reducing input costs and environmental impacts [7]. PA allows farmers to do the right thing in the right place at the right time by monitoring crop growth, soil moisture, and other environmental factors using real-time sensor data, leading to improved crop yields and reduced waste [8]. It can significantly increase productivity by optimizing resource use and reducing input costs. In addition, PA facilitates better decision-making in agricultural management by consolidating farmers' experience and insights, enhancing control over time. Additionally, it can help farmers maximize the use of minimum land units by using precision planting and management techniques, thereby reducing the need for additional land. In addition, PA facilitates better decision-making in agricultural management and accumulates farmers' knowledge for better control over time.

In precision agriculture, nanotechnology improves crop yields, reduces waste, and minimizes environmental impacts. The nanoscale modification of materials enables unique characteristics and benefits over conventional farming procedures. Using nanosensors for real-time soil and plant health monitoring may help farmers get a better handle on their crops by giving them more accurate data on where and how much water and fertilizer they need. NPs can be used as delivery vehicles for pesticides and fertilizers, reducing their environmental impact [9]. Nanotechnology can also enhance the properties of agricultural materials, such as plant fibers and seeds, making them more resistant to pests and weathering [9]. However, research is needed to understand potential risks and environmental impacts on soil, water, and human health. Nanotechnology in PA can revolutionize crop growth by improving efficiency and sustainability while reducing waste and environmental impacts. The following points elucidate the integrative potential of nanotechnology in conjunction with precision agriculture.

2.1. Improved Nutrient Utilization

The global demand for increased food production continues to rise, necessitating innovative approaches in agriculture that could enhance crop productivity while minimizing environmental impacts. Applying nano-scale materials, particularly NFs, has demonstrated the ability to improve crop nutrient utilization efficiency while reducing the adverse effects of over-fertilization [10]. Nanotechnology can significantly enhance the efficiency of nutrient delivery to crops by encapsulating nutrients in NPs, allowing for targeted and controlled release [11]. NFs are typically synthesized by encapsulating nutrients within nano-scale carriers, such as metal oxide NPs or polymeric nanocapsules, which allow for the controlled release of nutrients, minimizing nutrient losses due to leaching or volatilization [12]. Studies have shown that the application of NFs can result in significant improvements in nutrient uptake efficiency in plants. For example, wheat grain yield was increased by 51% in a study when ZnO NP-coated urea was applied compared to the control group [13]. Similarly, zinc oxide NPs were reported to increase the zinc uptake efficiency in rice plants, resulting in higher grain zinc content and improved plant growth [14]. In addition to enhancing nutrient utilization efficiency, nanotechnology-based PA can also contribute to developing more targeted and sustainable nutrient management practices. For instance, nano-sensors have been designed to monitor soil nutrient levels, allowing farmers to optimize nutrient application rates and timings based on real-time data [15]. This approach not only improves nutrient utilization in crops but also reduces the environmental impacts of agriculture, such as eutrophication and greenhouse gas emissions [4].

2.2. Enhanced Pest Control

Nanotechnology-based PA offers a promising alternative to traditional pest control methods, addressing challenges such as efficacy, environmental impact, and safety [16]. It enables the development of materials and devices at the nanoscale level, allowing for targeted and efficient delivery of pesticides and other pest control agents. Nanopesticides, for instance, can improve the solubility and stability of active ingredients, allowing for targeted delivery and controlled release, thus reducing the amount of pesticide needed and minimizing non-target effects and environmental contamination [17]. Integrating nanopesticides with PA enhances pest control by optimizing pesticide application based on real-time monitoring of pest populations and environmental conditions [18]. For example, NPs can be engineered to target specific pests or plant structures, ensuring efficient pesticide delivery and the development of new types of pesticides that are effective at lower doses [19]. Nanotechnology-based PA also reduces environmental impact, as NPs allow for more targeted delivery of pesticides, minimizing the amount of pesticide released into the environment. Examples include the use of NPs to deliver RNA interference (RNAi) molecules for highly targeted and effective pest control [19] and the use of nanocapsules for targeted pesticide delivery, improving efficacy and reducing environmental release [20].

Furthermore, nanotechnology-based PA improves safety for farmers and consumers by minimizing direct pesticide exposure by developing less toxic pesticides. Using nanobiosensors to detect pests and diseases early reduces the need for large-scale pesticide applications and improves safety for farmers and consumers [21].

In addition to the benefits mentioned above, nanotechnology-based PA promotes sustainable agriculture practices and contributes to increased crop yields. The targeted delivery of pesticides and pest control agents using NPs reduces the chemicals applied and helps prevent the development of pesticide-resistant pests, which in turn ensures the long-term effectiveness of pest control measures and contributes to overall agricultural sustainability.

Nanotechnology-based PA also facilitates the development of innovative pest-control methods. For instance, researchers use nano-formulations by combining multiple pest control agents, such as biopesticides and chemical pesticides, to provide a synergistic effect for improved pest control [22]. This approach can lead to better pest management while reducing the reliance on chemical pesticides. Moreover, nanotechnology can aid in monitoring and managing pest populations through advanced sensing and diagnostic techniques. Integrating nanobiosensors and remote sensing technologies can provide real-time data on pest populations, crop health, and environmental conditions, enabling farmers to make informed decisions regarding the optimal timing and location of pesticide application [21].

2.3. Advanced Environmental Monitoring

Nanotechnology stands as a transformative force in advanced environmental monitoring within precision agriculture. Its primary application lies in employing nanosensors capable of continually monitoring soil, water, and plant parameters. Such nanosensor-based monitoring provides indispensable data to optimize agricultural management practices [23]. Notably, these nanosensors can detect changes in soil parameters, including moisture, nutrient levels, and pH. A prime instance of this utility is the deployment of zinc oxide nanoparticles as nanosensors, which are particularly adept at detecting phosphorus levels in the soil [24]. The precise detection abilities of these nanosensors permit an optimal application of water and fertilizers, consequently preventing over- or under-fertilization and fostering healthier crop growth. When integrated with precision agricultural technologies, these nanosensors significantly enhance decision-making accuracy and efficiency [25], boosting crop productivity and sustainability. Additionally, such a synergistic integration of nanosensors and precision agricultural technologies reduces nutrient runoff and conserves water.

2.4. Variable Rate Technology (VRT)

Variable rate technology (VRT) is a critical component of PA that allows for the precise delivery of inputs, such as fertilizers, herbicides, and pesticides, based on variations in soil type and crop health. Farmers can reduce waste, optimize crop growth, and maximize yields by applying inputs only where needed. NPs can further enhance the effectiveness of VRT by serving as carriers for these inputs. VRT-based NPs can be used as carriers for fertilizers, herbicides, and pesticides, allowing for precise delivery of these inputs to specific field areas, which is particularly useful in situations where there are variations in soil type or crop health, as NPs can be targeted to areas where inputs are needed most [26]. In addition, VRT can adapt the appropriate seeding rate for each field type [27]. The use of nanocarriers in VRT has several advantages. First, using nanocarriers allows for the precise delivery of inputs, reducing waste and minimizing the risk of environmental damage. Second, nanocarriers can protect inputs from degradation, increasing their effectiveness and reducing the need for reapplication. Nanocarriers can help optimize crop growth by delivering inputs only where needed (Figure 2).

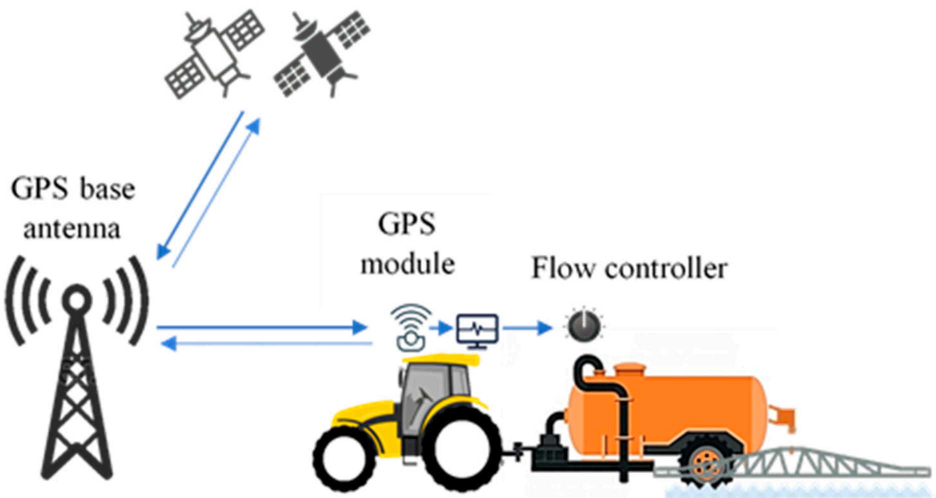

Figure 2. Representation of a digital map-based variable rate fertilizer and pesticide application system.

2.5. Automated Machinery

Automated machinery is critical to PA, allowing for more efficient and accurate farm operations. Integrating nanosensors with automated machinery can further enhance the precision and efficiency of agricultural operations. Nanosensors are tiny sensors designed to detect specific compounds or environmental conditions. Nanosensors can improve accuracy and efficiency in various ways in automated machinery. For example, nanosensors can monitor soil moisture levels, allowing automated irrigation systems to adjust water delivery rates in real-time. By providing accurate and timely feedback on soil moisture levels, nanosensors can help prevent overwatering or underwatering, which can negatively impact crop growth.

In addition to soil moisture, nanosensors can detect various environmental conditions, such as temperature, humidity, and nutrient levels [24]. This information can then be used by automated machinery to adjust operations in real-time, optimizing crop growth and minimizing waste. The integration of nanosensors with automated machinery has several advantages. First, it allows for more precise and efficient operations, reducing waste and optimizing crop growth. Second, it reduces the need for human intervention, freeing up labor resources for other tasks. Also, it can provide farmers with real-time feedback on environmental conditions, allowing them to make informed decisions about crop management.

2.6. Data Analytics

Data analytics is critical in PA, allowing farmers to make informed decisions about planting, fertilizing, and harvesting crops. NPs can improve the accuracy and precision of data collection, leading to more reliable analytics. For instance, farmers may employ NPs to better understand the state of their crops by testing for the presence of certain chemicals or diseases in soil or water samples.

Nanoparticles (NPs) can serve as sensors to identify contaminants in water and soil. For example, gold NPs can be used to detect the presence of heavy metals in soil samples. In a study, researchers developed a sensor based on rGO/AuNPs/tetraphenyl porphyrin nanoconjugate-based electrochemical sensors that could detect cadmium ions in food and soil samples with high sensitivity and selectivity [28]. Similarly, magnetic NPs can be used to detect the presence of bacteria or viruses in water samples and successfully remove them [29]. In a study, researchers developed a magnetic nanoparticle-based biosensor that could detect *Escherichia coli* in water samples with high sensitivity and specificity [30].

2.7. Nanomaterials Use in Plant Growth

The application of nanomaterials in agriculture has gained increasing attention due to their potential to enhance plant growth and productivity. Among the different types of nanomaterials, nanocarbon, nanocellulose, and nanolignocellulose have been reported to have promising effects on plant growth. Nanocarbons, including carbon nanotubes (CNTs), graphene, and fullerenes, have shown great potential for improving plant growth. For example, a study showed that applying CNTs to tomato plants significantly increased growth [31]. Similarly, graphene oxide (GO) application can enhance plant growth. A study found that applying GO to wheat seedlings increased plant height, root length, and dry weight [32]. Nanocellulose, including cellulose nanofibrils (CNFs) and cellulose nanocrystals (CNCs), has been shown to stimulate plant development [33,34]. CNFs have been shown to enhance root growth and increase the absorption of water and nutrients by plants. In addition, cellulose anionic hydrogel-based nanofibers benefit sesame seed germination [35].

Nanolignocellulose, a combination of lignin and cellulose NPs, has also been reported to affect plant growth positively. Nanolignocellulose is known to enhance the absorption of water and nutrients by plants and promote the development of root hairs. A study found cellulose nanofibre application can change soybean leaf surface hydrophobicity, conferring resistance against *Phakopsora pachyrhizi*, an obligate biotrophic fungal pathogen [36].

2.8. Summary of Synergies between Precision Agriculture and Nanotechnology

The synergies between precision agriculture (PA) and nanotechnology can revolutionize sustainable crop growth by improving efficiency and sustainability. Key sectors such as nutrient supply, pest management, environmental monitoring, variable rate technology, automated machinery, and data analytics can benefit from integrating modern technologies and data-driven decision-making tools with nanoscale materials and devices. The integration can lead to better nutrient utilization, targeted and efficient pesticide delivery, real-time monitoring of soil and plant parameters, and precise input delivery, ultimately optimizing crop yields, reducing waste, and minimizing environmental impacts.

3. Advantages of Nanotechnology in the Agriculture Systems

3.1. Improved Seed Germination and Plant Growth

The need for increased crop production necessitates a higher seed germination rate or percentage. However, environmental contamination and several abiotic stressors deleteriously affect seed germination and seedling vitality [37]. Low seed viability is a significant issue in arid and semiarid regions because abiotic variables are known to delay seed germination. In addition, laboratory-tested seeds with higher germination rates frequently fail field tests. [38]. Such problems require a deliberate strategy for resolution. There are various methods to improve a low seed germination rate. The technique of priming such seeds with NPs has recently attracted the scientific community's interest. In recent years, the influence of NM on seed germination has been scrutinized to increase the germination rate. In a study, TiO_2 NPs enhanced spinach germination, dry weight, and chlorophyll content [39]. Biopriming with plant growth promoting rhizobacteria (PGPR) improves seed germination and crop development through several mechanisms. Priming using metal oxide NPs with PGPR for "bionanoseed" has been tried, but it requires additional research to identify a reliable approach for enhancing germination [40].

Contrarily, several NPs have been shown to inhibit seed germination due to toxicity effects [41–43]. Recent developments have assessed the toxicity of NPs in vitro, in vivo, and at the biomolecular level [44,45]. The toxicity of NP to seeds depends on NP size, seed size, and the capacity of the seed surface to absorb NP. Consequently, research is necessary to identify plant-specific NPs and their application rates [40]. Table 1 shows the effect of some NPs on plant seed germination.

Table 1. Effect of nanoparticles on seed germination.

Nanoparticle	Plant	Germination % Improvement	Reference
Chitosan and zinc oxide	rice	20.00	[46]
Ferric oxide	wheat	41.60	[47]
Nano phosphorus	mung, black gram and cowpea	20.83, 38.1 and 20.83	[48]
Silicon dioxide	wheat	16.78	[49]
Silicon dioxide	soybean, maize, wheat and lupine	11.14, 4.65, 9.61 and 2.31	[50]
Silver	wheat	20.0	[51]
Silver	fenugreek	5.30	[52]
Titanium dioxide	radish	20.00	[53]
Titanium dioxide	wheat	16.30	[54]
Titanium dioxide	perfumed cherry	65.00	[55]
Zinc oxide	cowpea	3.18	[56]
Zinc oxide	canola	7.23	[57]
Zinc oxide	wheat	13.80	[58]

3.2. Improved Micronutrient Supply

Plants require micronutrients in minute amounts for growth. Contrarily, most of the agricultural land is deficient in many micronutrients. The crops grown in such regions suffer from yield loss due to micronutrient deficiency. The consumption of micronutrient-deficient foods affects human health, thus causing anemia, growth reduction, reduced reproduction capabilities, and decreased mental and physical ability [59]. The Food and Drug Administration (FDA, Silver Spring, MD, USA) of the USA approves healthy and nutritious food for a healthy and long life [60]. Such soils, therefore, need fortification in the form of fertilizers. The fraction of micronutrients added as fertilizer reaches the plant. Excess micronutrients get washed off with rain into local water bodies. In addition, micronutrients present in the soil gradually chelate and become unavailable to the plant. Of the total micronutrient-based fertilizer applied to the soil, less than 5% is used by plants due to the supply-demand gap between micronutrient fertilizer and plants [61].

Using NPs loaded with micronutrients could strategically solve the problem of micronutrient wastage through targeted delivery to the nutrient demand sites. Due to their smaller dimensions and higher surface area, certain NPs can act as nutrient carriers. Micronutrients attached to NPs are released slowly into the soil to ensure constant availability. The NF has a smaller size and a high specific surface, increasing solubility, diffusion, and availability of nutrients in plants. Through the slow release of micronutrients from fertilizer granules, NF can control nutrient release from fertilizers, thus improving plant nutrient use efficiency, which restricts nutrients from getting fixed in the soil and thus preventing their release into the environment [62]. Micronutrients enclosed inside NP microcapsules are quickly absorbed and translocated within the plant, effectively nourishing it. NFs are highly water-soluble structures, remain stable for longer durations, hold higher effectiveness after field application, can be controlled for timely release, are highly specific, less eco-toxic, and possess simple delivery and disposal modes [63]. NPs deliver nutrients to target sites in plant root systems. Nutrients are loaded on NPs by adsorption, and further attachment of NPs is mediated with ligands, followed by encapsulation in a nanoparticulate polymeric shell and entrapment in the polymer [63].

3.3. Biotic and Abiotic Plant Stress Alleviation

Biotic stress refers to stress caused by living organisms, such as pests and diseases, while non-living factors like drought, salinity, and heavy metal toxicity cause abiotic stress [64]. Several NPs are reported to alleviate biotic and abiotic stress in plants (Table 2) [65]. NPs have been shown to improve plant growth, yield, and quality by enhancing photosynthesis, nitrogen absorption, and stress tolerance [66]. NPs can also help manage biotic stress by acting as natural pesticides and herbicides or inducing plant systemic resistance [67–69]. Similarly, NPs can alleviate abiotic stress by reducing oxidative damage and enhancing plant antioxidant defense systems. Different types of NPs, such as metal-based, metal oxide-based, carbon-based, and polymer-based, have been investigated for their potential in plant stress alleviation. For example, soil application of silver NPs enhanced plant growth and reduced biotic stress due to *Aspergillus* in rice by inhibiting the growth of pathogens [70]. Similarly, zinc oxide NPs based sprays alleviated abiotic stress in tomato plants by reducing oxidative plant damage [71].

Table 2. Alleviation of various types of abiotic and biotic plant stress through nanoparticle application.

Stress Type	Stressor (Biotic/Abiotic)	Nanoparticle	Plant	Effect on Plant	Reference
Abiotic	salinity	titanium dioxide	broad bean	protects photosynthetic machinery, enhances salinity tolerance	[72]
	drought	silica	wheat	improves water retention and nutrient uptake	[73]
	salinity	zinc oxide	rice	enhances salt tolerance by maintaining ion balance	[74]

Table 2. *Cont.*

Stress Type	Stressor (Biotic/Abiotic)	Nanoparticle	Plant	Effect on Plant	Reference
	heavy metal contamination	iron	wheat	chelates heavy metals, reducing toxicity	[75]
	UV radiation	cerium oxide	arabidopsis	protects chlorophyll from UV degradation	[76]
	cold stress	graphene oxide	pearl millet	protects the cellular structure, enhances cold tolerance	[77]
	nitrogen deficiency	carbon nanotubes	birdsfoot trefoil	facilitates nitrogen fixation	[78]
	phosphorus deficiency	hydroxyapatite	wheat	enhances phosphorus availability	[79]
	oxygen deficiency	silver	muscadine	combat hypoxia by boosting antioxidant activity	[80]
Biotic	viral infections	gold	barley	antiviral properties reduce disease incidence	[81]
	fungal infections	silver	barley, peas, oilseed rape, radish, cucumber, lettuce	antifungal properties reduce infection rates	[82]
	bacterial infections	copper	tea plant	antibacterial properties reduce disease occurrence	[83]
	pest infestation	chitosan	turmeric plant	insecticidal properties decrease pest damage	[84]
	herbivory	silica	soybean	reduces plant palatability to herbivores	[85]

Irrigation is a crucial agricultural input that requires a substantial quantity of land and water. Due to the uncontrolled use of pesticides, fertilizers, and other agrochemicals on farms, the local water bodies, underground water, rivers, and canals become increasingly polluted [86]. Recent advances in agricultural technology aid in preventing soil and water contamination on agricultural property. In addition, the solutions are accessible in the form of impervious materials capable of retaining water and releasing it slowly as needed. Together with wireless nanosensors, this technique could cut water intake and aid in drought mitigation. In addition, nanotechnology could assist in mitigating multiple types of stress to increase plant yield and promote sustainable agriculture.

3.4. Improved Plant Fertilization in Lower Dosage

Research studies have demonstrated that applying NPs can improve plant growth and productivity. Various types of NPs, such as those prepared by polymerization, emulsification, oxide reduction, and ionic gelation, effectively enhance crop yields [87]. The majority of such types of NPs are comprised of TIO_2 and CNTs. Additionally, NPs of Au, SiO_2, and ZnO help plant growth by boosting their ability to absorb nutrients [88].

NFs have a greater surface area for facilitating various plant metabolic reactions, increasing the photosynthesis rate to yield higher dry matter and crop yield. NF possesses different physical and chemical properties than bulk materials. For example, when applied in nanoform, rock phosphate increases phosphorus availability in the plant since the nanorock phosphate's direct application prevents fixation by soil [89]. The chief reason for the great attention on NF in the agricultural scientific community is its high penetration capacity, smaller size, and higher surface area. This material is unique due to specific properties that set it apart from comparable bulk materials. NF, in particular, is either synthesized from chemical fertilizers or derived from plants using nanotechnology. The specific production method enhances its capacity to improve soil fertility and boost crop productivity. NF can aid PA by improving crop yield and quality with optimum nutrient uptake and reducing fertilizer waste. They can manage nutrient availability that matches crop growth and could be able to provide nutrients throughout the growth period of the plant. NFs can increase soil fertility and are non-toxic and cost-effective as they are required in lesser amounts. Developing nanocomposites could facilitate the requirement of all essential nutrients through an intelligent delivery system.

Further studies on nanonutrient delivery in plant systems are needed to understand the effects on soil bacteria better. In addition, the fate of delivered NPs is required to be studied for optimized dose concentrations for PA. The NF holds a high surface area due to its small particle size, facilitating high reactivity with other compounds. Additionally, such NPs readily solubilize in water and other solvents. The particle size of less than 100 nm facilitates seamless penetration of NPs on plant-applied surfaces, such as leaves. The NP-encapsulated fertilizers enhance the availability of nutrients to crop plants. For example, NF developed from zeolite releases nutrients slowly, preventing nutrient loss due to denitrification, volatilization, and leaching in soil, mainly nitrate and ammonia [90]. The effect of NF on seed germination and plant growth is well documented [91–94]. NPs could penetrate directly inside seeds through the seed coat and alter the state of seed dormancy. The seed germination effect of NPs could be negative or positive, depending on the NP property [95]. For example, ZnO NPs impart toxicity to the root growth of garlic (*Allium sativum* L.) [96]. However, higher than the optimum concentration of NPs could also reduce instances of seed germination. In one study, the ZnO-based NPs application yielded higher peanut seed germination and root growth [97].

Medical science employs nanotechnology for targeted drug delivery. Similarly, in agriculture, nanotechnology has been repurposed to enhance the uptake and delivery of nutrients to plants. Nanometric transport platforms allow improved nutrient penetration into plant cells, increasing plant growth, yield, and quality. NPs can be engineered to encapsulate nutrients such as fertilizers, micronutrients, and pesticides, allowing for targeted delivery of these substances to plant roots or leaves.

The following types of fertilizers can be delivered to plants using NPs:

3.4.1. Delivery of Biofertilizers

Biofertilizers include live microorganisms that improve plant growth. Microorganisms like mycorrhizal fungi, *Rhizobium*, *Azotobacter*, *Azospirillum*, *Pseudomonas*, and blue-green algae are common biofertilizers used in agricultural practices [97]. These microorganisms convert complex organic matter into simpler compounds readily usable by plants. These compounds increase crop productivity. However, biofertilizers often fail to produce satisfactory results in the field due to storage issues, temperature sensitivity, and shorter shelf life [98]. Liquid biofertilizers containing water-in-oil emulsions and additives are used to remove the effects of desiccation. However, prolonged storage of living organisms in liquid biofertilizers still diminishes their vitality. Coating biofertilizer with polymeric NPs improves the desiccation resistance of the biofertilizer inoculum. Also, incorporating hydrophobic silica NPs in liquid formulations improves cellular viability by thickening the oil phase during storage [99]. Certain NPs, when applied with PGPRs like *Pseudomonas fluorescens*, *Bacillus subtilis,* and *Paenibacillus elgii* demonstrate plant growth promotion in vitro. In addition, NPs are needed in minute quantities compared to chemical fertilizers. One liter of nanobiofertilizer can fertilize many hectares of crops. Among NPs, gold and silver have been studied extensively. The application of gold NPs in conjunction with *P. fluorescens*, *P. elgii*, and *B. subtilis* has shown appreciable plant growth promotion [100].

3.4.2. Delivery of Chemical Fertilizers

Chemical fertilizers are applied to arable land to meet the soil's N, P, and K shortages. Using ammonia, urea, nitrate, and phosphate-based fertilizers has considerably enhanced crop production [101]. However, their application is not free from harmful effects. Usually, chemical fertilizers are applied to the soil in excess. The estimate shows that 40–70% N, 80–90% P, and 50–70% K-based fertilizers are lost in the environment, causing environmental pollution [102]. The nanomaterials can mitigate water pollution and algal blooms caused by the plant's discharge of unused fertilizer runoff into nearby water bodies and rivers. Nanomaterials have a higher surface tension than conventional materials, allowing them to sustain the release of fertilizers more effectively. For instance, nano-hydroxyapatite, a nanoscale phosphate fertilizer, has significantly enhanced phosphorus use efficiency compared to conventional phosphate fertilizers [103].

NMs can also be used as a coating material to limit fertilizers' environmental release [104]. For example, urea particles coated with zinc oxide nanoparticles have been reported to demonstrate a slower nutrient release rate, thus minimizing nutrient leaching into the environment [105,106]. This approach allows plants to use the applied fertilizers more efficiently, reducing their environmental footprint (Figure 3). By coating NM on fertilizer crystals, the excessive release of fertilizers into water bodies and rivers can be lowered, reducing pollution and mitigating the risks of algal blooms (Figure 3).

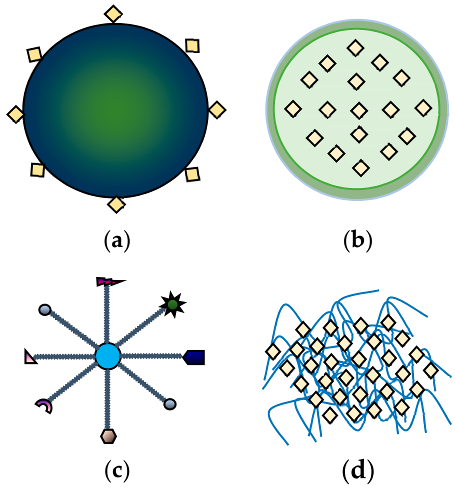

Figure 3. Representation of various nanomaterials for pesticide and fertilizer delivery: (**a**) adsorption on the nanoparticle; (**b**) encapsulation in the nanoparticulate polymeric shell; (**c**) attachment to the nanoparticle mediated by different ligands. The central circle represents the core, and the arms ending denote ligands; (**d**) entrapment in polymeric NPs.

3.5. Lowering the Dosage of Pesticides

The current global population explosion has led to a steep rise in demand for food, which has subsequently driven an unprecedented increase in the worldwide pesticide market. Unfortunately, many of these agrochemicals are finding their way into the human food chain, causing harm to both human and animal health, agriculture, and the ecosystem as a whole. The application of higher doses of pesticides is often necessary due to the development of pest resistance resulting from increased pesticide application rates [107]. In addition, the use of pesticides has substantially reduced the number of non-target insects, such as honey bees [108]. Unfortunately, these chemicals are not limited to agricultural areas and are present in the air, water, and soil, ultimately poisoning our environment [109]. Reducing pesticide use is crucial for mitigating environmental pollution and decreasing crop production costs.

Several studies have demonstrated the impact of metal NPs on insects and fungi. Modified approaches for pesticide delivery can help achieve this goal. NPs facilitate the transfer of pesticides or genes into plant cells and tissues to protect plants from pests [110]. Nanocapsules can deliver nanoencapsulation. Unlike bigger particles, nanoencapsulation allows targeted distribution, reduced dosage, and environmental protection [111]. Nanotechnology can contribute to the more efficient use of pesticides. For instance, nanofertilizers and nanopesticides have been developed to be applied directly to plant surfaces or roots [112]. These materials have a higher surface area-to-volume ratio, resulting in better plant uptake and utilization, reducing the need for excessive chemical application, and minimizing the environmental impact and potential harm to human health. Another application involves using nanomaterials for smart delivery systems, such as hydrogels or nanocapsules, that release nutrients or pesticides slowly and in a controlled manner [113]. These systems help ensure plants receive the right resources at the right time, reducing waste and environmental pollution.

The persistence of chemical pesticides in the soil is harming the environment. Using nanopesticides can retain their efficacy for longer durations within plant tissues, potentially reducing the need for repeated chemical pesticides [114]. Nanopesticide use may mitigate pesticide persistence by sustaining lower insect populations for longer durations, requiring less pesticide overall [114]. The "controlled release" approach is an effective way to reduce pesticide input and mitigate environmental issues. Clay nanotubes, such as halloysites, are a cost-effective carrier for pesticides. Halloysites can delay or extend the release time of pesticides while providing better contact with the associated surface, resulting in minimal environmental impact [115]. Some of the nanoparticle-based pesticides are described in Table 3.

Table 3. Nanoparticles effective against phytopathogens.

Nanoparticle	In Vivo/In Vitro	Phytopathogen	Reference
Carbon nanotubes	In vivo	Gray mold disease agent *Notrytis cinerea* on rose petals	[116]
Chitosan	In vivo	*Fusarium. oxysporum*, *P. capsici*, *Erwinia carotovora* subsp. carotovora and f *Xanthomonas campestris* pv. vesicatoria on tomato plants	[117]
Chitosan and chitosan-based	In vivo	*Pseudomonas syringae*, *Alternaria solani* and *F. oxysporum*	[118]
Chitosan–Gum Acacia Nanocomposites	In vivo	*F. oxysporum* f. sp. *lycopersici* in potato plants	[119]
Chitosan/Nano-TiO_2 Composite Coatings	In vitro	*Colletotrichum gloeosporioides*, *Cladosporium oxysporum* and *Penicillium steckii*	[120]
Copper oxide	In vivo	*A. carthami*, *Aspergillus niger*, *F. oxysporum* f.sp udum, *Xanthomonas axonopodis* pv. *punicae*	[121]
Copper oxide-graphene oxide nanocomposites	In vitro	*F. graminearum* and *Rhizoctonia solani*	[122]
Graphene oxide and zinc oxide	In vitro and In vivo	*Pectobacterium carotovorum*, *Xanthomonas campestris* pv. *carotae*, *Meloidogyne javanica*, *A. dauci* and *F. solani* on carrot	[123]
Iron oxide NPs	In vitro	*P. expansum*, *A. niger*, *A. alternata*, *M. plumbeus*, *P. chrysogenum*, *T. roseum*, and *R. solani*	[117]
Magnesium oxide	In vitro	Root-knot nematode (*Meloidogyne incognita*) and *Ralstonia solanacearum*	[124]
Magnesium oxide	In vitro	*P. expansum*, *A. niger*, *A. alternata*, *M. plumbeus*, *P. chrysogenum*, *T. roseum*, and *R. solani*	[117]
Magnesium oxide NPs-chitosan nanocomposites	In vivo	Fusarium wilt disease in tomato plants	[29]
Nickel-Chitosan	In vivo	Blast diseases in Asian rice (*Pyricularia oryzae*)	[125]
Silver	In vitro	*X. campestris*, *Pseudomonas syringae*, and *F. oxysporum*	[126]
Silicon dioxide, zinc oxide and titanium dioxide	In vivo	*Fusarium* wilt on *Meloidogyne incognita*	[127]
Silicon dioxide	In vivo	Powdery mildew in grapevine	[128]
Silica	In vivo	Control of bacterial wilt disease (*Ralstonia solanacearum*) in tomato plants	[129]

Table 3. *Cont.*

Nanoparticle	In Vivo/In Vitro	Phytopathogen	Reference
Titanium dioxide	In vivo	Tomato late blight	[130]
Zinc oxide	In vivo	Rice blast disease (*Magnaporthe oryzae)* in rice	[131]
Zinc oxide-chitosan nanocomposites	In vitro	*Rhizoctonia solani* and *Sclerotinia sclerotiorum*	[132]
Zinc oxide	In vivo	*F. oxysporum* on tomato plants	[133]

The following sub-section describes the various types of available nanoparticle-based pesticides that have been experimented.

3.5.1. Use as Nanoinsecticides

Several NM, notably Ag, have insecticidal effects against most plant insects [134]. The NM system activated by the environment is already being utilized in medicine [135]. However, its agricultural applicability is modest. In agriculture, numerous nanoformulations with delayed release have been created. However, few NPs employ an environmental trigger to release nanoinsecticides [136]. In addition, it is challenging to develop such insecticides due to the dynamic character of pest occurrences. However, if applied to pesticides, the most anticipated method might alter the nature of agriculture by removing the harmful effects of agrochemical applications by drastically lowering application rates. Such agents should respond to the external environment by releasing intelligent and effective pesticides. Microcapsule-based pesticide formulations exemplify the potential of nanopesticide technology, which might result in reduced insecticide use and tailored delivery to lessen environmental impacts, resulting in low toxicity. In addition, the shelf life of these substances is typically longer than that of chemical pesticides.

Several nanoparticle formulations were made against phytopathogens and insect pests [20,67–69,114,137]. For example, ZnO–TiO_2–Ag NPs were efficient against *Frankliniella occidentalis* Pergande, while Ag–Zn NPs were beneficial against *Aphis nerii* [138]. Nanosilica offers unique insecticidal characteristics. Nanosilica absorbs insect cuticular lipids and kills the insects. The surface-charged nanosilica is effective against various agriculturally significant insect pests [139].

3.5.2. Use as Nanofungicides

Phytopathogenic fungi account for around $45 billion yearly in crop losses worldwide [140]. Annually, the globe consumes 2.5 million tons of pesticides, resulting in about $100 billion in expenditures [141]. Chemical treatments for fungus control have harmed the environment and slowed economic growth since 90 percent of applied agrochemicals are lost in open fields owing to overland flow, damaging the ecosystem and raising farmers' costs [140].

Nanopesticides are the future of conventional pesticides, which have a higher pest fatality rate, are long-lasting, and need minimal treatment [88]. Nanofungicides reportedly eliminate fungal diseases from crops grown in irrigated fields or hydroponics, providing no environmental risks [142,143]. NPs eliminate fungal phytopathogens that attach to S protein groups of the cytosolic membrane by modifying cell permeability, damaging DNA, interfering with protein oxidation and the electron transport chain of the cell, creating reactive oxygen species, and inhibiting nutrient intake [144]. They are applied as foliar sprays to combat phytopathogens, which can also promote plant development [145]. Metallic NP-containing agrochemicals find widespread application as nanofungicides.

3.5.3. Use as Nanoherbicides

Herbicides serve a significant role in crop protection via weed management. However, its extensive use has caused environmental and economic issues. Large volumes of herbicides are applied to crops since their absorption rates in plants are less than one percent [146]. Frequently, farmers use herbicides at higher concentrations than recommended to promote crop development [147]. These practices foster the emergence of herbicide-resistant weeds. Herbicide resistance is a severe problem in agriculture, and new chemicals and strategies are needed to address it. One major goal of nanotechnology-based precision agriculture is reducing the need for and the environmental damage caused by pesticides. Nanotechnology interventions in the agricultural herbicide business might solve the chemical residue problem in an environmentally responsible manner without leaving any residues in the environment.

In such methods, herbicides are charged with NM before application to promote plant bioavailability and enhance weed elimination. Nanoherbicide development hinges on the selection of NM. The herbicidal chemical must fit the dimensions of the to-be-used NM and, preferably, interact with NM via chemical bonds. In one study, the application of ten times diluted poly (-caprolactone) (PCL) nanocapsules containing atrazine to *Amaranthus viridis* (slender amaranth) and *Bidens pilosa* (hairy beggarticks) inhibited fungal growth similar to a commercial formulation containing conventional atrazine doses [148]. In another study, nanoencapsulation of the herbicides imazapic and imazapyr effectively reduced their toxicity, potentially minimizing the impact on non-target organisms and the wider environment [149].

3.6. Summary of Advantages of Nanotechnology in the Agriculture Systems

This section highlighted the advantages of nanotechnology in agriculture, including improved seed germination and plant growth, enhanced micronutrient supply, alleviation of biotic and abiotic plant stress, and the ability to use lower dosages of fertilizers and pesticides through efficient delivery methods. Nanotechnology can assist in delivering both biofertilizers and chemical fertilizers and can also be used to formulate nanoinsecticides, nanofungicides, and nanoherbicides. Specific nanomaterials have also been identified as beneficial for plant growth (Table 4).

Table 4. Effect of different nanoparticles on plants.

Effect on Plant	Nanoparticle	Plant	Reference
Growth enhancement	zinc oxide	tomato	[150]
Improved seed germination through soil water retention	copper oxide	tomato	[151]
	silver	fenugreek	[51]
	silver	rice	[152]
	silicon dioxide	tomato	[91]
	hydrogels	wheat	[153]
Improved micronutrient supply through slow release	copper oxide nanoparticle-embedded hydrogels	lettuce	[154]
	nanocomposites of urea-coated hydroxyapatite and potassium encapsulated in nanoclay	tall fescue	[155]
	silicon dioxide	rice	[156]
	selenate and selenium	tomato	[157]
	iron oxide	tomato	[158]
Abiotic and biotic stress alleviation	silicon dioxide	sugar beet and maize	[159,160]
Lowering the dosage of pesticides	silicon dioxide	cucumber	[161]
	silicon dioxide	tomato	[162]
	copper oxide	pepper	[163]

Table 4. *Cont.*

Effect on Plant	Nanoparticle	Plant	Reference
Reduces pests	silver	rice	[164]
	copper oxide	tobacco	[165]
Photosynthesis enhancement	titanium dioxide	khus	[166]

4. Disadvantages of Nanotechnology in Agriculture Systems

Nanotechnology has been hailed as a revolutionary technology with the potential to transform various industries, including agriculture. While nanotechnology has promising applications in agriculture, it also poses several potential drawbacks and risks that cannot be overlooked.

NPs are tiny and can be easily carried by air or water currents, making them difficult to contain. When released into the environment, NPs can accumulate in the soil, water, and air, leading to potential ecological risks. For example, NPs can disrupt the soil's balance of macro and microorganisms, causing a decline in fertility [167–169]. They can also accumulate in plants and animals, potentially leading to adverse health effects [170].

The use of nanotechnology in agriculture raises concerns about human health. Exposure to NPs can have adverse health effects, such as respiratory problems, cardiovascular disease, and neurological damage [171]. Workers involved in producing and applying nanomaterials in agriculture are at a higher risk of nanoparticle exposure, which can have long-term health implications. In addition, nanotechnology in agriculture requires significant investment in research and development, which can be costly. Additionally, nanotechnology in agriculture may not be accessible to small-scale farmers who cannot afford the high costs of nanomaterials and related technologies, leading to an imbalance in the distribution of benefits from nanotechnology.

Using nanotechnology in agriculture raises ethical concerns about food safety and security [172]. There is a fear that nanomaterials in food may pose a risk to human health and safety, and limited research on the long-term effects of NPs exposure is available [173]. Additionally, using nanotechnology in agriculture may result in genetically modified organisms (GMOs) that raise ethical concerns for some people [174].

Summary of Disadvantages of Nanotechnology in Agriculture

Nanotechnology in agriculture is a relatively new technology, and there is limited regulation and oversight to ensure its safe and responsible use (Table 5). The lack of regulation raises concerns about the potential risks of using nanotechnology in agriculture and the need for robust regulations to protect human health and the environment [175,176].

Table 5. Disadvantages of nanotechnology in agriculture.

Disadvantage	Description	Reference
Ecological risks	Accumulate in soil, water, and air, disturbing soil microbes and lowering soil fertility and health. Accumulate in plants and animals, posing health risks.	[177]
Human health risks	Exposure can lead to health issues, especially for workers producing and applying nanomaterials.	[171]
High costs	Costly and could lead to an imbalance in the distribution of benefits, as small-scale farmers may not be able to afford it.	[178]
Ethical concerns	Raises concerns about food safety and security, with limited research on the long-term effects of consuming NPs and ethical concerns about GMOs.	[179]
Lack of regulation	Limited regulation and oversight raise concerns about potential risks and the need for robust regulations to protect human health and the environment.	[176]

5. Types of Nanotechnology Based Nanodiagnostic Systems

Plant pathology studies plant diseases, their causes, and prevention and control methods. Nanodiagnostic systems are an emerging field in plant pathology where nanotechnology is used for the early and accurate detection of plant diseases. These systems use nanoscale materials, such as metal NPs, quantum dots, and nanobarcodes, to detect phytopathogens early.

The following subsections discuss various available nanodiagnostic systems under precision agriculture.

5.1. Metal Nanoparticle-Based Systems

Metal nanoparticle-based systems are widely used in detecting phytopathogens. These systems are based on metal NPs, such as gold, silver, and magnetic NPs, which are functionalized with specific probes that recognize the target pathogen. Metal NPs have unique optical and magnetic properties that can be used to detect phytopathogens. For example, gold NPs can be functionalized with DNA probes to detect plant viruses [180].

5.2. Functional Quantum Dots

Functional quantum dots (QDs) are semiconductor nanocrystals that can be used to detect phytopathogens. QDs emit light at specific wavelengths when excited by a light source. They are highly sensitive, have a broad range of excitation wavelengths, and exhibit high photostability. These nanocrystals have unique optical properties, such as fluorescence, which can be used to detect phytopathogens [181]. In phytopathogen detection, QDs are often functionalized with specific biomolecules, such as antibodies or nucleic acids that bind to pathogen-specific molecules. As a result, infections can be found selectively in very complex biological matrices. For example, functional quantum dots can detect bacterial pathogens in plants [182]. QDs can detect pathogens at very low concentrations, enabling early disease detection. Additionally, QDs are highly stable, allowing them to be used over multiple detection cycles, making them a cost-effective option.

Moreover, QDs are highly versatile, as they can be designed to detect a wide range of phytopathogens, including viruses, bacteria, and fungi, allowing for a comprehensive approach to disease detection and management [182]. QDs possess significant potential for integration with other advanced technologies, including microfluidics and lab-on-a-chip systems, facilitating the development of highly sensitive, portable diagnostic instruments. Such synergistic technological combinations may prove exceptionally beneficial in fieldwork scenarios where swift, precise pathogen detection is integral to effective disease management. However, the use of QDs in phytopathogen detection is still relatively new. Further research is needed to fully understand their potential and limitations, including concerns about their toxicity and environmental impact.

5.3. Nanofabrication Imaging

Nanofabrication imaging uses nanofabrication technology to produce high-resolution photographs of plant diseases. This technique can detect phytopathogens early, which can help prevent the spread of the disease. For example, nanofabrication imaging can detect fungal pathogens in plants [182].

Nanofabrication techniques, such as electron beam lithography and nanoimprinting, create high-resolution nanostructures that specifically bind to target pathogens. These structures can be designed to amplify the signal produced by the target pathogen, resulting in increased detection sensitivity. For example, nanofabricated biosensors can sensitively detect specific biomolecules, such as DNA or proteins, from phytopathogens [183]. In addition, the nanopillars functionalized with specific antibodies bound to the virus cause changes in the optical properties of the nanopillars that could be detected using a microscope [184]. The researchers detected the virus at concentrations as low as 42–48 picograms per liter, demonstrating the technique's high sensitivity [185].

5.4. Nanopore System

The nanopore system is a real-time DNA sequencing technology that identifies phytopathogens. The system consists of a handheld device connected to a laptop or smartphone, making it easy to use and highly portable. Nanopore systems use nanopores, which are tiny pores in a membrane, to detect phytopathogens. These systems work by passing a sample through the nanopore, and the changes in electrical current caused by the interaction of the sample with the nanopore are measured. One of the main advantages of the nanopore system is its portability. The system can be used in the field to rapidly diagnose phytopathogens, especially in remote areas or places with limited access to laboratory facilities.

In the nanopore system, DNA or RNA sequence of the pathogen is matched with the public databases of nucleotides. The system detects a wide range of phytopathogens. For example, the system can detect viruses in plants [186]. Unlike traditional diagnostic techniques that require prior knowledge of the pathogen, such as bacteria, fungi, viruses, viroids, and phytoplasmas, the nanopore system can detect any pathogen sequence and match it with DNA sequence available in public databases. In addition, the nanopore system provides real-time results, which can help make immediate decisions about disease management strategies. The system can also monitor disease progression and evaluate the effectiveness of disease control measures. The technology allows for the sequencing of long reads in a short time and with high-throughput data analysis in real-time, thus enabling the identification of putative pathogens in samples with unidentified disease agents by DNA or RNA sequencing, which conventional diagnostic procedures can validate.

5.5. Nanobarcodes

Nanobarcodes are unique codes attached to NPs and can be used to identify phytopathogens. These codes can be read using specialized equipment to identify the specific pathogen. For example, nanobarcodes can identify bacterial phytopathogens [187]. Nanobarcodes consist of a unique combination of NPs that act as barcodes and can be used to identify specific pathogens. Nanobarcodes detect very low concentrations of pathogens and are designed to detect a wide range of pathogens, including viruses, bacteria, and fungi.

Nanobarcodes may be utilized in various detection techniques, including lateral flow assays, which are simple and quick field-based examinations [188]. Nanobarcode usage in these tests can improve their sensitivity and specificity, yielding more accurate and reliable results [189]. Nanobarcodes can also be used in other detection methods, such as microarrays and biosensors, which can provide more comprehensive information on the presence and identity of pathogens [190]. Nanobarcodes offer a significant advantage in their potential for multiplexing, enabling the detection of multiple pathogens in a single assay. This capability not only saves time and resources but also enhances detection accuracy.

5.6. Kit-Based Systems

Kit-based systems use commercially available diagnostic kits for detecting phytopathogens. The kits typically contain pre-prepared reagents and protocols for quickly and easily detecting phytopathogens. Using such kits eliminates the need for specialized equipment and expertise, making it possible for farmers and other stakeholders to quickly and accurately identify phytopathogens. These kits contain specific probes that recognize the target pathogen and are designed for use in the field. Virus detection in plants is one use of kit-based methods [182]. Commercially available kit-based systems provide a quick, cost-effective, reliable, and easy-to-use method for detecting phytopathogens. Non-specialists can use these kits for rapid detection of phytopathogens, often providing a more cost-effective option than hiring specialized equipment or experts. Kit-based systems are designed to be highly sensitive and specific, providing accurate results in detecting phytopathogens. Additionally, many kit-based systems are designed to be portable and easy to use, making them ideal for use in the field.

5.7. Summary of Nanotechnology Based Nanodiagnostic Systems

The nanodiagnostics demonstrates the promising future of nanotechnology in agriculture. Nanodiagnostic systems such as nanosensors, quantum dots, gold NPs, magnetic NPs, nanobarcodes, carbon nanotubes are leveraged for diverse applications. These include soil nutrient and heavy metal monitoring, plant disease and pest detection, genetically modified organism (GMOs) identification, plant growth monitoring, and irrigation control. Nanotechnology also provides solutions for tracing and identifying plant species and ensuring the traceability of agri-food products (Table 6).

Table 6. Types of nanodiagnostic systems and their applications in agriculture.

Nanodiagnostic System	Application in Agriculture	Reference
Nanosensors	Soil nutrient monitoring, plant disease detection, pest detection	[191]
Quantum dots	Detection of plant viruses, monitoring of transgenic plants	[192]
Gold NPs	Identification of GM crops, pathogen detection	[193,194]
Magnetic NPs	Detection of heavy metals in soil, water monitoring	[195]
Nanobarcodes	Tracking and identification of plant species, traceability of agri-food products	[187]
Carbon nanotubes	Monitoring of plant growth, detection of pesticides	[196]
Nanofluidic devices	Control of irrigation, soil water content measurement	[197]

6. Nanobiosensors in Diagnostics and Precision Agriculture

The unprecedented increase in the use of agrochemicals and fertilizers has led to an accumulation of nutrients and toxins in ground and surface waters. These toxic concentrations are responsible for higher costs of water purification, reduced fisheries, and decreased recreational activities [198]. Conventional agricultural practices are deteriorating soil quality and are responsible for the eutrophication of water bodies. In addition, bad farming practices damage the ecosystems of beneficial insects and other wild organisms and, therefore, must be replaced by precision agricultural methods.

Precision agriculture includes wireless field networking and nanosensors for observing and controlling farming practices. It manages site-specific crops and pre- and post-harvesting aspects [199]. Under precision agriculture, exploring the fascinating properties of functional materials from which nanobiosensors are built could help accurately analyze soil humidity, water, nutrients, and phytopathogens [200] (Figure 4). Biosensors are now available for detecting odors in food spoilage, and such sensors [201] are called “electronic noses”, followed by the development of other sensor types. The electronic nose uses an array of gas sensors to identify various kinds of odors. The gas sensors are composed of NPs like ZnO nanowires [202] and nanorods [203], which could detect impurities in vapor mixtures [204]. Such sensors work on the principle of change in their resistance with the passage of different gases resulting in variation in the generated electrical signals, which are used as a fingerprint for gas detection. A typical biosensor consists of four units: (1) a sensor, (2) a signal conditioning block, (3) a microprocessor chip, and (4) a radio module for wireless communications between the sensor and the monitoring station [187].

Recent nanotechnological leaps have enabled us to study biochemical interactions in plant cells and tissues due to various pathogens. The method uses a probe inserted in the xylem vessel at the root base. The probe measures xylem pressure, radial electrical gradients, and ionic activity [205,206]. Such tools help better understand pathogenicity mechanisms to improve crop disease treatment strategies [207,208]. However, the previous approach relied on the destructive sampling of pathogenic bacteria colonizing the xylem, which failed to provide helpful information about colorization patterns, biofilm development, movement, and re-colonization of bacterial pathogens in new tissues. However, implementing microfabricated xylem vessels containing nano-sized features lets us understand the features that were impossible with conventional methods [209].

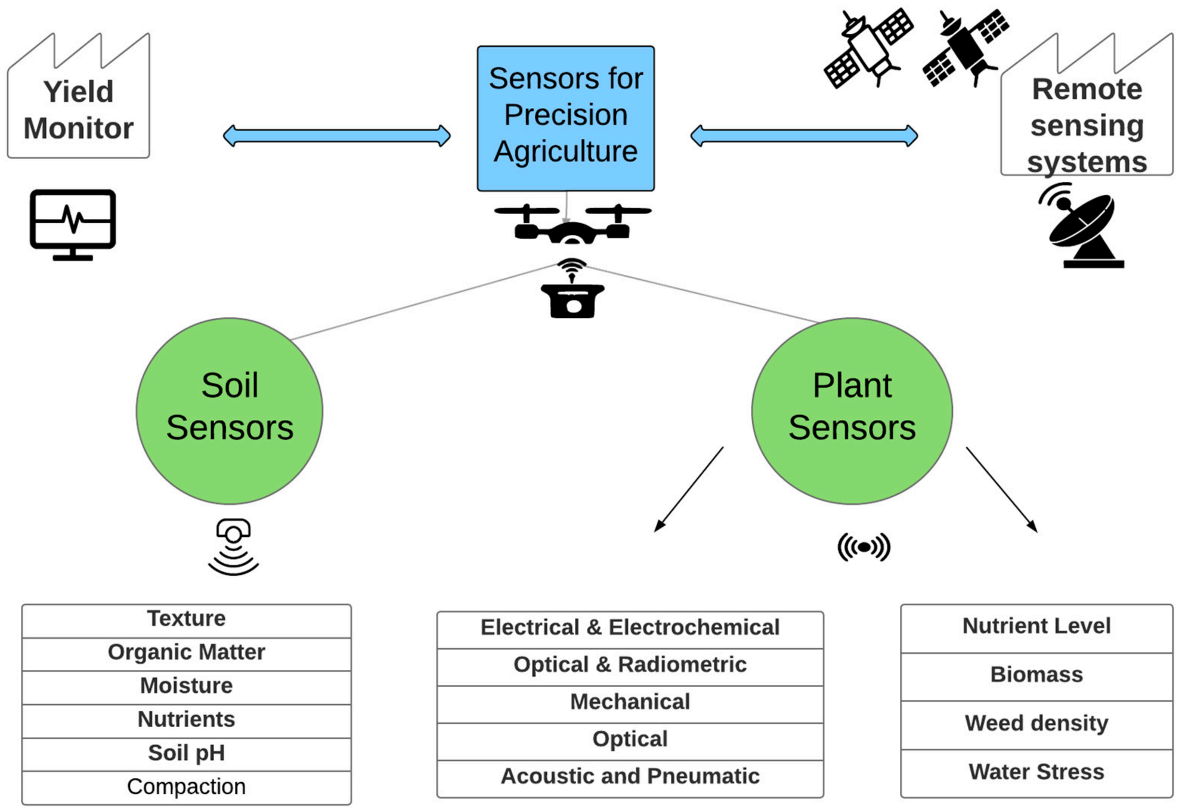

Figure 4. Functional representation of nanosensors in precision agriculture.

6.1. Monitoring of Soil Quality Parameters

Biomonitoring is a technique used to collect and analyze organisms, tissues, or fluids to determine their exposure to natural and synthetic chemicals. The information gleaned from these observations is valuable, as it provides insight into the number of chemicals that have entered the organism and led to corresponding changes. Biomonitoring is also an effective method for estimating the total dose absorbed by the organism, which can provide indirect access to monitor target site concentrations. The advancement of sensor technology has improved its sensitivity and reduced its size compared to conventional biosensors. Such biosensors are used to monitor fertilizers, herbicides, pesticides, insecticides, pathogens, soil moisture, and pH [210]. An ideal nanobiosensor should be stable over long storage periods and possess a lower reaction time. In addition, it should be small, biocompatible, non-toxic, non-antigenic, inexpensive, portable, accurate, and capable of producing repeatable findings [211]. Nanobiosensors are ultrasensitive devices and can detect viruses at ultra-low concentrations as they operate at the atomic scale with the highest efficiency and accuracy.

6.2. Monitoring Soil Pesticides/Herbicides

The insects are cosmopolitan in distribution and hold the highest population among pests. They infest all plants and products by injuring their parts or attack storage products to incur heavy crop losses. The regular use of pesticides in fields to combat pests can lead to the development of resistance among pest groups [212]. Additionally, pesticide chemicals degrade in the environment over time, which reduces their effectiveness for agricultural use. NM use in pesticide formulations could aid in reducing usage and attaining agricultural sustainability. NM includes C nanotubes, quantum dots, gold NPs, carbon black, and nanocomposites. Many nanostructured biosensors have been developed for pesticide detection in water and food [213]. Based on consumption rates, toxicological information, and environmental residual levels, the U.S. Environmental Protection Agency

(EPA) proposed a limit of 0.9 mg/L glyphosate in drinking water and an acceptable daily intake of 0.3 mg/kg/day [214].

6.3. Monitoring Soil Nutrients

Nanosensors are being developed as a promising real-time technology for monitoring soil nutrients. These sensors detect and quantify nutrients such as nitrogen, phosphorus, and potassium in soil samples. They use nanomaterials, such as carbon nanotubes, graphene, and nanoclays, to detect and bind with specific nutrients in the soil [215]. Nanosensors can provide farmers with accurate and timely information about soil nutrient levels, which can help them make more informed decisions about fertilizer application and crop management. This technology can assist in decreasing fertilizer waste, boost fertilizer efficiency, and lessen the potentially negative environmental implications of typical fertilizer application methods. One example of a nanosensor for soil nutrient monitoring is a graphene-based sensor that can detect nitrogen levels in soil [216]. The sensor is designed to be integrated into a wireless sensor network that can provide real-time data on soil nutrient levels to farmers.

6.4. Monitoring Soil Humidity

To ensure successful crop production, it is necessary to regularly analyze soil texture and moisture content. Relative humidity measurements determine the amount of water vapor in a gas mixture at a specified temperature. Standard-level deviations in soil moisture can significantly impact agricultural yields since these parameters vary spatially and temporally. Although conventional methods are available for estimating soil moisture levels, their accuracy is often low. Such methods require frequent calibration, reducing their stability and making them less preferable for use in agricultural settings.

Humidity-based nanosensors are increasingly replacing conventional methods for measuring soil moisture [217]. These sensors utilize electrical transduction with a hygroscopic probe, which changes its dielectric properties upon water absorption. Nanosensors fabricated from polymers, ceramics, and composites provide several benefits, such as increased stability, prolonged chemical and thermal durability, and enhanced environmental adaptability [218]. The widespread use of nanosensors in agriculture could significantly improve the precision of soil temperature and moisture measurements. Many of these devices are equipped with wireless communications systems that are economical, user-friendly, and can provide real-time data. Examples of nanosensors commonly used for soil measurements include carbon nanotube and graphene-based nanosensors [219]. For instance, a graphene oxide-based sensor is a type of humidity-based nanosensor that can detect changes in humidity levels from 0.1% to 90% [220].

6.5. Monitoring Plant Disease and Stress

Plant stress and nutrient deficiency are detected by monitoring plant physiology through imaging, spectroscopy, and fluorescence [221,222]. The described remote sensing methods provide vital information about leaf area, chlorophyll content, stomatal conductance [223], transpiration rate [224], water potential [225], and leaf temperature [226]. However, the methods are not helpful for the early diagnosis of plant stress and nutrient deficiency and are not economical for installation in individual plants [221]. NPs-based sensors are now being utilized to monitor plant disease and stress by providing an early detection system for plants. These systems measure the volatile organic compounds (VOCs) released by plants during biotic and abiotic stress or disease conditions. Nanoparticle based sensors can detect these VOCs by analyzing their physical and chemical properties, allowing for the identification of the specific stress or disease affecting the plant.

One example of a nanoparticle-based system for plant disease detection is a gold nanoparticle-based sensor that can detect the presence of bacterial pathogens in plants [227]. The sensor works by detecting the VOCs released by the bacteria, allowing for early detection of the disease before visible symptoms appear. Similarly, NPs have been used to monitor abiotic stress in plants, such as drought stress, by detecting changes in VOC emissions. Carbon nanotubes have been utilized in a sensor that can detect changes in VOCs associated with drought stress in plants [228,229]. The sensor can detect VOCs with high sensitivity and specificity, allowing for early detection of drought stress in plants.

6.6. Monitoring Irrigation

Due to the uncertainties posed by climate change, land water availability has reduced globally, and droughts and erratic monsoon patterns are becoming more frequent [230]. The current decade is facing a challenge in getting clean and needed water for human use, industrial purposes, and agriculture. The escalating use of agrochemicals in agriculture has exacerbated groundwater pollution. Our water resources are getting contaminated with microbial pathogens, salts, metals, agrochemicals, pharmaceutical compounds, personal care products, and radioactive elements [187]. A specific type of contaminant in water bodies is primarily due to anthropogenic activities like oil and gas production, mining, or natural processes like leaching [231], which require thorough treatment procedures for water recycling. Water treatment requires novel and sustainable technologies for recycling purposes.

Precision and site-specific irrigation management have emerged as potential solutions to enhance crop productivity under adverse climate change conditions [232]. The concept has appeared as a possible solution for improved crop productivity under adverse climate change. The method uses advanced technologies such as GPS, GIS, and automated machine guidance to apply water judiciously. This approach can be complemented with low-flying drones or sensitive satellites with high-resolution imaging capabilities to determine the water content of soil or plants and induce precise irrigation at the site of need. As a result, water consumption for irrigation can be reduced. However, several bottlenecks, such as cloud interference and high data processing requirements, still need to be addressed. Integration of crop simulation models with remote sensing technology enhances the efficacy of agricultural management and decision-making processes. The application of nanotechnology to microirrigation can enhance water quality and filtering techniques. Nanoparticle-based biosensors can detect and measure water-based contaminants in real-time and remove them using nanofiltration membranes [233]. Nanoparticle-based membranes can also desalinate water, reducing the likelihood of clogging on the filters and membranes.

6.7. Summary of Biosensors in Precision Agriculture

The section discussed the role of nanobiosensors in diagnostics and precision agriculture. These sensors monitor soil parameters such as quality, pesticide/herbicide levels, nutrient content, and humidity. They also play a crucial role in monitoring plant disease and stress and managing irrigation. The summary of biosensors' application in precision agriculture is also mentioned, highlighting their importance in achieving more efficient and sustainable farming practices (Table 7).

Table 7. Nanobiosensors in diagnostics and precision agriculture.

Type of Biosensors	Function	Material Type	Reference
Environmental biosensors, chemiresistor sensors	monitoring of soil quality parameters	polymers, metal oxides	[234]
Pesticide biosensors, electrochemical biosensors	monitoring soil pesticides/herbicides	enzymes, conducting polymers	[235,236]
Nutrient biosensors, potentiometric biosensors	monitoring soil nutrients	ion-selective electrodes, polymers	[237,238]
Moisture sensors, capacitive humidity sensors	monitoring soil humidity	ceramics, polymers	[239,240]

Table 7. *Cont.*

Type of Biosensors	Function	Material Type	Reference
Plant disease biosensors, fluorescence-based biosensors	monitoring plant disease and stress	quantum dots, fluorescent proteins	[194,241]
Irrigation biosensors, soil moisture sensors	monitoring irrigation	ceramics, metal oxides	[242,243]

7. Nanotechnological Applications to Reduce Agro-Waste and for Synthesizing High-Value Products

Agricultural residues are produced from harvesting and processing crops, fruits, vegetables, and trees in bulk during agricultural practices. Agro-waste mainly includes plant parts unusable for human consumption, including stems, leaves, shells, bark, seeds, pods, husks, etc. [244]. Agricultural waste is rich in lignocellulosic materials and could be exploited for economic and environmental benefits to produce organic acids, biofuels, protein-rich animal feed, microbe-based pigments, mushrooms, and enzymes [245,246]. Despite the large volume of agro-waste generated worldwide, only a small fraction is recycled. The majority is burned or used as animal feed [247].

Nevertheless, the issue of agro-waste burning is linked to environmental pollution and is restricted in several countries or provinces [248]. Agro-waste can be dealt innovatively through composting, producing bioactive compounds, nanomaterials, and biorefinery tools [249]. In addition, NPs can be used to encapsulate nutrients and other bioactive compounds, protecting them from degradation and increasing their bioavailability [250]. This technology can reduce the amount of agro-waste by allowing farmers to use fewer inputs while increasing the efficacy of their crops.

8. Tagging, Monitoring, and Tracking the Agroproducts Using Nanotechnology Methods and Devices

The wide variety and large volume of generated agroproducts need efficient tagging. Previously, laser-scannable barcodes with the Universal Product Code (UPC) were used for tagging agro-products [251]. They have been replaced in several countries by radio-frequency identification (RFID) tags, which consist of a wireless integrated radio circuit and an embedded identification code [252]. RFID provides several advantages over its predecessor, like more information storage at a sizeable scannable distance with simultaneous scanning of products [252]. RFID tags are also used in food packaging for tagging and tallying customer purchases.

A newer "nanobarcode" method that functions like UPC on nano-scalar levels has been introduced. Nanoplex technology-based nanoparticle-containing strips are used for encoding information. Nanoplex labels the device using platinum, palladium, nickel, and cobalt [253]. The nanoplex technology has developed "Sensor" tags (Silicon Enhanced NPs for surface-enhanced Raman Scattering), a 50 nm metal nanoparticle with unique codes that can be read from a meter length. Nanotags can be used to track agroproducts from farm to consumer. They can be incorporated into the packaging to track the temperature, humidity, and other environmental conditions during shipping and storage [254].

These nanotechnology-based tracking methods offer a range of benefits for the agriculture industry. By using nanotechnology to tag, monitor, and track agroproducts, farmers and food manufacturers can ensure the quality and safety of their products, reduce waste by identifying issues early, improve efficiency by tracking products through the supply chain, increase transparency, and build trust with consumers by providing information about the origin and safety of their products. PA practices have been adopted in the vineyards of Nakhon Ratchasima [255]. Similar kinds of methods are also adopted in Thailand [255], the USA [256], and Brazil [257].

9. Smartphone-Based Biosensors in Precision Agriculture

Traditional biosensing equipment are cumbersome, costly, and require cautious handling, which limits their utility in agricultural regions. Recent advances in lab-on-a-chip (LOC) technology have resulted in the miniaturization of standard biosensing devices [258]. When connected with smartphones, these devices have the potential to transform the process of agricultural data collection (Figure 5). Smartphones have great promise in smart farming due to their portability, affordability, and ease of access, particularly in rural areas. Smartphones are transforming our daily information consumption habits. The use of smartphones in agriculture as detectors or instrument interfaces has the potential to revolutionize how we obtain information. Furthermore, they possess considerable processing power to support agriculture-based applications and can be equipped with sensors for smart farming. These biosensors use the camera and other sensors on a smartphone to analyze data collected from plants, soil, and other agricultural samples, allowing farmers to make data-driven decisions about their crops. Among the primary benefits of smartphone-based biosensors are their affordability and portability. Moreover, they are readily accessible to farmers in developed and developing countries, allowing for widespread adoption and use. Additionally, they can be easily integrated with other PA technologies, such as unmanned aerial vehicles and remote sensing, to provide a more comprehensive approach to crop monitoring and management.

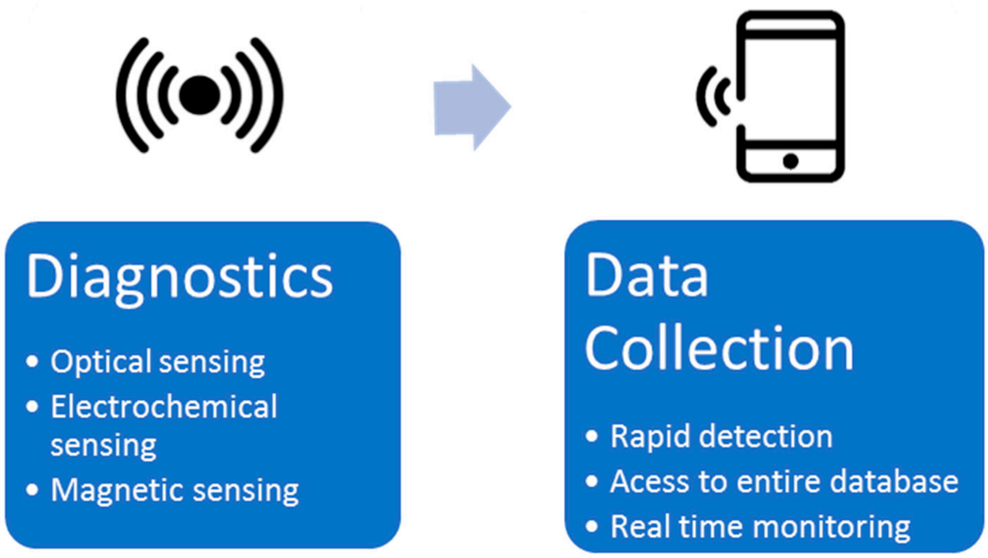

Figure 5. Smartphone based nanosensors in precision agriculture.

Nanosensors incorporated into smartphones can aid in early disease detection, fertilizer dosage calculations, and monitoring water supply to estimate crop maturity and yield [259]. Nanosensors can also detect soil nutrients and water stress. For example, they can analyze soil samples for nutrient content and provide recommendations for fertilization. They can also detect plant stress by measuring chlorophyll content, which can help farmers adjust their irrigation and nutrient management practices to improve crop health and yields. After gathering data from numerous phone sensors, the intelligent network system may transfer it elsewhere for in-depth analysis [258]. In a recent study, Surface-Enhanced Raman Scattering (SERS) chip-based nanosensors were utilized to quantify pesticide residue using a click-through mobile phone application. These nanosensors effectively identified 12 types of pesticides at concentrations as low as ten ppm [260]. Such advancements enable the identification of substances and metabolites on-site. Despite the challenges associated with their use, the benefits of smartphone-based biosensors are significant and can potentially revolutionize PA.

10. Precision Agriculture and Cloud Computing

Current research focuses on innovative techniques for boosting agricultural output with minimal environmental impact. Recent technological developments like cloud computing and green nanotechnology offer viable alternatives for more inventive and sustainable agriculture. In combination with technologies like the Internet of Things (IoT), cloud computing is transforming food supply chains through automation, precision agriculture, remote monitoring, forecasting, and decision-making. Cloud computing could aid in applying agrochemicals to cultivate improved crops. Precise agricultural procedures can enhance crop profitability and agricultural input [261].

Cloud-based computing stores centralized agriculture-related data, including soil parameters, weather, crop, fertilizer, input, agriculture marketing, etc., in the cloud. Cloud computing, a revolutionary technology for future computing and communication, involves interconnected devices sharing digital data with markets, social networks, knowledge base platforms, and crop protection agencies. The operation of these networks is based on remote sensing, geographic information systems (GIS), global positioning systems (GPS), sensor technology, RFID, and cloud computing. In IoT, agricultural farms and machinery continuously remain integrated with sensors, the internet, and database systems. IoT includes soil and plant monitoring, greenhouse environment monitoring, and food supply chain monitoring (Figure 6).

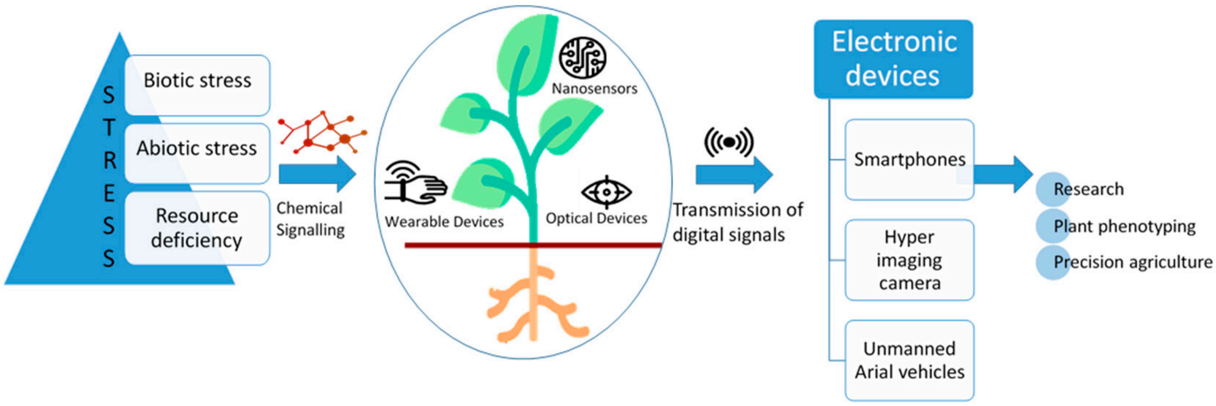

Figure 6. Application of plant based nanosensors in precision agriculture.

The chief advantage of cloud computing is that it is data-ready, allows local to global level communication, and reduces technical issues. Cloud computing is poised to improve agricultural growth and provide food security and safety, thus contributing to the GDP growth of nations with agriculture-centric economies.

11. Nanotechnology and Agribusiness

The global agribusiness market, worth US$20.7 billion in 2010 [262], is projected to increase to USD 244.2 billion by 2025, with a CAGR of 8.9% from 2019 to 2025 [263]. This sector faces challenges related to the complexity of agricultural economics and the difficulties of tracking supply-demand differences due to dispersed agricultural production sites and the diversity of farm products. However, recent nanotechnology and precision agriculture innovations are paving the way to address these issues effectively. The emergence of nanosensor-based supply chains and precision agriculture, a data-driven practice, offers potential solutions. Precision agriculture can enhance crop data access and improve efficiency, reducing costs by optimizing resource usage and waste management.

Similarly, nanotechnology can make agrochemicals more effective and less expensive, although its large-scale adoption is still in its early stages [264]. The current applications of nanotechnology in agriculture are primarily in food packaging and, to a lesser extent, in the tracking, tracing, storage, and distribution of agro-products [264]. Nevertheless, nanotechnology promises to revolutionize agribusiness by creating a 'smart supply chain'. This concept encompasses improved market product visibility, security, quality, safety, and overall supply chain efficiency [265] and can potentially simplify product diversity and geographical complexities. Nanotechnology can also enhance the properties of agricultural materials, leading to better crop yield and quality, thereby resulting in higher market prices and profitability [266]. Nanosensors can enable more effective soil and plant health monitoring, reducing the need for expensive fertilizers and pesticide applications, thereby minimizing production costs and environmental harm.

However, while these benefits are compelling, the high initial costs of nanotechnology and potential environmental risks should be considered. The long-term success of nanotechnology in agribusiness is dependent on continued research and development and the careful weighing of potential risks and environmental impacts. Nevertheless, the potential advantages of nanotechnology and precision agriculture are promising, indicating significant potential for enhancing profitability, sustainability, and efficiency in agribusiness.

12. Economic, Legal, Social, and Risk Implications of Nanotechnology

Agriculture-based information on soil nutrients, crop growth, and yield is gathered through surveys, field sampling, and laboratory analysis. However, the collected data remains incomplete, inaccurate, and delayed, thus unable to provide a complete picture of farmland. Precision agriculture seems intuitively appealing to many agricultural producers and professionals in agribusiness. However, a profitability study of the nano-agro farm model is necessary to determine if the intuitive appeal translates into actual profitability. The literature reports the low to moderate toxicity of NPs to plants and humans [43,171,267,268]. However, most NP exposure studies were done for a short duration and in high dosage under model media, which is inadequate for understanding the current risk posed to agricultural systems and humans [269,270]. From 2000 to 2018, the United States, China, India, Brazil, and Iran were the top five countries in the publication intensity of agro-based nanoparticle research [271]. A subsequent investigation indicated that between 2009 and 2021, the United States, China, and India were the predominant nations in nanotechnology research [272]. This conclusion was substantiated by the volume of their scientific publications in the field.

Nanotechnology has significant economic, legal, social, and risk implications that need careful consideration. From a financial perspective, nanotechnology can revolutionize various industries, from healthcare to energy to agriculture. It can improve efficiency, lower production costs, and provide new materials with unique properties. However, the high costs of research and development, as well as potential liability risks, must also be taken into account.

From a legal perspective, nanotechnology raises essential questions about intellectual property, product liability, and regulatory oversight. The novelty of nanotechnology means that traditional regulatory frameworks may not be sufficient to address the unique risks associated with these materials. As such, governments and regulatory agencies must work to create appropriate legal frameworks to ensure the safe and responsible development and use of nanotechnology [273].

The societal benefits of nanotechnology must be weighed against potential drawbacks, including potential impacts on human health, the environment, and ethical considerations. The potential for unintended consequences, such as releasing NPs into the environment or unforeseen health risks, must be carefully considered. Additionally, questions about equity, access, and the distribution of benefits and harms associated with nanotechnology must be addressed.

In addition, the risks associated with nanotechnology must be carefully evaluated and mitigated, which includes assessing potential health risks, environmental impacts, and societal implications and developing appropriate risk management strategies. Ongoing research and development, along with transparent communication and collaboration between stakeholders, will be critical in addressing these risks and ensuring the safe and responsible development and use of nanotechnology.

13. Conclusions

Nanotechnology is a promising technology that can significantly impact food and agriculture systems. However, the risk assessment of nanoparticle use needs evaluation. Nanotechnology-based precision agriculture could increase crop production through better management and conservation inputs. Precision agriculture is poised to revolutionize agriculture by accelerating the green revolution. Smart agriculture can aid in minimizing agricultural waste, thus reducing environmental pollution. Additionally, nanotechnology could protect the environment by employing alternative energy supplies to reduce pollution and help clean up existing pollutants.

The use of sensor-based technology would have a significant impact on future farming. These methods can enhance crop productivity by providing vital information about crop growth, thus helping farmers make better decisions. Advances in nanotechnology can revolutionize various agricultural sectors with the latest tools for rapid disease diagnosis and treatment and enhancing plants' ability to absorb nutrients. Several companies have formulated nanopesticides with particle sizes ranging from 100–250 nm that exhibit high water solubility, which translates into higher formulation activity. In addition, suspensions of oil-based NPs have been formulated in the range of 200–400 nm that can prevent or treat disease instances. Such formulations could apply to disease prevention in crops and harvested products.

Agricultural scientists regularly publish new recommendations and technological changes in farm practices in local magazines and newspapers to benefit the farming community. However, the adoption percentage of those recommendations or technologies among farming communities is primarily unknown. Moreover, there's a need for the development of data prediction methodologies to measure farmers' adoption rates of new technologies. Therefore, governmental policy adjustments are required to fund farmer-centric studies on adopting new technologies.

The interaction of NPs with soil is partially understood, and additional research is required to determine their impact on plant nutrition under field conditions. Like other elements, the effect of NPs on soil must be governed by the physical and chemical properties of soil particles. Further research is needed to observe the response of the terrestrial ecosystem to metal NPs, the interaction of pollutants under various climatic conditions, and their effect on the rhizosphere region, besides keeping their properties under multiple soil types and plant species.

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