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Review

Innovations in Modern Nanotechnology for the Sustainable Production of Agriculture

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Abstract: Nanotechnology has an extensive series of applications in agronomy and has an important role in the future of sustainable agriculture. The agricultural industries should be supported by innovative active materials such as nanofertilizers, nanofungicides, and nanopesticides. It is necessary in the current situation to meet the dietary needs of the constantly expanding world population. Nearly one-third of crops grown conventionally suffer damage, mostly as a result of pest infestation, microbiological assaults, natural disasters, poor soil quality, and a lack of nutrients. To solve these problems, we urgently need more inventive technology. The application of nanotechnology in agriculture provides intelligent methods for delivering nutrients, herbicides, and genetic materials for improving soil fertility, stress tolerance, and protection. The world is currently confronting significant issues related to the rising demand for enough food and safe food as well as dealing with the environmental damage caused by traditional agriculture. Nanomaterials have important applications in agriculture for increasing plant growth and development and the quality and quantity of the crops and controlling and managing agricultural diseases. The major objective of this article is to describe the various applications and importance of nanoparticles in the agriculture sector.

Keywords: nanofertilizer; nanosensor; nanobarcode; nanopesticide; nanofungicide

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1. Introduction

Nanotechnology is the learning of materials in the array of 1–100 nm. Currently, nanotechnology is applied in numerous fields that include biology, chemistry, physics, engineering, medicine, textile industries, paint manufacturing, cosmetic industries, agricultural fields, etc. [1]. The knowledge of nanotechnology was first formulated by the honorable Nobel Laureate Richard Feynman in his famous lecture at the California Institute of Technology on 29 December 1959. He explained the design of nanomaterials using a top-down approach [2]. Now, nanoparticles (NPs) are synthesized using various methods such as physical, chemical, and biological. In physical methods, higher energy, inert gases, and a larger area for implementation of instruments are used. It is costly and high radiation is used for the synthesis of NPs. The vapor phase method, condensation method, spray pyrolysis, laser ablation, and photo irradiation methods are used for the synthesis of NPs [3]. The chemical methods like the sol-gel method, reverse micelles, co-precipitation method, and chemical reduction method are utilized for the synthesis of material at the nanoscale level [4–7]. In this method, more toxic and harmful chemicals are used for synthesizing NPs. The drawback of this method is that it results in the release of harmful byproducts while synthesizing nanomaterials [8]. Some perspective chemical approaches such as solution combustion synthesis helps to avoid these negative effects [9–12]. Nowadays, an alternative method of synthesis that is used to overcome these drawbacks is the biological method, where biological materials like plants, microorganisms, and algae are used for synthesizing NPs. The advantage of this method is that it is cost-effective, fairly toxic-free, and environmentally friendly [13].

Biologically synthesizing nanomaterials using plant extract is eco-friendly as well as cost-effective and also energy-efficient. And in the entire process of biosynthesis neither high energy inputs nor harmful chemicals are involved [14]. Biogenic nanomaterials also play a vital role in both the innovative applications of modern science as well as in modern agriculture. The process of creating NPs with the help of biomolecules (obtained from viruses, fungi, bacteria, and plants) and biochemical reactions are termed as biogenic synthesis of nanomaterials [15]. The biological resources involved in the process of green synthesis of nanomaterials such as microorganisms (fungi, algae, virus, bacteria, and yeast act as a reducing agent), biodegradable waste, and plant extract are called "nanofactories, bionanofactories and biological factories" [16]. Green resources which can replace the old production methods have been preferred in recent decades for the production of nanomaterials [17]. NP agriculture is the main driver of development in rural areas. A strong agricultural economy brings social progress by increasing productivity, employment, and income [18]. These modern materials' novel and developing features have unquestionably gained the attention of agriculture industries [19]. The use of nanomaterials in agriculture helps to decrease nutrient losses to boost yields [20]. The advancement of science and technology helps the agricultural industry by supplying it with fresh approaches and addressing all challenging issues. With the development of nanotechnology, nanoformulations are regularly generated for sustainable agriculture and they are more effective since they contain fewer contaminants [21]. One of the potential fields where nanotechnology could provide sustainable crop management is agriculture. For instance, the release of chemicals using nano-based products has been successfully applied in a controlled and specifically customized manner, resulting in a clean and simple pest management system. In general, productivity and sustainability are regarded to be improved by the use of NPs in agriculture [22]. In the agricultural field, the use of nanomaterials has produced great results, such as efficient growth, higher output, and yield with better nutritional quality. Agri-nanotechnology is a technique to improve crops under different climate conditions. The excellent effects of metal oxide NPs on agriculture include efficient growth, enhanced output, and nutritional quality [23,24]. The use of NPs in agriculture is well-known. A wide number of applied scientific fields, including agriculture, use nanoemulsions with NPs of a large variety of sizes [25,26]. The applications of nanotechnology, or the use of nanomaterials in agriculture, can be handy to address the challenges associated with the creation of effective and potentially effective approaches for the control of insect pests in agriculture. Different types of NPs (Figure 1) have been transformed into nanopesticides and nanofertilizers, including carbon nanotubes, silicon, molybdenum, silver, copper [27,28], zinc [29,30], manganese [31], titanium [32,33], iron and its oxides [34], and nanoformulations of common agricultural inputs including phosphate, urea, sulphur, validamycin, tebuconazole, and azadiractin [35]. Recent developments in chemistry and material science have helped us master nanoparticle technology, which has significant implications for agriculture [36].

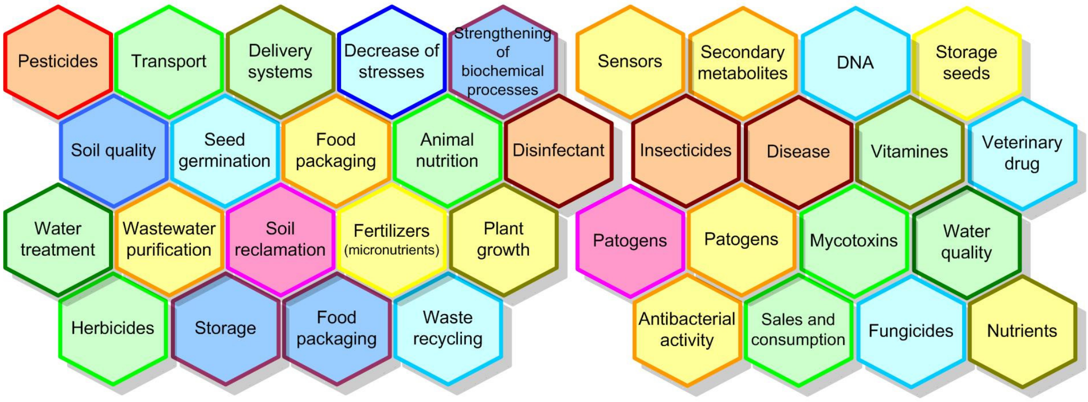

Figure 1. Role of nanomaterials in agriculture.

Agriculture plays an important role in improving economic growth as well as meeting the nutritional needs of people of all countries. Numerous factors affect sustainable agriculture such as insect/pests, weeds, economic status, and population. It is very important to develop the grade of the agricultural aspect to meet the needs and challenges [37]. A large quantity of chemicals are used both in fertilizers (30–40%) and pesticides to achieve the target crop yield. Potassium, nitrogen, and phosphorous have only 20–40% efficiency that may not be good for the soil in the long run. Therefore, the total yield of food crops is affected by this unfertilized soil in and around the plateau regions [38]. Several problems are faced by the farmers which include compound effects, economic crisis, negative effects of climatic change, and poor yield. The problems that the agricultural industry faces as a result of a growing global population, changing diets with increased demand for animal-sourced meals, and climate change make managing numerous risks more vital than ever [39]. To overcome these difficult circumstances, numerous technological advancements must be chosen to boost crop yields and raise farmer standards. Such technology involves the use of nanosensors based on the nanotechnology implemented in every concept of agriculture. Nanotechnology is a boon to agriculture to overcome excessive gas emissions (methanol, carbon dioxide, and nitrogen oxide) due to temperature changes and the alteration of rainfall trends, which play a major role in crop yield. This also improves the staple crop growth, food fabrication, nutritional benefit, efficiency in the controlled release of herbicide, and growth regulators, such as the atrazine herbicide nanocarrier capsules [40]. Aluminium (Al), zinc oxide (ZnO), zinc (Zn), titanium oxides (TiO_2), silicon (Si), cesium oxide (CeO_2), copper (Cu), and aluminum oxides (Al_2O_3), among others, are utilized to boost agricultural yield (Figure 2 and Table 1). These NPs protect plants and improve food sustainability, such as Ag, which has a bigger influence on yield quality than antibacterial characteristics and leads to a high nutritional value in the yield [41].

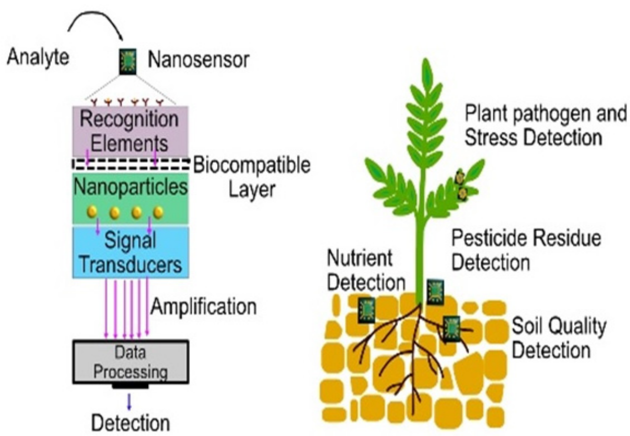

Figure 2. Most common approaches for nanosensor use in sustainable agriculture.

Table 1. Role of nanomaterials in sensor fabrication and its applications.

Name of Nanoparticle for Sensor Fabrication	Applications	References
Silver Nanoprobe	Detection of malathion residues in water and food samples	[42]
Silver NPs	Detection of triazophos in water and food samples	[43]
Gold and silver nanoparticle	Determination of organo phosphate pesticides	[44]
Thiazolylazopyrimidine-functionalized TiO_2 Nanoparticle	Detection of Cu (II) in water samples	[45]
Zinc oxide quantum dot	Detection of pesticide in water	[46]
Carbon quantum dot	Detection of flumioxazin	[47]
Green carbon dots	Ultra-sensitive fluorescent detection of pesticides	[48]
TiO_2/poly (CTAB) modified sensor	Detection of aminotriazole	[49]
Mercaptobenzoic acid labelled gold-silver-alloy-embedded silica NPs	Detection of sensitive quantitative thiram	[50]
Bimetallic zinc oxide and titanium dioxide nanoparticle	Control of *Spodoptera frugiperda*	[51]
Fluorescent carbon dots	Detection of water contaminants	[52]
CuO-TiO_2	Detection of methyl parathion pesticide in ground water	[53]
Silica carbon quantum dot	Detection of indoxcarb	[54]
Nanoparticle-Molybdenum nanocomposite	Detection of pesticide residues	[55]
TiO_2 designed carbon-based sensor	Detection and determination of fungicide carbendazim	[56]

2. The Application of Nanotechnology in Agriculture

Nanotechnology is considered the potential solution for solving various agricultural problems. It has received more attention in the last few decades. This leads to the development of a new and unique method of farm production for improving agricultural productivity [57]. It provides new agronomical agents with a delivery method to improve crop yield. Nanotechnology increases agricultural productivity through various delivery agents like nanopesticides, nanofertilizers, nanofungicides, nanoherbicides, and nanosensors for the identification of disease in crops, genetic engineering, plant monitoring, animal health monitoring, post-harvest production management, etc. [57]. Nanotechnology is also utilized to improve crop health without causing damage to the soil. It also reduces nitrogen lost due to leaching and soil microorganisms. NPs afford 'magic bullets', which comprise chemicals, and herbicides or genes that target specific crop components for the proclamation of their content. Nanocapsules are very helpful in the effective dispersion of herbicides over the cuticles and tissues in plants via the deliberate and steady proclamation of the dynamic materials, spot-targeted distribution of several macromolecules required for enhanced plant disease resistance, effectual nutrients application, and improved plant growth [58].

Nanosensors (nano-based delivery systems) will possibly facilitate the effective utilization of agronomic natural resources such as nutrients, chemicals, and water over precise agricultural practices. The farm managers could gain the ability to distantly sense the infecting insects or facts of stress levels like drought with the help of nanomaterials and universe allocating arrangements through satellite imaging of the field [59]. Once the crop is found to be affected by pests or the soil is in drought conditions, the automatic modification of insecticide applications or an irrigation point scan be completed. It also perceives the occurrence of plant diseases and the level of nutritive components in the soil. The nano-encapsulated deliberate proclamation of fertilizers tends to store fertilizer utilization and reduce ecological contamination [3].

3. Nanoproducts

3.1. Nanofertilizer

Nano- and biofertilizers, which are more effective and environmentally friendly than the outmoded chemical fertilizers, are now an important part of agriculture [60]. Nanofertilizers will considerably help us reduce urea consumption, cut urea imports, and lower the cost of urea subsidies by improving nitrogen usage efficiency [61]. Nanofertilizers deliver nourishment in a regulated manner in response to a variety of cues, such as heat, moisture, and other abiotic stresses. With the help of various chemical, physical, mechanical, or biological procedures, nanofertilizers are created, or modified versions of traditional fertilizers, bulk fertilizer ingredients, or derivatives of various vegetative or reproductive portions of the plant [62]. Nanofertilizers are thought to be a cutting-edge strategy for preserving nutrients, particularly nitrogen, as well as the environment [63]. They are used to improve the fertility and productivity of the soil and the quality of agricultural output [64]. In nanoscale polymers, the release of nutrients and growth stimulants is controlled, gradual, and efficient [65]. Nanofertilizers have high surface areas and particles that are smaller than the pores of plant roots and leaves to promote penetration into the plant from the applied surface and increase uptake and efficient use of nutrients [66]. When the particle size of the fertilizer is reduced, the specific surface area and particle density increase, giving nanofertilizers more surface area to interact with and increasing nutrient penetration and uptake [67]. Nanofertilizers increase the availability of nutrients to growing plants, which improves plant growth overall by increasing the production of dry matter, chlorophyll, and photosynthesis [68]. The low cost of natural zeolites and the recent increase in public awareness of the phenomenon have evoked significant economic interest in the development of zeolite-based nanofertilizers [69]. Numerous studies have shown that nanofertilizers improve crop growth, yield, and quality, resulting in a higher yield and higherquality crop product for animal and human consumption [20–22,70]. Nutrients from nanofertilizer are transported and delivered to cells more efficiently through 50–60-nm-wide nanoscale passageways between cells. Nanofertilizers have increased cuticle absorption and are more soluble and reactive, allowing for targeted administration and control [71].

Copper belongs to the groupof metals recognized as trace elements. In general, these metals have high density and high atomic mass around a value of 20, which include metals like copper, zinc, nickel, and lead. Cu occurs through Cu^{2+} also Cu^{+}. It performs as a structural component in directing proteins and is one of the chief constituents in photosynthetic electron transport, oxidative stress, cell wall metabolism, etc. [72]. In plants, copper is one of the important elements for the manufacture of chlorophyll. Copper's performance as a cofactor in enzymes includes superoxide dismutase (SOD), oxidation, polyphenol oxidase, plastocyanin, and amino oxidase [73]. Copper induces numerous enzymes and plays a role in RNA synthesis and the progress of the photosystems (Figure 1). It is an important component for plant growth and it is involved in several functional methods. It is a significant cofactor for metalloproteins [74]. Copper is essential for making biomass, chlorophyll production for photosynthesis, and the germination of seeds [75]. High-entropy-alloy NPs were found to be effective as nanofertilizes [76].

3.2. Nanopesticides and Nanofungicide

Nanopesticides have taken the place of traditional pesticides. Conventional pesticides deliver a nanoformulation with metal NPs or polymers, which is one of the most difficult areas of the pesticide industry [77]. Nanopesticide nanocomponents are quite small and additives that do not exist in conventional pesticides are typically very harmful in nanopesticides. The advantage of pesticide nanoencapsulation is the controlled and gradual release of the active component through manipulation of the nanocapsule's outer shell, which delivers a small dose over a long period of time, reducing unwanted pesticide runoff. Nanopesticides have also improved plant pest and disease management [78]. To protect plants, the following nanopesticides are used: Ag, Cu, SiO_2, and Zn. Chemical pesticides and fertilizers increased food output significantly but at the expense of crop quality and soil fertility [79]. These nanopesticides increase solubility while decreasing soil runoff [80]. Target-specific nanopesticides should help to reduce non-target plant damage and the amounts of pesticides released into the environment. The nanomaterials used to make pesticides have a number of advantageous properties, including high stiffness, permeability, thermal stability, and biodegradability [81]. The use of pesticides is one of the most effective ways of protecting plants from insects, fungi, and weeds. To protect our environment and save non-target species, we must use natural and environmentally friendly pesticides as well as small amounts of chemical pesticides [82].

Copper is utilized as both a nanopesticide and nanofungicide. It is an imperative disease management device for both organic and conventional methods of cultivation. The pest-like arthropods include phytophagous insects and mites that destroy both the grown crops and stored agricultural products [83]. For instance, the red flour beetle *Triboliumcastaneum* is a pest that particularly affects the stored agricultural produce and foodstuff, damaging their quality and destroying them (Figure 1). This beetle also decreases the germination percentage of grains. Copper NPs have fungicidal and insecticidal activity against pests that affect the crop. Hence, they can be used as copper-based nanopesticides, nanofungicides, nanofertilizers, and nanoherbicides [84,85]. There are many other copper-based pesticides and fungicides such as copper ammonium complex, copper oxychloride, copper sulfate, copper hydroxide, and copper oxide [86]. The active form in all copper-based products is Cu^{2+} copper ions. Organisms like bacteria, fungi, algae, and molds that are sensitive to tiny amounts of copper ions have broad-spectrum activity against microorganisms. This occurs because of the interaction with nucleic acids that affect energy transportation, disruption of enzymes, and integrity of cell membranes [87].

Nanopesticides were developed to replace conventional pesticides [88]. The nanopesticide components in nanopesticides are extremely small and the additives in nanopesticides that are in common pesticides are often very toxic.

3.3. Nanoinsecticide

Among them, nanocapsules are by far the most popular method for releasing insecticides under control. It is also used to nanoformulate organic pesticides such as neem oil [89]. Food is a fundamental necessity for the world's ever increasing population and, as a result, there is an ever increasing need to grow more food, prompting efforts to better protect agricultural crops from pest infestation. Polymer-based nanoformulations have been used to encapsulate the majority of pesticides. Nanoinsecticides have the following advantages over bulk substances: controlled release that increases the effectiveness of both natural and chemical insecticides, reduced rate of application, easy and safe handling, greater susceptibility to photodegradation, and lower toxicity to non-target organisms. Insecticides have been encapsulated in a wide range of polymer and non-polymer-based nanoformulations, including NPs [90]. Nanofibers, nanogels, nanospheres, micelles, nanoemulsions, and nanocapsules are all examples of nanomaterials [91]. The effective use of biodegradable polymers of natural origin rather than synthetic ones for encapsulation is a result of the current rise in environmental awareness. A commercial formulation of the pesticide bifenthrin is also used. These tests will establish a new benchmark for improved pesticide formulations capable of gathering plant-based systemic resistance. Synthetic pesticides may pollute the environment if used frequently due to their high residue levels. Because many insect pests are becoming resistant to insecticides, a new approach to pest control is also required.

3.4. Nanoherbicide

Herbicides are traditionally used to prevent the growth of undesirable weeds. Weeds planted alongside crops typically inhibit their growth [92]. Herbicide use may affect plant development and growth. Herbicides are a type of pesticide that is used to prevent or eliminate weeds. Herbicides can be injected into tissues and cuticles using nanocapsules, which have demonstrated delayed and continuous release of active ingredients. Herbicides that are more stable in the soil can reduce germination rates and fresh weights. Thus, pre-emergence herbicides with inhibitory effects that delay weed germination are desirable [93]. They are typically unaffected by conventional treatment, have high toxicity, and have a long half-life. Key nano-based materials, on the other hand, such as nanopolymers and nanoshells, have a wide range of scientific applications. Better soil motility, as revealed by the tobacco mild green mosaic virus (TMGMV), provides a potential platform for a medication carrier for agricultural applications. According to Santaella and Plancot [94], pesticides are delivered to plant parasitic nematodes using TMGMV as a nanocarrier. Carbon-coated AuNPs created via the simple heat treatment of intracellular biogenic NPs have been found to be an improved abiotic carrier for plant transformation [95].

Copper oxide NPs are utilized as nanoherbicides for controlling the weeds that affect plant growth. The copper-based nanoherbicides enter through the root, translocate in vascular bundles and to other parts like photosynthetic cells, and inhibit the glycolysis pathway and energy transportation through an electro chain that takes place in roots and parts of the plant. This affects the weed plant and causes starvation of the plant, reducingthe growth and development of the crops, which leads to the death of the crop [96].

4. Nanogrowth Promoter

Chemical fertilizers are essential for boosting agricultural production globally to meet the rising food demand of the world's expanding population [97]. The three main commercial fertilizer kinds that are most frequently utilized are nitrogen, phosphate, and potassium. According to reports, the global ammonia uses for industrial and agricultural purposes increased steadily during the previous decade at 2.0% of the compound's annual growth rate. In order to address the critical challenges of food security, sustainability, crop production, and eco-safety, modern agriculture is holding the creative approach of nanobiotechnology for the creation of nano-biofertilizer (Table 2) [98]. The biofertilizer (which contains nutrients and bacteria that stimulate plant growth) is covered with nanoscale polymers in the formulation of nano-biofertilizer (nanoencapsulation) [99].

Table 2. Effect of NPs in plant system.

Organisms Name	Mode of Application	Responses	Reference
Spinacia oleracea	Nanofertilizers	Increased photosynthesis and growth of the crop	[100]
Solanumly copersicum	Nanofungicides	Controls late blight disease caused by *Phytophthora infestans*	[101]
Maize (*Zea mays*)	Nanofertilizers	Crop growth and progression	[74]
Fungal disease	Nanofungicides	Fungal disease (*Fusarium* sp). treatment in plants	[102]
Pomegranate bacterial blight	Nanobactericide	The growth of *Xanthomonas axonopodispv. Punicae* inhibited	[103]
Disease in tomato	Nanobactericide	The growth of *Phytophthora infestans* inhibited	[101]
Wheat	Nanofertilizers	Increases the growth and yield	[104]
Lettuce	Nanofertilizers	Increases photosynthesis process, increases transpiration rate and increase crop production	[105]
Phaseolus radiates and *Cucurbita pepo*	Nanoherbicides	Reduction in seedling development, decrease in biomass and impediment of root elongation and growth	[106]
Cucurbita pepo and Elodea densa	Nanoherbicides	Reduced growth of the weed plant and reduction in development of weed plant	[107,108]

Table 2. *Cont.*

Organisms Name	Mode of Application	Responses	Reference
Lolium perenne and *Lolium rigidum*	Nanoherbicides	Causes DNA damage, accumulation of oxidative stress molecules	[109]
Fagopyrum esculentum and *Cucumis sativus*	Nanoherbicides	Decrease in growth of the plant induce oxidative stress, increase in SOD and CAT	[110]
Tribolium castaneum	Nanopesticides	Controls and kills the agricultural arthropods	[87]
Zea mays	Nanofertilizers	Decreased GPX and CAT, and succinates dehydrogenase activity.	[74]
S. lycopersicum	Nanofertilizers	Enhanced dry weight and flavonoid production	[111]
H. vulgare	Nanofertilizer	Increases flavonoid content in plants	[112]
A. thaliana	Nanofertilizer	Enhanced anthocyanin content	[113]
Anopheles stephensi and *Tenebrio molitor*	NanopPesticides	Good larvicidal activity present in CuO NPs	[114]
Spodoptera littoral	Nanopesticides	Decreases the mortality and biological features of the insect	[81]

5. Nanobarcode Technology

In day-to-day life, barcoding plays an essential role in livestock and agricultural management. Due to its precise efficiency, it has been used extensively as an identification tag that is detected by UV lamps and optical microscopes. They are encoded by doping special earth with multi-fluorescence material in micro-meter-sized glass nanobarcodes which are used extensively in the agricultural industry [115]. The nanoparticle should be readable by a machine, long-lasting, easily encodable, smaller than micron-sized taggant particles that are used under the process that is semi-automated, and highly scalable for the production of nanobarcodes. The stripped nanorods of nanobarcodes are made by electroplating metallic particles such as gold, silver, aluminium, zinc, etc. The multiplexed analysis of nanobarcode technology may be effectively used in ID tags in the field of the genetic marking of drought, insect, pest, and salinity-resistant plants in a cost-effective manner [116]. Nanotechnology is unique in tagging agro-food products and conventional transportation.

Nano-bioprocessing and nanobarcoding are also helpful in monitoring the crop yielding quality, apart from disease detection. Barcoding processes have been developed for the specific detection of reactions with a distinct label. One among them is DNA microarray in which the reaction of positional encoding has been carried out to detect a specific kind of mixed reaction. On the other hand, the radioisotope, which is responsible for a particular disease or fertilizer, is encoded as the marker [117]. Tagged phytopathogens with the microscopic probes are detected through fluorimeter. A battery-powered nanobarcode is currently being developed; once completed, it will be paired with a Global Positioning System (GPS) enabling the easy identification of viruses and pesticides of any sort. The quantum dots are also used as nanobarcodes developed by a group of scientists for the detection of phytopathogens by gene-expression-quantification techniques [118]. Dasgupta et al. [119] have presented a discussion of barcode technology applications that are less focused and affirm that this might be a big breakthrough in developing the nanobarcode thrust area.

5.1. Nanosensors in Agriculture

The antibacterial impact and wastewater rehabilitation capability have been the primary emphasis in the development of silver NPs used in agricultural issues [120]. The Food Safety Authority of Ireland states that silver NPs were employed in the food packaging industry to kill food-borne pathogens from long-stored food products in the year 2008. According to an initial study, silver nanoparticles inhibit powdery mildew disease at 100 ppm concentration by eradicating the fungal hyphae and promoting the growth of conidia in the Cucurbitaceae family [121]. The organophorous pesticide present in the environment and post-harvest food has been determined by the silver nano-entreated biosensor [122]. Zhang et al. [123] have shown that manufactured silver nanoparticle monolayers can improve sensitivity for Raman detection and aid in the detection of methyl parathion concentrations. According to a phytotoxicity study, silver NPs accumulated in the inner and the outer cell wall feign toxic content in the cell wall mechanism due to the complex mechanism of the cell wall. Though changes in the concentration of the nanoparticle vary, the size of the nanoparticle remains the same, developing chemical variations [124]. To identify possible pathogen issues in plant and postharvest foods, silver NPs are utilized as bio-nanosensors and electrical nanosensors.

A triangular silver nanoparticle with exceptional optical characteristics and heightened sensitivity to its nanoenvironment was recently produced [125]. Developing chitosan-mediated biosensors encoded with the capability to cascade the CD4-binding domain of the host-virus via the inhibition of disulfide bond regions has been achieved. They have also been responsible for the interaction of genetic viral material by inhibiting RNA production and extracellular virions. They absorb the heavy metal depositions in agricultural fields depending on their thermal and chemical stability. The silver-nanoparticle-based biosensor detects the carcinogenic nitrile pollutant with hyper-branched polyethyleneimine. The 100 nM concentration of nitrite detection is achieved with the combination of nitrate mixture and hydrogen peroxide in the acidic condition. The generation of peroxynitrous acid aggregates the silver nanoprobe, which is analyzed through fluorescence quenching [126]. Thus, the key findings of this study provide the door for an unknown pathway that might be enhanced in silver-nanoparticle-based nanosensors [127]. The main approaches of the use of nanosensors in agriculture are presented in Figure 3.

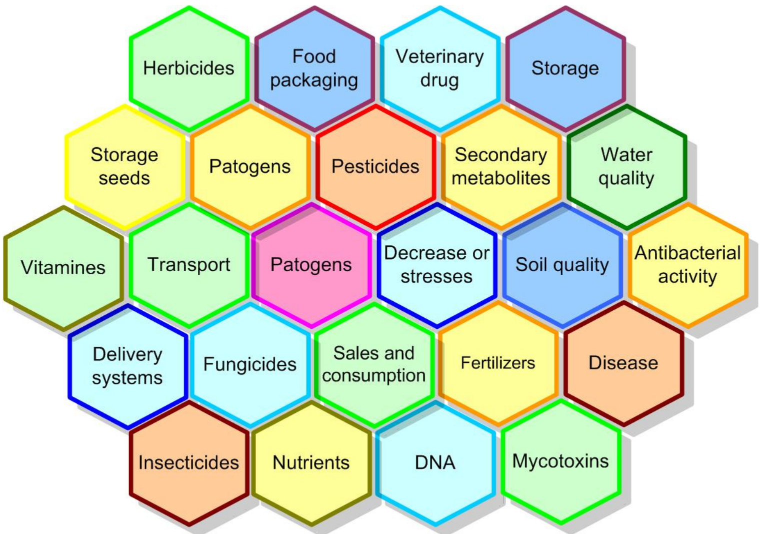

Figure 3. Main approaches of the use of nanosensors in agriculture.

5.1.1. Nutrient Deficiency Detection Using Nanosensors

One of the major problems faced by farmers is nutrition deficiency in crop cultivation to obtain sustainable crop yield over a fixed time period all over the world. This is mainly due to the lesser supplement of fertilizer as well as soil fertility and this could be rectified through timely detection by implementing the nano-biosensor before being visually exhibited (Indian farming). On the other hand, the smart delivery systems help to deliver the nutrition compounds loaded with pre-programed, self-regulated, spatially-targeted, and functional biosystems to avoid biological barriers to successful targeting [128].

5.1.2. Nanosensors for the Detection of Heavy Metals

The presence of heavy metals in agriculture, such as mercury, arsenic, lead, chromium, nickel, cadmium, and copper, is considered harmful to both people and the environment. Cd(II)-EDTA-BSA antigen and goat anti-mouse immunoglobulin (IgG) were disseminated over the NC (nitrocellulose) membrane, which was further treated with a concentrated colloidal gold probe on a glass fiber membrane to create immunochromatographic strip nanosensors, which are highly sensitive sensors that can detect cadmium levels [129]. Using a modified reverse microemulsion technique, amino-capped cadmium telluride at silicon dioxide fluorescent silica NPs was created. To create cadmium telluride (CdTe), silicon dioxide (SiO_2), cadmium selenide (CdSe) ratio metric probes, an optical nanosensor to detect cadmium, and the dual-stabilizers which capped cadmium selenide quantum dots were covalently attached to the silica surface [100]. Calorimetric nanosensors were created by implanting fresh dithiocetal-grounded stimuli-receptive molecular gates on MSN filled with a reporter dye that can detect mercury [130]. To detect Pd, cationic-(3-(acetylthio)-propyl-pyrazin-1-iumligand was used to stabilize another calorimetric nanosensor made from gold NPs (II) [131]. Fe_2O_3 NPs produced via chemical coprecipitation, coated with silica, and afterward electrostatically coupled with cysteamine-capped cadmium telluride quantum dots (CdTe QDs) yielded multimodal nanosensors that can detect mercury [132]. A form of nanosensor known as surface plasmon resonance was created when ECAgNPs were made by combining varying ratios of epicatechin and $AgNO_3$, followed by magnetic stirring, and was later employed for lead detection [133]. The hydrothermal synthesis of NH_2-UiO-66 produced an electrochemical sensor that efficiently detects copper, cadmium, and lead. The cross linking agents such as N-hydroxysuccinimide (NHS) and 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) were used to produce Fc-NH2-UiO-66, which was then dispersed on trGNO nanosheets [134]. In order to create multifunctional magnetic-fluorescent NPs, which were subsequently used as nanosensors, carboxymethyl chitosan was used as an encapsulating agent to pack Fe_3O_4 NPs and quantum dots. As a result, many kinds of nanosensors were developed to find dangerous heavy metals [135].

5.1.3. Nanosensors for the Detection of Pathogens

Nanosensors are designed in a way that makes them useful for a variety of detections, showing a good impact on agriculture. Gold nanorods were created utilizing the seed-mediated growth technique, and then they were immobilized on the surface of the fiber core. The fiber was then sunk in a solution of *Cymbidium mosaic virus* (CymMV) or *Odontoglossum ringspot virus* (ORSV) antibody to functionalize the gold nanoparticle surface and build an optical particle plasmon resonance (FOPPR) immunosensor to detect CymMV or ORSV (Lin et al., 2014). To identify the presence of Tomato Ring Spot Virus (ToRSV), Arabis Mosaic Virus (ArMV), and Bean Pod Mottle Virus (BPMV), amino-functionalized iron oxide/silicon dioxide metal NPs (NH_2-Fe_3O_4/SiO_2 MNPs) were created from metal NPs and these MNPs were then covalently immobilized with antibodies [123]. Gold (III) chloride trihydrate ($HAuCl_4$) and sodium citrate dehydrate were utilized to synthesize gold NPs of various sizes and a layer-by-layer assembly was employed to change the electrode that detects *Ganoderma boninense* in electrochemical sensors [136]. In order to detect *Phytophthora cactorum* through an electrochemical nanosensor and for amperometric sensing, stannic oxide (SnO_2) and titanium dioxide (TiO_2) were utilized as electrochemical detection elements and screen-printed carbon electrodes were changed with SnO_2 or TiO_2 NPs before usage [137]. Gold NPs created by the citrate reduction of gold (III) chloride trihydrate were also used to create an electrochemical biosensor. In order to identify *Pseudomonas syringae*, the tris-(2-carboxyethyl)-phosphine was added to a mixture of *Pseudomonas syringae* DNA. Nanosensors are designed to be able to detect a variety of entities, making them essential in the agricultural industry [138].

5.1.4. Nanosensors for the Detection of Pesticide Residue

Various nanosensors can also be used to detect pesticides that pose a risk to both crop plants and consumers. Imazapyr, a pesticide that was detected using fluorescent nanosensors, is produced by employing a hydrothermal technique involving Ytterbium (III) oxide (Yb_2O_3) coated with 3-aminopropyl-triethoxysilane [139]. Atrazine-imprinted NPs are created using the emulsion polymerization process and then attached to the gold surface of the surface-plasmon-resonance (SPR)-based affinity sensor to detect atrazine [140]. Surface-plasmon-resonance-based fiber-optic nanosensors are produced by chemically synthesizing tantalum pentoxide (Ta_2O_5) NPs contained in a reduced graphene oxide matrix, then adhering to silver-coated fiber-optic probes to detect fenitrothion [141]. For a fluorescence sensor, a copper oxide/multi-walled copper nanotube (CuO/MWCNT) is prepared by precipitating the copper nitrate by adding an aqueous NaOH solution to detect glyphosate [142]. Electrochemical luminescence sensors that were made via the layer-by-layer assembling of grapheme-gold NPs and luminol-gold NPs-L-cysteine-copper (Lu-Au-Lcys-Cu(II)) composites can also detect glyphosate [143]. Methyl parathion is detected using an electrochemical sensor generated with copper oxide-titanium dioxide (CuO-TiO_2) nanocomposites that were coated on the glass carbon electrode using a simple liquid control precipitation process [53]. Electrochemical aptasensors produced with FeO NPs generated using a chemical co-precipitation process was placed on fluorine tin oxide (FTO), then aptamer immobilization occurred in the iron-oxide-doped chitosan/FTO electrode using streptavidin, and an electrochemical nanosensor generated via the electro-catalyst of copper oxide NPs was created on 3D grapheme, produced using a hydrothermal process in which both detect malathion [144,145]. In order to create optical nanosensors that can detect dimethoate, silver nanodendrites were created using a laser-assisted photochemical technique and mounted on the microsphere end-shaped optical fiber surface, whereas optical sensors made by converting NPs which are produced using the co-precipitation process of lanthanide metal-EDTA complexes to prepare sensor film were dissolved in tetrahydrofuran with the addition of dioctyl phthalate, PVC polymer, and NIR dye to detect metribuzin [146].

6. Conclusions

The main issues with nanotechnology-enabled goods relate to the potential usage of large quantities of NPs, which have hazardous consequences at varying degrees at increasing concentrations. The continuous use of nano-enabled items, particularly in agriculture, may raise their concentration in the soil and the crops themselves. The health of humans could be harmed by even a small amount of NPs. Increased toxin levels have the potential to impede and slow growth. However, the form, size, concentrations, basic materials, and coatings of NPs have a unique impact on their toxicity. There is a wide variety of nanotechnology-enabled items in use that have the potential to decompose into new classes of hazardous contaminants such as metals, metal-oxides, carbon, and semi-conductor materials. Green nanotechnology, a multidisciplinary area developing clean, safe, and environmentally acceptable substitutes for items now utilized in numerous industries, is addressing these concerns. Based on recent findings, this review examined the utilization of nano-enabled items and identified some intriguing traits. In conclusion, the focus of the research should be on figuring out how items containing nanotechnology interact with the effects on epigenetics.

We revealed several categorized existing and co-existing features of nanosensors and their applications. This emerging device is eco-friendly and rapidly analyzes environmental features, highlighting the interaction between scrutinized stuff and the limits of materials used in nanosystems. Furthermore, nanosensors will be utilized in agriculture for independent management, interpretation of the exchanges among plant roots and other soil organisms, nutrient maneuvers, and disease and deficiency prevention, including the sustainable development of crop traits. Finally, the development of nanosensors will seek to provide better efficiency, and higher accuracy with satellite communication.

Nanoparticle-treated crops not only show improved growth and better yield, but also better resistance to affliction by insects, pests, fungi, and weeds. NPs increase the potency of the plant, yield, and solubility, and decrease pests, insects, and weeds that grow laterally with crops, decreasing the use of chemical products. The significant interest in the utilization of nanotechnology in the agricultural field has unique and specific applications such as nanofertilizers, nanoherbicides, nanofungicides, nanopesticides, and nanoinsecticides to trail the products, which would increase the yield. In conclusion, nanotechnology can be readily applied to achieve better quality and a higher yield of produce. It can be utilized as nanofungicide, nanoherbicide, and nanopesticide to protect the crop.

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