Chapter

Potential Applications of Nanotechnology in Agriculture: A Smart Tool for Sustainable Agriculture

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Abstract

Most of the early uses of nanotechnology have come from material sciences, although applications in agriculture are still expanding. Due to a few comprehensive reviews, we described application of nanomaterials along with their fate in soil and interaction with soil and plant system. From synthesis to metabolism, nano-fertilizers like zinc, silver, selenium, titanium oxide have enhanced the physio-chemical characteristics of crop plants in every manner conceivable. On the other hand, it has the potential to minimize pesticide use by boosting reactivity and surface area of nanoparticles. Nanotechnology in pesticides will, without a doubt, replace the current way of pesticide application because of its efficacy. Nano-based approaches can readily overcome the constraints of conventional soil remediation technologies. While soil nanomaterials mobility has been investigated in a limited number of research studies, it's likely the most critical gap in knowing the real risk of their transport. As well as enhancing plant nutrient absorption, nanomaterials may also be used to regulate soil microbial activity and stimulate plant defenses. When it comes to shipping food, nanotechnology has made things easier by extending the shelf life of most foods. While it offers tremendous potential for agricultural applications, the health effects of nanoparticles on plants, animals, and humans must be thoroughly investigated.

Keywords: nanotechnology, nanomaterials, agriculture, pesticide, fertilizer, plant defense, soil remediation, agricultural waste

1. Introduction

Agriculture is the most important and reliable enterprise, as it provides food and raw materials for industries that require them. The depletion of natural resources and the increase in world population demand that agricultural production become more economically feasible, ecologically sound, and productive. Changes such as these are crucial to attaining a number of goals inside the last year. Therefore, environmental performance should be employed and involvement from food chain ecosystems concerning agricultural foodstuff production must be incorporated. When it comes to eliminating poverty and hunger from today's world, the agricultural revolution is a must-have phenomenon. In this scenario, well-known lenders are living below the poverty line and are dispersed in rural areas where agricultural expansion has not been as successful. Therefore, we need to make a significant stride forward in agriculture. All these considered, the global food supply was increased enormously in recent farming techniques pertaining to the Green Revolution. The influence on the environment and on ecosystem services was also unanticipated and harmful, which highlighted the need for more sustainable agriculture techniques [1, 2]. Excessive and improper use of fertilizers and pesticides in soil and surface waterways has been well established to increase nutrients and toxins, incur health and water purification expenses and decrease fishing and recreational alternatives. Agricultural practices that contribute to the eutrophication of aquatic habitats by degrading soil quality and may require increased fertilization, irrigation and energy expenses to maintain productivity in degraded soils. They also destroy profitable insects and wild animals.

Nanotechnology may be possibly the best solutions to eradicating the problems. Nanotechnology has got gained strenuous attention these days due to that will its diverse applications. Aside from that, there will be numerous future benefits, such as improved food quality and defense, a reduction in agricultural inputs, enrichment by absorbing nanoscale nutrients from your soil, etc. the usage of nanotechnology to be a persistent burden. For example, nanopesticides and nanofertilizers can assist in generating returns without decontaminating soils, water, and protecting against a few insect infestations and microbial issues [3]. As a result of nanotechnology, new agrochemical agents and totally new delivery methods are available to boost crop yield, and pesticide applications are expected to be reduced. Agriculture can benefit from nanotechnology in a number of ways, such as: nanoformulations of agrochemicals for the application of pesticides and fertilizers for crop progress, the use of nanosensors in crop protection with the identification of diseases, and nanodevices for genetically modifying crops and postharvest management, among other things [4, 5].

Nanotechnology has a lot of promise in agriculture, but there are still a few concerns that need to be addressed as part of the risk assessment. Nanoparticle attractants made from biopolymers such as proteins and carbohydrates have a low impact on human health as well as the environment in this regard [6]. When it comes to gardening products, nanotechnology may be used at every stage of the process, from manufacture to storage to labeling and distribution [7]. Because of its potential to enhance plant absorption of nutrients, detect disease, and manage pest infestations, nanotechnology can transform the agricultural and food sector.

2. Nanoparticles

The word "nano" is derived from the Latin nanus, which means dwarf or little. Nanoparticles (NPs) are tiny particles with a diameter of 1–100 nm. When a particle has a diameter between 1 and 100 nm, it is classified as a primary nanoparticle [8]. Nanoparticles, whether or not regarding normal or perhaps made origins have got inside the array of 1–100 nm inside one or more dimensions. A nanometer (nm) is a SI unit of length equal to 10–9 meter. NMs are materials with a length of 1–1000 nm in at least one dimension; however, they are usually characterized as having a 1–100 nm diameter. The U.S. Food and Drug Administration (USFDA) also describes NMs as "materials with an area of roughly one dimension and depending on dimensions of approximately 1 to 100 nm" [9]. To put it another way: according to International Organization for Standardization (ISO), NMs are "materials with any external or internal nanoscale dimension or surface structure at the nanoscale" [10].

Typically, nanometer will be a single billionth of the meter. Nanoemulsion, carbon dioxide nanotubes, quantum dots, nanorods, small and also nano- encapsulation and so forth. Morphology-aspect proportion or perhaps dimensions, hydrophobicity, solubility-release regarding dangerous types, surface or perhaps roughness, surface area types contaminations or perhaps adsorption, in the course of activity or perhaps historical past, reactive O2 types (ROS) O2 / H2O, ability to make ROS, construction, structure, competing holding web sites together with the receptor and also dispersal and also aggregation will be the crucial qualities regarding nanoparticles. Nanoparticles have several unique properties including a greater charge density and reactivity, considerably more strength, increased heat resistance, a lower melting point, and different permanent magnetic properties linked with nano-clusters. Distinctions inside the uncovered surface area regarding diverse nanoparticles cause differences inside atomic syndication throughout the nanoparticles, which often affect the particular electron exchange fee kinetics among metallic nanoparticles and also matching adsorbed types. These types of distinctive qualities provide the subsequent benefits to nanoparticles within farming, for example, greater solubility within the suspension, greater transmission associated with seedling jackets as well as consequently rising origins, much better bioavailability associated with substances towards the seedling radicals, supplying real focus as well as managed discharge associated with fertilizers or even pesticides within reaction to particular problems, enhanced specific exercise as well as eco-friendly along with security as well as calm transportation.

Nanoparticles tend to be seen as a distinctive bodily as well as chemical substance functions such as surface area, pore size, particle morphology, and reactivity because of their rigorous programs within the farming area. Nanoparticles are used in nano fertilizer, nano-pesticides as well as herbicides that are helpful to improve plants development, to manage extreme utilizes associated with chemical substances fertilizers as well as improve survivability towards biotic tension. The effects of various nanoparticles on plant development and phytotoxicity have been documented by a number of substances such as magnetite (Fe3O4) nanoparticles, alumina, zinc, and additionally zinc oxide in relation to seed germination [11]. Wheat can benefit from the addition of nanoparticles to their environment. The particular Zn takes on essential function inside place metabolic rate simply by influencing the actions regarding hydrogenase and also carbonic anhydrase, stabilization regarding ribosomal fractions and also activity regarding cytochrome. Place digestive enzymes stimulated simply by Zn get excited about carbs metabolic rate, servicing with the strength regarding cell filters, necessary protein activity, rules regarding auxin activity and also pollen creation. Magnesium (Mg) is involved with numerous physical as well as biochemical activities; it's an important component concerning growing development as well as improvement and performs a vital part within grow support systems within abiotic tension circumstances. The actual common perform associated with Mg within vegetation is most likely it's part since the main atom from the chlorophyll molecule within the light-absorbing complicated associated with chloroplasts and it is a factor to photosynthetic fixation associated with CO2.

3. Potential application of nanoparticles as fertilizer in agriculture

Having the limited resources, development of agriculture for the higher growth now becoming the management practices, and fertilizer management has proved the significant in a remarkable way [12, 13]. Considering the novel method of fertilizer application as a form of nanoparticles has stimulated the attributes of plant growth by the upgradation of soil system [14]. As the field condition, fertilizers variation, pH of soil etc. are being the major determinant but the slow-release mechanism of nutrients improves the efficiency of fertilizer use efficiency [15]. The activities of plant root system also accelerated by the use of nanoparticles [16]. Researchers [17] addressed chemical fertilizers as the prime factor for crop production while at the same time it also degraded the soil fertility. But the controlled use of nano-fertilizer has improved the physio-chemical attributes of the crop plants in every possible way from synthesis to metabolism. It has made more efficient practices to improve the system of agricultural practices with the new idea like precision farming involving with the technology like slow release, quick release, specific release, moisture release, heat release, pH release, ultrasound release etc. [18]. Although nanotechnology in agriculture has proved the blessings but it also has come with great risk for every living communities [19]. Therefore, to implement the advancement of agriculture sector for developing countries like Bangladesh need to grasp this huge potential of nanotechnology without delay.

4. Nanotechnology in pesticides use

To meet the hunger of the over populated countries higher yield is the prime concern and to meet the yield potential use of pesticide has covered the whole system of farming [20]. Pesticides are chemical substances enormously used to eliminate and control the harmful organisms that cause economic damage to agricultural production [21]. Every year insect pests and plant pathogens cause significant crop loss, which is around 14% and 13%, respectively, with an approximate value of U.S. $2,000 billion globally [22]. It has been reported that a minimal amount, approximately less than 0.1%, of pesticide reaches the sites of action due to loss of pesticide in the air during the application, and as run-off, spray drift, off-target deposition, and photo-degradation, the remaining bulk contaminates the surrounding environment [23, 24]. Again, these toxic chemicals are responsible for various health issues such as neurological effects, respiratory diseases, cancer, Parkinson's disorder, fetal diseases, infertility, diabetes, and genetic disorders [25]. With the rising demand for pesticides throughout the world to minimize the effects of pathogens and pests, measures should be taken to reduce pesticides' excessive application by finding appropriate alternatives. Due to the extensive use of conventional pesticides, bioaccumulation, which is caused due to biomagnifying of persistent organic pollutants and the development of resistance in the target pests, is a major concern in this generation [26, 27]. Therefore, a craze has already been started to minimize the excessive pesticide use. With the application of nanotechnology in manufacturing various nano-based pesticides, we can easily overcome these limitations [28]. Nanotechnology can reduce the application of high amounts of pesticides as nanomaterials have a high surface area with enhanced reactivity, thus lowering the cost with increasing yields [29]. Thus, the less frequent application is good for costs and human and environmental safety, ultimately a great asset for sustainable agriculture [30].

Nano based pesticides, fungicides, herbicides, molluscicides, nematicides, miticide, and nanoparticulated growth regulators are effective against various pests such as insects, rodents, weeds, fungi, viruses, bacteria, and mites [31–34]. They are also eco-friendly as they increase the formulation properties, including dispersion of water, chemical solidity, adhesion, permeability, and finally, controlled-release [35, 36]. The solubility rate of poorly soluble active ingredient can be increased with nano pesticide formulations, which ultimately helps the active ingredient release slowly and effectively. For example, nanoparticle formation like nanoencapsulation of agrochemicals such as insecticide or pesticide can increase the absorption rate and the slow and efficient release of various agrochemicals to a particular host plant for pest control [37, 38]. A small amount of nano-pesticides gives better crop protection because of their high reactivity at Nanoscale compared to their bulk counterparts [39]. For example, for the development of various nano-pesticides, we can use some effective chemical ingredients like silica, silver, carbon, and aluminium silicate [40].

Nanoparticles can be used effectively in pest control through the use of porous silica loaded with water-soluble pesticide for the ability to slow-release [41]. The cuticular lipid barrier is found in insect pests, which can be obstructed by the nano-silica component [42]. Nanoscale alumina has been used effectively against two insect pests: *Rhyzopertha dominica* (F.) and *Sitophilus oryzae* (L.), and these nano aluminium particles have shown high mortality [43]. *S. oryzae* (L.) can also be controlled with Ag NPs, synthesized from leaf extracts of *Euphorbia prostrate* with 100% mortality rate [44]. On the other hand, combinative applications of compounds like nanoparticles of silver-zinc combined were applied against one of the destructive pest, *Aphis nerii*, with a high level of mortality [45]. Ag NPs decrease the longevity of cotton bollworm (*Helicoverpa armigera*) upon treating larvae and pupae [46]. In addition, CuO NPs controls cotton leafworm larvae (*Spodoptera littorals*) with mortality of 100% [47]. The application of *Bacillus thuringiensis*-coated ZnO NPs is effective nano pesticides that delay the larval and pupal development period of cowpea weevil (*Callosobruchus maculatus*) [48]. A large number of chemical companies have started marketing nanoparticle-based pesticides in recent years, for example, Subdue M.A.X.X., Primo M.A.X.X., Banner M.A.X.X., Ospray's Chyella, and Penncap-M [49, 50]. Beyond any doubt, nanotechnology in pesticides is going to take over the conventional method of pesticide use for its efficiency. We also need to assess the credibility of nanomaterials in pesticide as it is totally new and directly related to the environment [51].

Nanotechnology is a significant research strategy which enables easy understanding of technology for the modern world. From the enormous efficiency of nanotechnology pesticide based on nanoparticles, encapsulation of nanoparticles or nanoparticle-based DNA transfer to enhance the pest resistant are some examples of smart and precision farming [52]. Because it can stimulate the improvement of farming by means of application in nanoscale strategies [53]. Which will enable the hazardous use of chemicals in farming sector by stimulating the approach of farmers to implement the precision farming. The present strategies of farming are the application of pesticide without considering the actual efficiency or persistent. That is why nanotechnology-based use of pesticides like nano-encapsulation, controlled release mechanism could be useful for the betterment of sustainable agriculture [54].

5. Use of nanobiosensors

The Advancement in the 21st century of agricultural science new ideas like nanotechnology evolved the system of cultural practices. Now a novel strategy for this aspect is the nano-biosensors. These nanoscale miniature devices are used to detect analytes at extremely low concentrations. It is a method of integrated approach with the combination of computer, electronics or nano-sciences in respect to the concern of biology [55, 56]. The sensors are being used to control moisture and pH level of soil, monitor temperature, crop nutrient status, insects, plant diseases, weeds etc., ion detection with the effectiveness of fertilizer or pesticide application strategy [57]. This real-time monitoring is accomplished by deploying wireless nanosensor networks over cultivated fields, which provide critical data for agronomic intelligence operations such as crop planting and harvesting at the appropriate times. The main strategy of this mechanism is to being the cost-effective production in agriculture by promoting the techniques of less input for the farming activities [58]. Nanobarcodes and nanoprocessing might potentially be used to track agricultural product quality. Scientists at Cornell University exploited the notion of supermarket barcodes to decode and identify diseases in a cheap, efficient, faster, and easy way. They developed minuscule probes, sometimes known as nanobarcodes, that may be used to track numerous diseases in a farm and be identified using any fluorescent-based equipment.

6. Nanomaterials for soil remediation

Soil is an inevitable medium for plant growth and food production; also, it operates planetary processes for the existence of life on earth. That is why soil is the most crucial component for the terrestrial ecosystem to flourish [59, 60]. Soil operates various vital events like biogeochemical cycles, water cycle, earth's climate, pollutant detoxification, biogenic gas regulation, ecosystem restoration, and biodiversity maintenance [61, 62]. Soil can be contaminated by various chemicals like heavy metals, pesticides, and POPs that can be remediated effectively with nanomaterials' help. For example, nano-based materials can be used to convert heavy metals to their less toxic forms, pesticide degradation, and bioremediation of contaminated soil. Besides, nano-based sensors are useful components for detecting harmful pesticide residue in the soil, like detecting Mn impurities with grapheme nanoribbon [63, 64].

For soil remediation, conventional physical and chemical methods are available, but there is a risk of secondary contamination due to these remediating agents' high quantity uses [65]. Again microbial-based soil remediation is eco-friendly but not sufficient for higher costs [66]. These limitations can be easily eliminated with nano-based techniques such as nano fertilizers, nano biosensors, nano pesticides, and different nano-remediation processes [55, 67, 68]. Conventional soil remediation methods are mainly in situ and ex situ types where nano-remediation is normally on-site method without transportation of soil, which makes this cost-effective [69, 70].

Nanoparticles possess various mechanisms such as redox reactions, adsorption, ion exchange, surface complexation, and electrostatic interaction, which are useful for the adsorption and degradation of pollutants [71]. Moreover, other features include lower temperature modification, shorter interparticle diffusion distance, and multiple surface chemistry that make these materials appropriate catalysts for the remission of the concerned soil pollutants [72]. Nanoparticles are very much fruitful for the degradation of common industrial contaminants such as chlorinated organic compounds, petroleum nano aromatics, nitrates, heavy metals (arsenic (As) lead (Pb), copper (Cu), zinc (Zn), nickel (Ni), cadmium (Cd)), insecticides, and dyes [73–76]. For instance, specific organic and inorganic compounds such as natural short-ordered aluminosilicate, the surface of titanium oxide, and humic acids can be coupled with Ni through a multiwalled carbon nanotube. These components are effective nano-bioremediation for the sustainable agricultural system [77, 78].

Nano-scale zero-valent iron (nZVI), titanium dioxide (TiO2), zinc oxide (ZnO), multiwalled carbon nanotubes (MWCNTs), fullerenes, bimetallic nanoparticles are widely used NPs for soil remediation because of their large surface area, high reactivity, and reduction capability [70, 79–81]. Surface-modified nano-scale carbon black can reduce the bioavailability of Cu and Zn; also, nanometer hydroxyapatite can remove Cd pollution from the soil, which promotes plant growth [82, 83]. On the other hand, nanometer zeolite can remove Cu and Pb; both are organic and heavy metal pollutants of soil [84]. Some researchers [85, 86] showed that Cd and Zn pollution could be repaired with the help of a ferric tetroxide nanometer.

Apart from all positive impacts, nanomaterials caused toxic effects on organisms dependent on soil [87]. For instance, copper nanoparticles negatively impact rats, as copper's toxicity is related to the particle size [88]. Again, some heavy metal ions can be dissolved with metal nanomaterials, which is toxic for the ecology. Nano-TiO_2 and its byproducts affected the antioxidant system and oxidative stress reaction of earthworms, one of the essential soil organisms [89, 90]. For this reason, we should pay more to keep an eye on the biological toxicity of nanomaterials used in soil remediation. Though the development of the appropriate use of nanotechnology for remediation of polluted soils is essential with the help of numerous uses of nanomaterials, we also need a comprehensive understanding of the human and environmental risk–benefit balance by using these nanomaterials [91].

7. Fate of nanomaterials in soil

In assumption, soil is meant to be the biggest receiver of NPs. When nanoparticles or nanoformulations are given to plants, the substance eventually makes its way to the soil, where it may be used. Because of its proximity to plant roots and microbes, the nanomaterial establishes a unique connection with them once it is in the soil. In addition to soil, which is the most abundant source of natural nanoparticles, both as primary particles and aggregates, it is also regarded an externally significant environmental matrix. Dissolution, transformation, and aggregation/disaggregation are among of the mechanisms that regulate the fate of NMs in soils. In soils, several of the mechanisms that determine NM fate and behavior, such as straining, deposition/mobilization and diffusive transport are substantially different (**Figure 1**). The significance of these factors varies depending on the NM and soil conditions [92, 93]. Because dissolution destroys them and aligns their destiny and bioavailability with the soluble components, dissolution may be critical for some NMs. Examples include the fast dissolving of ZnO, which is likely to be ephemeral in soil unless coated with compounds that prevent dissolution. When it comes to dissolving, pH is the most essential factor to take into consideration.

For example, researchers [92] used a worldwide database to compare soil saturation extract pH and ionic strength to NMs critical coagulation concentrations. Since the pH and Ionic Strength of most soil solutions are below the critical coagulation concentration of most nanomaterials, homoaggregation would be sluggish in most soils. As in aquatic contexts, heteroaggregation is anticipated to play a major role in soils because soil porewaters frequently include larger quantities of natural colloids in suspension. In most soils, NM condensation will occur in the topsoil with limited transport to the depths, resulting in increased straining (**Figure 1**). In soil porewaters, NOM has been reported to stabilize NMs and prevent both homo- and heteroaggregation, according to several studies [94]. NM movement in soils has been studied in a limited number of researches, and this is likely the most important gap in understanding the true danger of NM transport. NM transport researches in soils have evolved from utilizing inert stationary phases (e.g., quartz beads) in columns to employing real soils in the recent decade. It appears that the CNTs are retained in soils due to their large aspect ratio, resulting in considerable straining. There is a high concentration of fullerenes in soils due to interactions with soil organic matter.

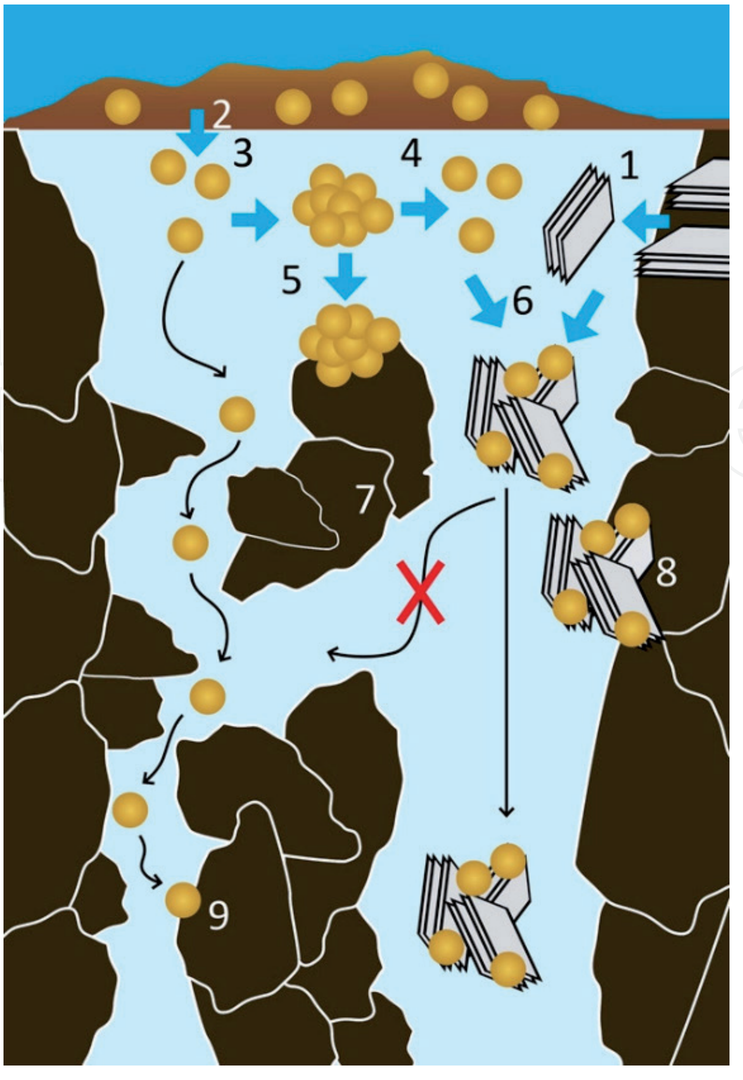

Figure 1.
The key mechanisms that determine the fate of natural colloids and nanomaterials in soils. 1, colloid generation; 2, engineered nanomaterial leaching from biosolids; 3, homoaggregation; 4, fragmentation; 5, sedimentation; 6, heteroaggregation; 7, size exclusion; 8, straining; 9, deposition; 10, convective transport [92].

8. Effect of nanomaterials on soil/plant systems

Nanotechnology has opened up new avenues for increasing nutrient efficiency and lowering environmental protection expenditures. The fact that fertilizer usage efficiency is just 20–50% for nitrogen and 10–25% for phosphorus is alarming [95]. According to researchers [96], the introduction of nanofertilizers as an alternative to traditional fertilizers would remove nutrient buildup in soils, therefore eliminating eutrophication and drinking water pollution. The main idea is to improve the efficiency of native and applied phosphorus in soils to keep the ratio of applied and plant absorption P near unity. Because nearly all P fertilizers contain heavy metals and, more significantly, deliver P to plants in accessible forms, there is a need to regulate critical and harmful components linked with phosphorous in the pedosphere–hydrosphere continuum. Nanofertilizers increased the quality of agricultural goods, eliminated environmental risks, and needed less fertilizer than conventional fertilizers [97]. Because the rate of release of absorbed nitrogen (or fertilizers compounds) is much slower than that of adsorbed ionic forms of nitrogen, zeolites could be used for nitrogen capture and storage [98]. Researchers [99] noticed that zeolite chips containing urea in their cavities can be used as a slow-release nitrogen fertilizer material. When zeolites were loaded with nitrogen, potassium, phosphorous, calcium, and a set of minor and trace nutrients, few researchers [100] discovered that the honeycomb-like layered crystal network slowly released nutritional ions "on demand."

According to another researcher [101], application of a nanocomposite comprising N, P, K, certain micronutrients, mannose, and amino acids improved nutrient absorption in grain crops. A group of researchers [41] used zinc–aluminum layered double-hydroxide nanomaterials with plant growth regulators and discovered that the products released chemicals in a regulated way. These studies showed that nanotechnology may be used to build advanced supply tools with great success. There are carbonaceous chemicals that are secreted into the soil that allow N and/or P mineralization from organic matter and P mineralization from soil inorganic colloids in nutrient-depleted soils. As environmental signals, these root exudates may be utilized to make nanobiosensors, which could then be integrated into new nanofertilizers, according to the authors' hypothesis.

It's well-known that current fertilizers create soil acidity, alter soil carbon profiles, harm beneficial microorganisms, weather clay minerals, and collect heavy metals in the soil. As receptacles, novel nanofertilizers use plant-nutrient ions intercalating or adsorbing on clay minerals. Salts make up the majority of current fertilizers, with one component consisting of plant-nutrient ion(s), whereas the other component isn't particularly beneficial or harmful at all. To enhance soil structure, reduce salt concentration, and promote crop development in salt-affected soils, nanotechnology can be utilized to improve soil structure. The following are some areas where research might be initiated: CaCO3 solubilization, Na2CO3 prevention, adding K+ to clay minerals, and increasing precipitation are all examples of ways to reduce salt concentration in soil solution, improve drainage, and/or replace Na + with Ca2+ and/or K+.

In order to determine the influence of nanoparticles on soil microbial activity, soil respiration and enzymatic activity must be measured. Soil enzymatic activity and bacterial abundance may be affected by metallic nanoparticles [102]. They can also cause free radical damage to bacteria' cell membranes, DNA and mitochondria. Even beneficial microorganism communities may be threatened by the introduction of nanoparticles (NPs) into the natural environment. In flooded paddy soil, TiO2 and CuO nanoparticles reduced soil microbial biomass and enzymatic activity, as well as their community structure. Increased Fe3O4 nanoparticle concentration dramatically reduced the number of bacteria in soil, and produced cavities, holes and membrane breakdown in the microorganisms [103].

Bipolaris sorokiniana and *Magnaporthe grisea* were exposed to silver ions and silver nanoparticles to determine their effects [104]. These treatments effectively inhibited colonization of both fungi, with an EC50 much lower than the ionic Ag treatments. Scientists have demonstrated antibacterial activity of Ag nanoparticles and polyvinylpyrrolidone (PVP) against three types of bacteria [105]. Researchers have shown that Zinc oxide nanoparticles (ZnO NP) are as antibacterial as silver nanoparticles (AgNPs). Sulfur dioxide (ZnO) was typically more toxic to bacteria in the Gram-positive group than the Gram-negative group. *Staphylococcus aureus* was treated for 8 hours, and *Salmonella typhimurium* for 4 hours [106]. When it came to *Botrytis cinerea* and *Penicillium expansum* colonization, the S NPs (35 nm) were shown to be more efficient than the larger particles.

9. Nanomaterials to mitigate environmental stresses in plants

Plants are sessile organisms and undergo abiotic stressors that impact their development and production throughout their life cycle. In response to environmental stressors, plants generate defensive mechanisms at multiple levels through modification of their biochemical and morphological routes as well as their molecular pathways (the changing of genetic expressions). But these are not sufficient to annul all the adverse effects of environmental stress. The salinity reduces, for example, the osmotic potential of the soil, resulting in food disequilibrium. Improve ionic toxicity negatively impacts many important biochemical or physiological activities including photosynthesis, protein synthesis and lipid metabolism. The rising world population and the concomitant decline in food supply, with ongoing environmental changes, are currently in a difficult state. Therefore, scientists' main focus is to develop strategies to expedite the plant adaptation to environmental changes.

In the worldwide scenario, salt stress alone reduces crop yield by roughly 23 per cent according to current agricultural practices. In previous study on nano-SiO2 treatment on tomatoes and squash plants, there have been numerous beneficial results on the usage of nano fertiliser in salty circumstances [107, 108]. The use of silica nanoparticles increases plant tolerance to drought stress by promoting plants' agronomic parameters, physiology, biochemistry, delay senescence, and maintained water status of plants exposed to the water-deficit condition [109, 110]. *Crataegus sp*. has enhanced dryness tolerance with varied concentrations of silica nanoparticles, changing their physiological and biochemical processes [111]. Researchers think that growing agricultural plants with shorter life cycles is particularly efficient in areas susceptible to drought or flash-flood here early crop maturation is a critical component for sustained crop output [112]. Studies revealed that the life cycle of the wheat crop used in nano fertilizers is considerably shorter than the traditional wheat crop used in fertilizers, which is 130 days compared with 170 days (date of sowing to yield production) [113].

Although several investigations of the use of nanomaterials to plant development have been carried out during stress environments, the fundamental components remain mostly unexplored. However, researchers believe that, under unfavorable environmental circumstances, the impacts of nanomaterials on crop development are partially attributable to the enhanced enzyme activity. The activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) are regulated by nanoparticles [114]. Increased SOD activities have been observed by the application of TiO2 nanoparticles on onion seedlings [115]. At lower levels of TiO2 the activity of the enzyme is greater. The buildup of free proline and amino acids is escalating by nanomaterials (nano-SiO2 and nano-ZnO). The consumption of nutrients and water might also rise. The use of these nanoparticles further enhances the activity of the antioxidant enzymes such as SOD, CAT, POD and reductase nitrates. Nanomaterials can also control the expression of stress genes. For example, microscope research showed that silver nanoparticles in *Arabidopsis* can regulate a number of genetic expressions [116]. These genetic responses, which are produced by nanomaterials, are therefore directly related to plant stress defense.

10. Nanomaterials in plant defense mechanisms

Plants represent the boundary between the environment and the biosphere, thus understanding how nanomaterials influence them is crucial for ecological evaluations and assessments of environmental impact. Terrestrial plants can be threatened by metal-based nanoparticles (NPs); yet, little is known about plant defense systems that could combat nanotoxicity. When cells are subjected to nanoparticles and oxidative pressure develops, the equilibrium between cell function as well as antioxidative defense systems is altered. A group of researchers [3] described

Nanoparticles	Mode of action	References
Chitosan	Total phenolics and NO signaling molecules are elevated, as is the expression of defense-related genes, such as numerous antioxidant enzymes.	[118]
TiO_2	SOD, catalase, and peroxidase (POD) activities are increased, and reactive oxygen free radical buildup is reduced.	[119]
Multi-walled carbon nanotubes (MWCNTs)	Antimicrobial pathogens cannot complete their life cycle because ROS defense response cascade is activated. ROS, such as super peroxides and H_2O_2, are generated.	[120, 121]
Silicon	An improved resistance against fungus in maize	[122]
Copper oxide	Raise the levels of SOD and CAT, as well as lipid peroxidase	[123]
Cerium oxide	Rice seedlings are exposed to lipid peroxidation and photosynthetic stress when exposed to CeO_2 (modifications of antioxidant defense system)	[124]
Zinc oxide	GSH levels and CAT activity are both higher.	[125]

Table 1.
Nanoparticles and its mode of action.

cell membrane damage due to oxidative stress, as well as DNA degradation are all caused by biochemical factors that produce unnecessarily high reactive oxygen species (ROS). Different defensive mechanisms can be triggered by plants in response to stress [117]. As an example, using nanoparticles to boost plant defenses is one of the most intriguing aspects of this technology (**Table 1**). An enzyme and a non-enzymatic agent are used in plants' antioxidant defense system. These agents include SOD, CAT, APX, ascorbate peroxidase (APX), and glutathione reductase (GRT) (GR).

It has been demonstrated that nanoparticles of cerium oxide imitate enzymes for scavenging. This feature increases the plant's defensive system. As a result, microbial pathogens are prevented from completing their life cycle by multiwalled carbon nanotubes (MWCNTs). Changes in enzymes are prevalent as a result of fluctuations in ROS levels [126]. ROS play a major role in the start of plant disease resistance responses, since they are essential signals for resolving defensive gene installation. To further understand plant defense mechanisms against nanoparticles, more research is needed.

11. Nanotechnology in food industry

Food production must double by 2050 to satisfy the demands of the world's increasing population, food production must double by 2050, and new strategies are needed to fight hunger [127]. The rising global human population has resulted in a larger population to feed, and agricultural production has not kept pace with this growth. This imbalance has shown the actual need for food preservation for food items to reach people worldwide. The establishment of nanotechnology in the food sector has made it easier for food to be transported to various areas globally by increasing most food items' shelf life. The latest developments in nanostructured materials that significantly affect the food sector are novel methods in food nanotechnology (**Table 2**). Nanotechnology in today's food sector has played a significant role in food processing, food packaging and food preservation. Many areas of food science have been revolutionized by the fast growth of nanotechnology,

Nano-Technology	Description	Example	Reference
Nanostructures food ingredients	Nano-engineered additives	Titanium dioxide (TiO2) is a Nano-engineered additive that is used as a colorant, and an antibacterial agent.	[128]
Nano-Emulsion	Nano structured Emulsion	The Nano-Emulsion method is used to produce low-fat mayonnaise and ice cream that are as creamy as their full-fat counterparts, providing customers with healthier choices.	[129]
Nano-encapsulation	Delivery systems for additives and bioactive	Nano-encapsulation is the process by which bioactive chemicals are incorporated, absorbed, or dispersed.	[130, 131]
Food packaging	Silver, Zinc oxide, Titanium oxide, Silver oxide used in the food packaging.	In green asparagus, silver nanoparticles inhibit the development of aerobic psychrotrophic bacteria.	[132]
Nanosensors and nanobiosensors	Quality control and food safety assist in the detection of any subtle changes in food color as well as any gasses produced due to spoilage	Gold, platinum, and palladium are used to make the gas sensors. The gold-based nanoparticles can detect the aflatoxin B1 toxin present in milk.	[133]
Food processing	Fortification	Incorporation of nutraceuticals, viscosifying and evaporating agents, vitamin and mineral fortification	[134]

Table 2.
Current uses of nanotechnology in food industry.

particularly those involving food processing, packaging, storage, transportation, functioning, and other safety concerns. A wide range of nanostructured materials (NSMs), from inorganic metal, metal oxides, and their nanocomposites to nano-organic materials with bioactive agents, has been applied to the food industry. **Figure 2** shows the application of nanotechnology in the food business [136].

12. Nanomaterials for recycling agricultural waste

Demand for agricultural goods is rising rapidly as the population grows. More food items are being produced to satisfy this increasing demand, resulting in a rise in waste materials. Waste is a significant issue throughout the globe, and it is produced by a variety of agricultural, industrial, and urban activities. Agricultural wastes are such kinds of wastes derived from various agricultural activities, including processing raw agricultural products; plant debris; excessive use of pesticides and fertilizers that enter into our ecosystem; wastes from animal farms and slaughterhouses; salt and silt drained from fields and finally harvest wastes. In other words, these are leftovers from the production and processing of raw agricultural goods, including fruits, vegetables, meat, poultry, dairy products, and crops [137]. Large amount-of agricultural wastes are generated every year throughout the world that can be solid, liquid, or slurries in form depending on the agricultural activities, posing a threat to the environment (**Table 3**). We are exploiting our environment using excess amounts of agrochemicals like pesticides and fertilizers every year.

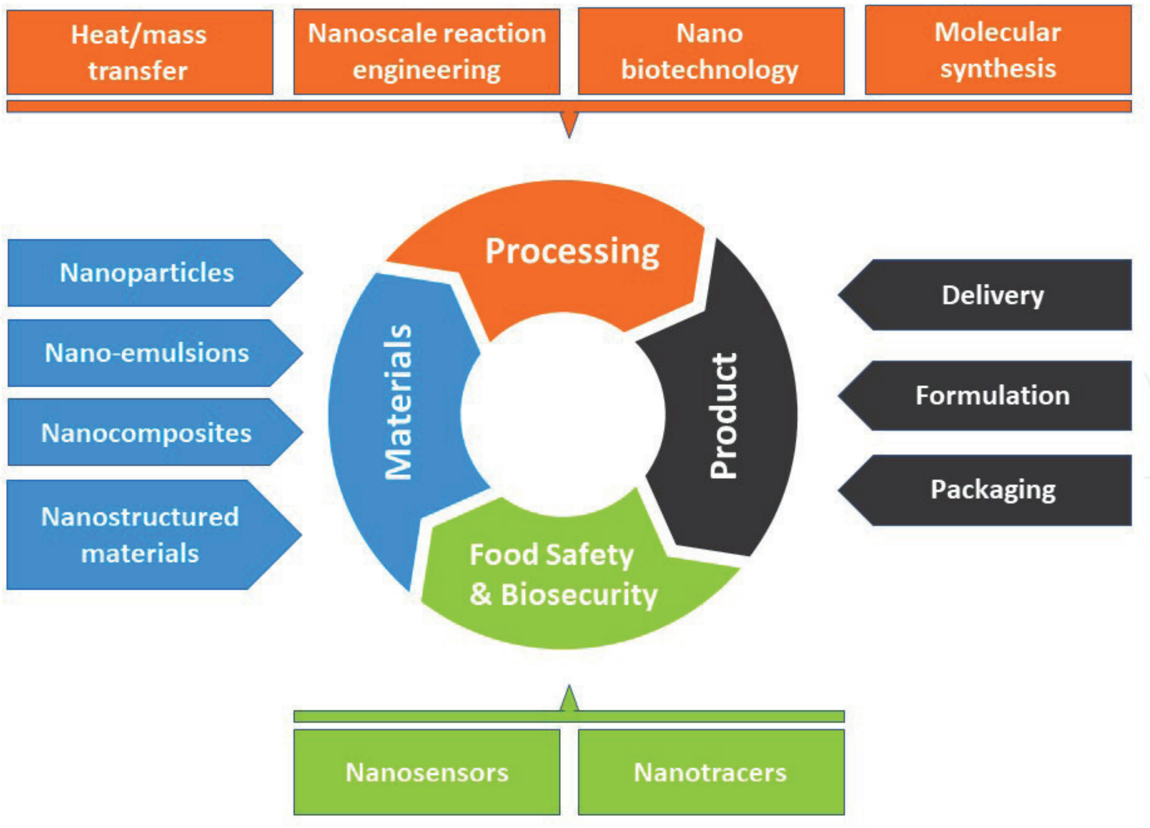

Figure 2.
Application areas of nanotechnology in food industry [135].

Classification	Origin point	Wastages
Garbage	Domiciliary/merchandise	Kitchen waste (food), poultry/slaughter house
Settlings	Domiciliary/retailer	Dead leaves, wood wool, shredders waste, waste tyre rubber, polyethelene, plastic bottles, etc.
Ashes	Households/industries	Rice husk ashes, coal fly ashes
Pharmaceuticals	Industries/households	Expired medicines, scraps etc.
Waste microbes	Industries/households	Metal ion-treated cells, fungi refusals, bacterial cellulose discard, etc.
Agricultural waste	Beverage industries/food processing industries	Palm oil mill effluent, defatted seeds, orange peels, etc.

Table 3.
Classification of waste as per their source of origin [138].

These chemicals are generally persistent and have a significant impact on the environment as well as human health due to the bioaccumulation in food. For sustainable agriculture, we badly need an efficient way to properly use agricultural inputs and reduce these wastes to minimize environmental pollution. Through nanotechnology, pesticides and fertilizers can be converted and reused. Some nanomaterials for the remediation of soil polluted by agrochemicals are encapsulated and slow released fertilizers and pesticides under specific conditions; controlled release of plant growth hormones and concentration of ammonium nanoparticles that can be recycled as fertilizer [139, 140].

Photocatalysis applications, coupled with nanotechnology, offer effective results and enormous possibilities for the reduction of certain harmful chemicals from various herbicides, bactericides, and fungicides (**Table 4**). For example, for the elimination of pesticide residues from water, therefore decontamination of water is effective with the process of photocatalysis coupled to a nanomaterial [153]. On the other hand, nano-sensors can detect various chemicals and toxic pollutants that are harmful to humans. The application of nanomaterials coupled to specific antibodies can generate lights that can be used to identify and quantify agrochemicals like pesticides and fertilizers [139].

Apart from this, rice husk, a by-product from rice-mill, can be an excellent source for nano-silica production, making glass materials and concrete. This renewable nano-silica ultimately reduces the rice husk disposal problem through nanomaterials. Waste from the cotton industry, such as cellulose or other low valued products like yarns and cotton balls, can be reduced with nanomaterials' help. For example, with the use of electrospinning and newly developed solvents, 100 nm-sized fibers can be produced and use as an absorbent of various fertilizers or pesticides, which is useful for targeted application at the desired time as well as location [154, 155]. Nanocellulose can be extracted from the residues of banana cultivation like pseudostem, foliar parts, and shells, which will be the replacement of certain synthetic fibers. On the other hand, gold nanoparticles, which are numerously used in semiconductors and bio-medical areas, can be synthesized from agricultural wastes of grape seed, skin, and stalks [140, 156].

From the last couple of years, the production of ethanol from maize feedstock has increased the global price and demand of maize, and researchers are working on various nano-engineered enzymes that authorize simple and cost-effective modification of cellulose into ethanol from waste plant parts [131]. Nanomaterials also inspire the metabolism of microorganisms like the efficacy of lipid extraction can be improved with the help of nanotechnology without disrupting the microalgae. Nanomaterials like calcium and magnesium oxide nanoparticles can be used successfully as biocatalyst transporters for the transesterification of oil to bio-diesel [157].

Due to the mass production of agricultural goods, many wastes are generated every year from this sector, and with the application of nanomaterials,

Agricultural wastes	Nanomaterial associated	References
Rice husk	Calcium hydroxyapetite NPs	[141]
Olive mill wastewater	Titanium (IV) oxide anatase, iron (III) oxide nanorods NPs	[142]
Waste cooking oil	Magnetic NPs, Mesoporous silica/ superparamagnetic iron oxide core shell NPs, Molybdenum oxide/Zirconia NPs	[143–145]
Water with high phosphate content	Iron NPs	[146]
Peels of Pomegranate	Silver nanoparticles	[147]
Coconut shells	Silver nanoparticles	[148]
guava	Silver nanoparticles	[149]
Sugarcane waste	Silver and Gold nanoparticles	[150]
Banana peel	Gold nanoparticles	[151]
Grapes waste	Gold nanoparticles	[152]
peanut skin extract	Iron nanoparticles	[79]

Table 4.
Nanomaterial-associated waste management.

these wastes can be reduced, reused, and recycled effectively. Also, this new technique can be an asset for poor nations having poor sanitation, water scarcity, and inadequate resources [2, 158]. When crops are harvested, additional connected problems exist, such as crop waste, nearly 80% of the farm's biomass. The production of agricultural waste is hundreds of millions of tons annually [159]. Every year, a large amount of food and agricultural goods are wasted as agro-waste throughout the globe. It estimates that about one-third of the world's food produced for human use is lost or destroyed each year [160]. Minimizing agricultural product losses reduces resource pressures and therefore reduces the need for chemical fertilizers and pesticides [161]. It is thus time to manage waste strategically to recycle, recycle and reuse agro-purpose.

Nanotechnology is now confined to the energy, food hygiene, telecommunications, agriculture, and healthcare sectors and has now covered environmental protection and waste management. Green nanoparticles production is becoming more popular in a straightforward, ecologically friendly manner. The continual deposition of agricultural wastes or byproducts in nature has become a significant concern. Nanotechnology has the potential to be used in the reduction of waste generated during agricultural production. Agricultural wastes, including natural and non-natural wastes, may also be effectively used to produce nanoparticles.

13. Conclusion and future perspectives

Nanotechnology has a wonderful possibility in agriculture. Research on nanotechnology uses in agriculture is less than ten years old. However, given the growing inadequacy of traditional farming techniques and the excess capacity of the terrestrial ecosystem demands, we have little alternative but to investigate the nanotechnologies in all agricultural sectors. New technology is generally acknowledged as essential to the creation of national prosperity.

There's been a substantial improvement upon nanoparticles dependent programs in agriculture industries. Scanty reviews can be found about the suitable utilization as well as improvement associated with eco-friendly nanoparticles in several fields. Therefore, execution associated with nanomaterials may uplift the actual farming requirements and supply advantages in various methods. However, among the main constrict may be the toxicity associated with nanoparticles. Therefore, to conquer the actual poisonous results, various logical methods are now being created. One particular technique entails the utilization of (i) Natural organizations or even their items concerning manufacturing associated with nanoparticles that type among the eco-friendly procedures about functionality associated with nanoparticles. (ii) Bioconjugation as well as encapsulation associated with nanoparticles along with bioactive substances is guaranteeing area that prevents toxicity. (iii) Nanotechnology also offers options about degrading continual chemical substances into safe as well as occasionally helpful elements. (iv) Nanotechnology may effort to supply as well as essentially improve the actual systems presently utilized in environment recognition, realizing as well as remediation. (v) To be able to obtain prosperous utilization as well as commercialization associated with nanomaterials, various knowledge ought to work with others to style biomimetic nanomaterials as well as their assessment within the agriculture field.

In conjunction with information on the agriculture production system, nanotechnology demands a solid understanding of science as well as of production and material technologies. The severity of this task can draw talented brains into a career for agriculture. To succeed in this sector, human resources require advanced training, which is urgently necessary for new instruction programs, particularly at the graduation level.

Conflict of interest

All authors wish to confirm that there is no potential conflict of interest.

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