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The impact of nanoparticle accumulation on plant growth and soil: A review

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Abstract

This period has benefited greatly from nanotechnology, which is now widely used in many branches of science and technology. Since agriculture provides the majority of the raw materials used in industry, it is critical to have technology that promotes high yield, improved crop production, and sustainable, affordable crop protection. A great deal of study is being done worldwide in the area of using nanoparticles in agriculture. Recently, the market has been filled with nano-based materials such as nanoparticles and nanoformulations, nano-based fertilizers, nano-pesticides and insecticides, nanofungicides, and other formulations for the management of plant diseases. Although there are numerous benefits to this technology, several vices are raising concerns among researchers and practitioners. It is anticipated that uncontrolled nanoparticle exposure to soil will have a deleterious effect on the soil microbiota and, in certain situations, adversely affect key adaphic parameters such soil toxicity and infertility. Numerous responses of soil fungi and soil bacteria to nanoparticles have been seen in the investigations carried out thus far. It has been documented that stress caused by various means affects the enzymatic activity of the microorganisms. Silver nanoparticles have been shown in several investigations to reduce soil FA-hydrolysis. Further investigation is required to tackle the metal-stress caused by nanoparticles in various microorganisms. This review covers the entire spectrum of the negative effects of nanoparticles on soil fertility, as well as how they affect various soil properties and plant growth. It also identifies research gaps related to the use of nanoparticles in soil and offers recommendations for future research to develop environmentally friendly nanoparticle applications.

Keywords: microbiota, sustainable, nanotechnology, nanopesticides, and insecticides

Introduction

In the material and biological world, nanotechnology is one of the many technologies that find broad applications. Targeted molecules can be efficiently transported to atomic and subatomic levels using nanoparticles, which are 10-9 in size. This allows for the production of new products with desired properties. A bottom-up approach, which involves arranging individual atoms and molecules into nanostructures and more closely resembles chemistry or biology, is an alternative to the top-down approach, which entails shrinking the size of the smallest structures to the nanoscale, such as photonics applications in nanoelectronics and nanoengineering. One billionth of a meter is called a nanometer. In general, the term "nano" describes a size range of 1 nanometer (nm) to 100 nm in at least one dimension, and it pertains to the creation or modification of objects or materials that fall into that range. Nanotechnology is becoming the preferred technique to solve the problem of making technology more environmentally friendly, sustainable, and precise in its application. While nanotechnology research and applications in other industries are steadily gaining traction, mainstream research in tool processing and agriculture has not yet caught up ^[1, 31]. The microbial activity is increased with the use of nanoparticles, which improve soil fertility and promote organic cycles in

the soil. This helps to address wastelands, infertile areas, and hazardous landscapes to support farming and vegetation. The use of nanoparticle-mediated nanofertilizers helps to improve crop growth and fertility in the current croplands. In general, nanotechnology increases agricultural productivity for a larger population. Given that the agriculture industry bears a major portion of the global food production burden, the development of technology, and in particular nanotechnology, is likely to stimulate and define the next stage of development of agricultural practices, raising animals, using pesticides, and precise gardening techniques ^[2].

Using nanotechnology in agriculture

Approximately 60% of the population works in horticulture, which is the cornerstone of most developing economies. About half of India's workforce is employed in the farming sector, which accounts for 18% of the country's GDP. With the aid of nanoparticles (100-250 nm), which are used in various industries to create definitions for nanoparticles and increase their solubility in water, nanotechnology affects the efficiency of horticulture through the use of nano-fertilizer, nanopesticides, and nanoherbicides, which function as smart delivery systems to plants. A vital part of the ground is the soil, which is a mixture of minerals, organic matter, gasses,

fluids, and living things that sustains life as we know it.

Soil

The capacity of soil to function as a living framework in conjunction with the environment and land use limitations, to maintain or improve the quality of the water and air, to sustain plant and living organism well-being, and to perpetuate the efficiency of living systems, is known as soil well-being. A diverse network of soil organisms that help to regulate Plant disease, pests, and insects, encourage a healthy cooperative interaction between plant roots; recycle basic plant supplements; improve soil structure, which has a favorable impact on the soil's capacity to hold water and nutrients; and increase crop production [3]. Four key elements—the cycle of nutrients, insect and disease control, soil structure maintenance, and carbon transformations—are crucial to the health of the soil. To be more precise, we can state that all of these variables are largely dependent on the biochemical processes and microbial activities carried out by tiny soil-dwelling microorganisms. In 2011, NPs in biology and medicine were estimated to be worth US\$17.5 billion; additional estimates place this value at US\$53.5 billion in 2017 and US\$79.8 billion in 2019 [4]. An estimated 4 t of silver nanoparticles are used annually [5]. The production of zinc nanoparticles (NPs) is anticipated to reach 5500 t annually, which are used to replace bulk counterparts in various goods [6]. The modeling and analysis-based studies offer some insight into the production, use, and risky disposal of different nanoparticles in large quantities (hundreds of tons) annually. Ag, Al, C, Ce, Cu, Fe, Si, Ti, and Zn are among the metallic oxide-based nanoparticles that collect in the environment in relation to sludge, soil, and other waste materials. The majority of other natural resources, such as the air and water, are heavily contaminated with nanoparticles [7]. It is anticipated that when NPs increase, there will be a high concentration in the environment and maybe a greater risk to living things. The possibility of antagonistic interactions between living organisms and nanoparticles would increase in the presence of residues and deposits in significant amounts [8]. Nanoparticles have been shown to impact the microbial variety and plant growth in the environment after being released into the environment. They have also been shown to impact the microscopic characteristics of soil, such as the humic acid level and soil bacterial community [9, 10]. Issues related to ecology, toxicology, agriculture, security, well-being, mechanical elements, strategy, and administration are becoming more pressing as nanotechnology is used in more and more applications. A few uses include the intentional release of NPs into the environment, which results in increased quantity and concentration over time [11] without highly toxic qualities; bioaccumulation and prolonged exposure and presentation have predictable consequences on the evolved lifestyle, which remain unexplained [12].

Nanoparticle types

Nanoparticles' size, morphology, physical characteristics, and composition can all be used to determine their arrangement into different forms. Several types of nanoparticles have been identified, including those based on carbon, metal, ceramic, semiconductor, polymeric, and lipid

materials. They can be categorized as magnetic or non-magnetic nanoparticles in addition to being classed as quantum dots, nanotubes, nanofibres, nanorods, nanosheets, aerogel, and nanoballs [13] based on their morphology. Silver (Ag), gold (Au), titanium oxide (TiO₂), iron oxide (Fe₂O₃), zinc oxide (ZnO), and copper (Cu) are examples of metallic nanoparticles. The most commonly used nanoparticles as antimicrobial operators in water treatment and material businesses, including gadgets, drug transport tranquilizers, and agribusiness, are silver nanoparticles. [14] Gold nanoparticles are employed to diagnose cancer, while TiO₂ is utilized as a photocatalyst since it is non-toxic.

Nanoparticles of silver

The size range of silver nanoparticles is 1-100 nm. Typically depicted as silver, but with a large surface area and few molecules, it contains a large amount of oxides. Depending on the use, various types of nanoparticles can be created. Because of their unique physiochemical characteristics, silver nanoparticles (AgNPs) can be applied in a variety of fields, such as the medical, food, and mechanical industries. When compared to bulk silver, silver nanoparticles have a higher antibacterial impact due to their large surface area and portion of surface molecules [15]. Silver nanoparticles' antimicrobial properties have been used to combat a variety of human infections [16-18]. For the sake of product assurance, the maximum capacity is frequently still under investigation. Thus, there is growing interest in managing plant diseases through the application of silver nanoparticles' antibacterial properties [19]. In experiments, silver nanoparticles have been used as pesticides to reduce the weight of rodents in crops. There are three ways to join silver nanoparticles: physically, chemically, and organically. Due to the need for absurd circumstances and hazardous artificial materials in physical and chemical methods, biomaterial-based methods are widely used. Extraordinary analysts have arranged silver nanoparticles from various sources (plants, bacteria, fungi, etc.) due to their single-step union and environmental friendliness. Plants have been treated with these silver nanoparticles to get rid of dangerous germs. In a research facility, the introduction of silver nanoparticles to snails in the soil lattice was found to reduce the snails' ability to move and thrive. Additionally, about 20% of the snails were treated with the silver nanoparticles, which also prevented the recurrence of the parasitic population in the surrounding soil [20]. It has been demonstrated that spherical-shaped silver nanoparticles in the size range of about 10 to 20 nm may be effectively managed for spot blotch disease in wheat when made from the culture supernatant of *Serratia* sp. BHU-S4. When applied to the wheat spot blotch pathogen, *Bipolaris oryzae*, silver nanoparticles demonstrated potent antifungal action. A study was conducted [21] to examine the impact of 20 nm-diameter silver nanoparticles on fenugreek (*Trigonella foenum-graecum*) seeds. Various concentrations of silver nanoparticles were used, and the findings showed that very high seed germination. These results showed that seed germination potential, means germination time, seed germination record, seed power file, crisp weight, and dry weight could all be much improved by using silver nanoparticles.

Nanoparticles of zinc oxide

One of the most fundamental micronutrient deficiencies that negatively affect farming productivity in antacid soils containing calcium carbonate is zinc insufficiency [22]. Calcium carbonate-containing soil is a notable agricultural resource in regions of the world that are bone-dry or Mediterranean in climate. To alleviate zinc deficiencies in soils, zinc oxides (ZnO) and zinc sulfates (ZnSO₄ •H₂O) or (ZnSO₄ •7H₂O) are typically used as zinc manures [23]. In soils containing calcium carbonate, the use of zinc oxide nanoparticles as zinc composts may increase zinc breakdown and bioavailability. Due to its small size (less than 100 nm) and high surface-to-volume ratio, zinc oxide nanoparticles have an antibacterial effect over large zinc particles [24]. This allows for improved contact with tiny organisms. When a cell's antioxidant capability is surpassed, reactive oxygen species (ROS) produced by zinc oxide nanoparticles have the potential to cause cell death [25-28]. It has been demonstrated that zinc nanoparticles cause free radical production in wheat, which raises malondialdehyde and decreases glutathione and chlorophyll levels [29]. Zinc oxide nanoparticles, which have an approximate size of 16-20 nm, have been employed as an antimicrobial against bacterial strains, including *Staphylococcus* Front Nanosci Nanotech, 2019 aureus, *Bacillus subtilis*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, *Escherichia coli*, and other parasitic strains, such as *Candida albicans* and *Candida tropicalis*, through the use of the agar plate dissemination technique. When compared to other bacteria, *Staphylococcus aureus* had the most intense zone of inhibition (23.8 ± 0.76). *Parthenium hysterophorus* L.'s circular and hexagonal zinc oxide nanoparticles have been combined in an expensive, environmentally friendly, and simple method using unique groups of 50% and 25% of *Parthenium* leaf separates with sizes of 27 ± 5 and 84 ± 2 nm, respectively. The size-subordinate antifungal activity of these zinc oxide nanoparticles against plant parasite diseases, such as *Aspergillus flavus* and *Aspergillus niger*, was studied. When measuring zinc oxide nanoparticles at 27 ± 5 nm, a extreme zone of inhibition was observed against *Aspergillus flavus* and *Aspergillus niger*. Zinc oxide nanoparticles produced by *parthenium* synthesis have proven to be excellent antifungal specialists and condition-neighborly [30]. By using the leaves of *Catharanthus roseus* (L.) G. Wear leaf separates; zinc acetic acid and sodium hydroxide were used to create round-shaped zinc oxide nanoparticles with a typical size of 23 to 57 nm. The gram-negative microscopic organisms *Escherichia coli* (ATCC 25922), *Pseudomonas aeruginosa* (ATCC 15442), gram-positive *Staphylococcus aureus* (ATCC 6538), and *Bacillus thuringiensis* (ATCC 10792) were tested for the antibacterial activity of the orchestrated zinc oxide nanoparticles. *Escherichia coli* were pursuing zinc oxide nanoparticles, but *Bacillus thuringiensis* showed resistance to them; *Pseudomonas aeruginosa* was more vulnerable.

Titanium dioxide nanoparticles (TiO₂)

Titanium dioxide, a common photocatalyst used in the creation of color pigments, is a compound of titanium, a strong, corrosion-resistant metal [100]. Titanium stimulates the production of more starches, enhancing plant growth and photosynthesis rate [32]. It has been observed that titanium

dioxide has a reactive activity that degrades pesticides [33]. Because titanium dioxide lacks hazardous and toxic components, its photocatalytic property can be used to ensure plant safety while also having a high level of pathogen elimination effectiveness. Through dye doping and other sensible techniques, researchers are trying to increase the phytopathogenic sanitization productivity of titanium dioxide thin films [34]. Researchers are also more likely to choose plants to synthesize titanium dioxide nanoparticles from. Titanium dioxide nanoparticles, clustered and circular, with a normal size of 32.58 nm, have been integrated from *Psidium guajava* leaf concentrate [35]. *Aeromonas hydrophila* (MTCC-1739), *Proteus mirabilis* (MTCC-442), *Escherichia coli* (MTCC1677), *Staphylococcus aureus* (MTCC-3160), and *Pseudomonas aeruginosa* (MTCC-4030) were the bacteria against which these nanoparticles were tested. The maximum inhibitory zone was seen against *Staphylococcus aureus* (25 mm) and *Escherichia coli* (23 mm) in the presence of titanium dioxide nanoparticles at a fixation rate of 20µg/mL. Compared to the conventional anti-microbial plate, the incorporated TiO₂ nanoparticles demonstrated superior antibacterial efficacy. This reduced the likelihood of anti-infection agents developing resistance to bacterial species blockage. In comparison to ascorbic acid, the plant concentrate and the titanium dioxide nanoparticles derived from it exhibited the highest level of cancer-prevention agent activity. *Eclipta prostrata* leaf extract has been successfully used to synthesize spherical clusters of very polydispersed titanium dioxide nanoparticles with a size range of 36 to 68 nm [36].

Using nanotechnology in Agriculture

Farming and other agricultural activities form the backbone of many developing countries, as agribusiness generates significant revenue and the majority of the workforce is employed in this sector. There are currently about 6 billion people on the planet, half of whom reside in Asia. Many people who live in poor or emerging countries struggle with daily food insecurity as a result of environmental changes or unstable political environments, although there is an abundance of food in the developed world. The goal is to create crops with high yields that are resistant to drought and dry pests in emerging nations. The food industry in emerging economies is driven by consumer demand, which is currently for products that are more beneficial and fresher. Nanotechnology has been applied to farming and other agricultural operations for target-specific delivery of biomolecules (such as proteins, nucleotides, and activators) and controlled arrival of agrochemicals (such as composts, pesticides, and herbicides) [37]. Fertilizers with a possible discharge capacity and pesticides with improved broad range bother insurance productivity have been developed with the help of nanotechnology [38]. Nanotechnology has been applied to identify plant diseases, enhance supplement absorption, regulate plant hormones, transfer DNA to plant cells, and produce nanocapsules for use in antibody delivery in animal husbandry. There are a few uses for nanotechnology in the preparation, storage, bundling, and transportation of rural goods at every stage of development [39]. That being said, the great bulk of horticultural research involving nanotechnology is still in its infancy and has not yet gained widespread acceptance.

Effect of nanoparticles on soil

The greatest nanoparticle receptor is found in soil. The behavior of nanoparticles in soil and the assessment of their risk in ecosystems with arable soil or in other actual environmental situations is a hot issue nowadays⁴⁰. The natural matrix is soil, which is abundant in natural nanoparticles in the form of primary particles and agglomerates/aggregates. Given their capacity to accumulate in the soil and their possible extraordinary resistance to degradation, artificial introduction of nanoparticles into the soil could have a major impact.

According to Ben-Moshe and colleagues (2013), nanoparticles have an impact on a variety of soil microbiological characteristics. One of the main concerns in the area of sustainable soil usage is the preservation of soil microbial biodiversity and biomass^[41]. The concentration of nanoparticles in the soil, the kind of soil, and the soil's enzymatic activity all affect the soil. Dehydrogenase enzyme activity was found to be negatively impacted by high nanoparticle concentrations^[42]. The influence of nanoparticles on the rate of soil self-cleaning and the balance of nutrients, which forms the foundation for controlling plant feeding processes and enhancing soil fertility, is another detrimental effect^[43, 44]. Researching soil nanoparticle presence and their impact on soil biodiversity is important^[45].

The microbial community in the soil and the potential for pollutants to harm microorganisms are influenced by various features of the soil, including pH, texture, structure, and organic matter content^[46]. Pollutant mobility in soil may be impacted by nanoparticles. Thus, a comparison of the NPs' toxicity in different kinds of soils is necessary. Fly ash and digestate-supplemented soil decreased the bioavailability of pollutants. According to a different study, the distribution of particle sizes and the organic matter's makeup affect the microbial communities in polluted soils^[47]. A deliberate manipulation of the soil's composition, texture, and other attributes using different substances can also change the way the nanoparticles work. A small soil modification called biochar is used to improve soil fertility and productivity.⁴⁸ demonstrates the little impact of CeO₂ NPs on plants in soil treated with biochar. Little research has been done on how NPs and soil treated with charcoal interact.

Nanoparticles' impact on crop growth

The production of nanoparticles has been growing quickly due to their widespread use in agriculture and their application in farming and other agricultural practices. This has increased the likelihood of the nanoparticles settling on the field's soil and blending with it (fertile soil of forms). As of right now, it's known that some nanoparticles have an impact on yield, plant growth, and crop improvement. Additionally, a large number of these particles are accumulated in different plant tissues, including the edible portion of plant tissues. Assessing the impact of nanoparticles on human health and the environment is a challenging task. Because of their minuscule size (nanometer range), nanoparticles are thought to be the most dangerous type of poison found in manages. Various studies have looked into how nanoparticles affect yields. For example, germination, reduced shoot and root development,

poisonous quality, and decreases in photosynthetic rate and chlorophyll contents have been observed in onion, spinach, coriander, wheat, rice, soybean, mung bean, radish, lettuce, grain, cucumber, and tobacco^[49-57].

Nanoparticles' impact on plant growth

Plants can be affected by nanoparticles in a variety of morphological and physiological ways, depending on the kind and composition of the particles. The synthesis of the substance, the size, the surface area, the reactivity, and, most importantly, the extent of their success determine a particle's survivability^[58]. Researchers' findings showed that nanoparticles could have both beneficial and detrimental effects on the growth and development of plants. The impact of engineered nanoparticles (ENPs) on plants depends on the composition, concentration, structure, biochemical properties, and physical characteristics of NPs as well as the type of plant (Table 3)^[59-64].

Nanotechnology's function in photosynthesis

The process that plants, green algae, and certain other bacteria use to make food is called photosynthesis. For plants to go from light vitality to concoction vitality, photosynthesis is essential. Only 2-4% of the radiation's available energy is converted by plants into new plant growth^[65]. By using two characteristics of cyanobacterium in place of carbon settling in the tobacco plant, Lin *et al.* (2014) cultivated novel tobacco plants. *Synechococcus* lengthens; compared to native plants, these newly created plants have a higher photosynthetic production.

According to a paper, SWCNTs in the detached chloroplast increased photosynthetic activity in plants by multiple times compared to control levels. They also enhanced most extreme electron transport rates and let the plants to detect the distinguishing chemical nitric oxide^[66]. In photosynthetic frameworks, metal nanoparticles can increase the productivity of synthetic vitality synthesis^[67]. By binding to the AuNPs and Ag nanocrystals, the chlorophyll in the photosynthetic response focus creates a new half framework that may lead to many instances of more energetic electrons because of plasmon surface response and rapid electron-separation. The components for improvement could be useful in the design of frameworks for gathering light.

Impact of grain size dispersion of nanoparticles

It was discovered that there was a plausible correlation between the field soil's grain estimate distribution (such as the amount of sand and earth) and AgNMs' harmful effects on tiny organisms that oxidize smelling salts. Previous analyses have shown that in soils with a greater grain estimate distribution, the maintenance of nanomaterials generally increases and the bioavailability falls^[68]. It is found that soils having a higher sand concentration or a lower mud content are more vulnerable to AgNM buildup. There was a moderate correlation between increased danger and sand content; however the relationship between AgNM toxicity and sand content was not linear.

There was a strong, mostly consistent relationship between AgNM harmfulness and mud content. It has recently been observed that the maintenance of AgNMs in common soil increases with the granulometric mud content^[69]. This

could promote the heteroaggregation of AgNM and mud standard ticles, increasing their total size and reducing their accessibility to microorganisms, resulting in a lower lethality. The placement of structures containing earth particles may also prevent particle arrival. It proves that the most important soil characteristic influencing the lethality of AgNMs is, by all accounts, the spread of soil grain measures.

Impact of nanoparticles on soil pH

One important aspect that has a direct bearing on soil fertility and health is the pH of the soil. It is a sign of how acidic or alkaline the soil is. The pH of the soil influences the nutrients that are available to plants. It has been demonstrated that the makeup of the soil determines how basic or acidic the soil is. Plants generally prefer a pH range of 5-7. It has been noted that the buildup of various nanoparticle types, such as Zn, Ag, Au, Cu, etc., may have an impact on the pH of the soil. It was discovered that the toxicity of nanoparticles to nematodes and microorganisms is also influenced by the pH of the soil. The impact of soil pH and organic matter on ZnO nanoparticle toxicity in relation to *Folsomia candida* [70]. The bacterial community was found to be more sensitive to the heightened toxicity of zinc nanoparticles compared to dissolved zinc [71]. It was recently discovered that paddy soil's pH might be altered by copper oxide nanoparticles. Soil pH rises because of copper oxide nanoparticles, ultimately influencing soil properties. The pH of the soil may also have an impact on insects' ability to absorb silver nanoparticles that have collected in the soil [72]. The main element that appears to control soluble metal concentrations is the pH of the soil. pH and zinc solubility have a negative correlation [73]. Furthermore, calcareous soil had a larger percentage of clay than acidic soil, which increases zinc retention in the soil and reduces zinc availability to microorganisms because clays are thought to adsorb zinc ions by both specific adsorption and ion exchange. Soil organic matter content has also been linked to zinc availability. Because values were very low and similar in both soils, the influence of soil organic matter concentration on Zn availability to microorganisms in this study should be regarded as unimportant. The effects of nanomaterials are strongly influenced by the transformations they go through in the natural world. AgNM are oxidized in nature, and the death effect may be caused by the release of silver particles [74]. The pH of the soil affects both the oxidation of AgNMs and the particle release. This is consistent with other research showing a relationship between the particle content in soil pore water and the toxicity of AgNMs to earthworms [75]. The majority of ZnO nanomaterials' effects are also generated by particle release, suggesting that the results should be comparable to those observed for AgNMs. Similarly, the effect of ZnO nanoparticles on *Folsomia candida* growth revealed that the hazardous nature of metallic nanomaterials depended on soil pH and that the risk increased in increasingly acidic soils. For all forms of zinc, the effect of pH on Zn breakdown is reflected in the effect of zinc danger on *Eisenia fetida* multiplication [76].

Impact of nanoparticles on organic carbon content of soil

We also studied the influence of the natural carbon content

on AgNM toxicity since this parameter may alter the impact of nanomaterials [77]. Although the natural carbon content varied from 0.93% to 3.85%, there was no correlation found between the natural carbon content of the five soils we tested and the lethality of silver nitrate or AgNM. The text contains indications that environmental factors may modify the effects of nanomaterials, especially those that release particles. For example, as the broken down natural carbon content increased, the toxic character of AgNMs toward the freshwater zooplankton *Ceriodaphnia dubia* and *Daphnia magna* decreased completely [78]. Given that natural materials, such as sewage sludge, interact with AgNMs, with sorption rates greater than 90% for uncoated particles [80] and lower rates for functionalized particles, AgNMs are less adaptable in soils with a high content of natural problem [79]. Concentrates including pure societies and biofilm networks have been shown to have additional natural problems. For instance, humic acids and exopolysaccharides have been shown to stabilize microorganisms and lessen the toxicity of AgNMs [81]. For example, it was challenging to determine whether the proximity of humic acids from the Suwannee River had an effect on the growth of *Pseudomonas fluorescens*. In any event, the majority of these findings come from studies that tested the effects of natural carbon on amphibian life forms, though there is a growing lack of similar data on soil life forms. AgNMs and the particles they release have already been shown to interact with natural soil additives, reducing the long-term negative effects on the total amount of microbial activity that results in nitrate accumulation [82]. Surface adsorption onto a common natural issue is one of the suggested strategies for preventing AgNM disintegration (which thus forestalls AgNM oxidation and the arrival of silver particles) and the waning effect of fulvic and humic acids, which converts oxidized materials back into silver metal [83].

Nanoparticles' impact on microbial diversity

TiO₂ and CuO nanoparticles reduce the microbial biomass of the form soil and the chemical's action, which influences their structures in overflowing paddy soil, as demonstrated by the investigation led by [84]. Similar results were obtained by Biometal when they considered the effects of ZnO, TiO₂, CeO₂, and Fe₃O₄ nanoparticles on soil enzymatic activities (catalase, phosphatase, urease, and invertase) and bacterial networks of saline-soluble base and black soils. The results showed an impact on soil microbial activity, alterations in the soil bacterial network, and risk to naturally occurring nitrogen fixation. The obtained results show that a high convergence of Fe₃O₄, the substance of microscopic organisms in the soil was completely reduced by NPs. Zinc oxide and CeO₂ NPs inhibited enzymatic activities and had an impact on the plate checks of *Azotobacter*, *P-solubilizing*, and *solubilizing* microscopic organisms [85]. Titanium dioxide nanoparticles (NPs) reduced the abundance of useful soil microorganisms and enzymatic activities while impeding the influence of microbes on activity, occurrence, and variety [86, 87]. According to [88] Maliszewska (2016), biogenic Au NPs up to a concentration of 33 mg kg⁻¹ don't affect the qualities of soil or their processes, and they can be classified as non-destructive. However, clinical disconnects (*Bacillus subtilis*, *Escherichia coli*, *Klebsiella pneumonia*, *Pseudomonas aeruginosa*,

Salmonella typhi, and *Staphylococcus aureus*) treated with ZnO NPs incorporated by organic and concoction techniques showed antibacterial exercises (development of a zone of inhibition) [89].

Both pathogenic and helpful microorganisms were thought to be largely deadly to copper ions, which are released by Cu NPs [90]. The impact of CuO and AgNPs on leaf microbial decomposition was examined, and the results indicated that leaf breakdown rate decreased upon exposure to these NPs (Table 4) [91-95]. The researchers found that high concentrations of TiO₂ can interfere with the symbiotic interaction between bacteria and plants and stunt the growth of clover. The mobility of the nanoparticles in natural soil was low, and there was no discernible improvement in the plants' uptake of titanium dioxide. The trials revealed a concentration-independent uptake of MWCNT by the plants and a decrease in the quantity of red clover blossoms in the event of high concentrations. The mobility of MWCNT in soils was also limited. The microbial communities that interact with the plants changed in composition because of very high concentrations of both TiO₂ and MWCNT (Table 5) [96-99].

In summary

Nearly all areas of agricultural research and agriculture sciences have accelerated thanks to nano-biotechnology. It is commonly known that using nanomaterials in science and agriculture offers many benefits over traditional techniques. Nanotechnology-based biofertilizers are very beneficial to the growth and development of plants. When it comes to fighting disease and dangerous insects, biopesticides and fungicide-free methods work better. Nano-biotechnology has made it very simple to transport DNA for crop studies. The accumulation of nanomaterials in soil that is not monitored or controlled is a cause for concern. Since the late previous decades, the toxicity of nanomaterials has been established. Studies show that the toxicity of nanomaterials is a major problem that is only becoming more prevalent. It is important to prevent the needless deposition of nanomaterials since they have a direct or indirect impact on the health and welfare of humans through the microbial community and soil health.

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