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*Review*
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# Advancing Phytoremediation of Contaminated Soil through Nanoparticle-Based Approaches: Current Progress and Future Perspectives

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**Abstract:** The quality of the land, water, and atmosphere are all impacted by environmental contamination. Considerable efforts have lately been made to reduce pollution-causing sources and repair or improve natural soil and water resources. Nano-phytoremediation is more efficient and less hazardous than chemical and physical approaches. They are becoming more and more significant in this field as well as in academia. Different plant species have demonstrated the ability of nanoparticles to remediate soil and water. It is also to be expected that new environmental clean-up methods will be significantly influenced by the most recent biotechnology research. The aim of this paper is to summarise the most significant advancements in phytoremediation immediately. Plants have considerable development potential from the perspective of their phytoremediation qualities. These plants take in contaminants from the soil, water, and other natural resources. New strategies that are targeted by pollutants include segmenting enzyme activity into plant structures. Most contaminants, including heavy metals, are covered by industrial effluents and have been the subject of epidemiological research. It is fascinating to research the risks of these pollutants to develop preventive action against them. This will help us understand the fate of nanomaterials in the environment and environmentally sustainable techniques to remove them from the atmosphere.

**Keywords:** nano-phytoremediation; environment; nanoparticles; pollution; heavy metals.



## 1. Introduction

Soil contamination includes the defilement of soil by different anthropogenic (farming, modern, wastewater) exercises, which include the expansion of supplements, pesticides, and residue to the soil. Then again, industry and urbanization further contaminate the dirt with strong squander, weighty metals, solvents, and a few other sluggish, corrupting natural and inorganic substances [1-4]. The contamination comes from point and nonpoint sources, including dissolvable salts (real and fake), bug poisons/pesticides, removal of current and urban waste in agribusiness, and heavy compost use [5–9]. According to some definitions, phytoremediation is the employment of green plants, the accompanying microorganisms in the soil, soil renewal techniques, and agronomic practices to destroy, contain, or transform common hazardous chemicals into harmless compounds [10]. It is the hasty use of living plants, the mistreatment of common objects and vegetables, etc., for the in-situ removal of impurities from soils, slop build-up, surface water, and groundwater. It allows a clean-up method that is driven by cost and solar energy [11-15]. It is a clever remediation technique that combines plants to absorb particles into their tissues and remove climate-related components [16,17]. The ability to assemble, degrade, or concentrate new compounds from soil, water, and air is innate to plants. The main goal of phytoremediation is to remove harmful and toxic metals from the environment [18]. To cultivate the phytoremediation cycle for standard clean-up, physiological and atomic phytoremediation systems are sought in later assessments. Utilizing food waste is important for dealing with the use of food, vegetable, and everyday item waste [19]. Point sources include radiation, effluents, strong conveyance from projects, vehicle use, and metals from refining and mining [20-23]. Waste can be dispersed from its source through the environment, through obviously, into the actual soil, as well as into water channels and bodies. It then makes its way into the system of progress, where it has a negative impact on human existence either directly or indirectly [24]. Other metals, like cadmium, nickel, and mercury, have no physiological function but often result in harmful disorders at a higher concentration, while other metals, including copper, iron, manganese, and zinc, are essential for living processes, they do not have this property [25]. Ingestion of high-risk metals like cadmium, chromium, mercury, and lead can harm humans and other living things by causing kidney and lung damage, bone deterioration, liver damage, and other effects [26-29]. Even though dirt acts as a purportedly certified route through its sieving activity, a manufactured channel through adsorption, precipitation, and chemical alterations, and a bio-sensible channel by isolating common materials, it does not have an endless capacity to complete these jobs [30]. Unlike air pollution, which has a direct impact on human lives, soil pollution causes indirect damage to humans and other animals. Any material development that poses a risk to its ability to function can be categorized as soil pollution, including those substances known as poisons or toxins. As a potential method for removing numerous poisons in situ, phytoremediation has just come to light [31-34]. Rhizoremediation and microorganism-assisted phytoremediation seem effective at removing and degrading common contaminants from damaged soils, especially when combined with suitable agronomic organization and improvement techniques [35]. Phytoremediation is generally viewed as the environmentally responsible alternative to the typically terrible physical and chemical treatment techniques used [36]. Making local or genetically modified plants remove common chemicals has made enormous strides. According to one definition of phytoremediation, plants use direct or indirect methods to eliminate or purge pollutants from soil and water [37]. In an emerging progression, the harmful counterfeit materials arranged in soils, deposits, groundwater, surface water, and, amazingly, the air are cleared out and changed by plants and the rhizosphere bacteria that are connected to them. A practical, non-intrusive, and modest method of soil clean-up is phytoremediation [38]. Nanotechnology is a broad area of study focused on materials and applications that occur at a very small scale. Most people generally accept that nanotechnology deals with structures less than 100 nanometers (nm) and involves developing materials or devices within that size [39]. Due to their small size, which allows them to concentrate their electrons and cause quantum effects, nanoparticles exhibit various extraordinary features compared to bulk material [40]. Since they are novel compounds with verifiable characteristics, scientists in various fields have given them much consideration. For example, allotropic types of carbon, fillers, and efficient gas adsorbents for natural clean-up and as aid vehicles for various inorganic chemicals [41,42]. To be clear, ordinary and inorganic nanoparticles can be together categorized as two types of nanoparticles.While some inorganic nanoparticles may combine fascinating nanoparticles, important metal nanoparticles (like gold and silver), and semiconductor nanoparticles, common nanoparticles may combine carbon nanoparticles (fullerenes) or be created using decomposed common materials, such as orange strip, potato strip, and so on (like titanium dioxide and zinc oxide) [43], Nanoparticles usage in natural applications is growing significantly. This results from the particles' enormous surface area when separated from mass-size particles; as a result, their reactivity must be drastically altered for the intended or typical mediated responses for natural applications [44,45].

## 2. Technological advances in phytoremediation

Nano bioremediation (NBR) is the process of eliminating conventional toxins (such as heavy metals) from contaminated areas using nanoparticles/nanomaterial framed by plant and natural components, and NBR is a newly developed framework for removing dangerous compounds in order to facilitate natural cleansing. Burning, bioremediation, substance remediation, and authentic remediation are the current stages of advancement for cleaning up contaminated complaints. With ongoing improvements, bioremediation now provides a financially viable and environmentally safe option to remove pollutants from the atmosphere [46-48].

## 3. Nanoparticle interactions with plants

The size, kind, and design of the particle strongly influence how quickly plants absorb it. The primary consideration for the nanoparticle to attack inside the plants and spread from roots to various parts of the plants is size. Another factor that affects how effectively plants absorb nanomaterials is their entry procedure [49].

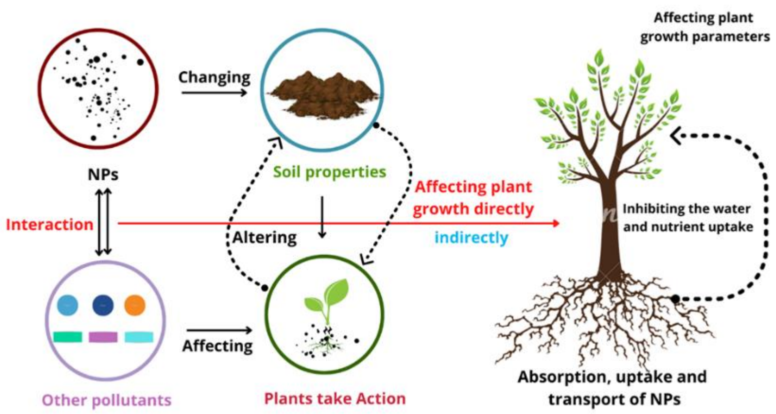


**Figure 1**. Nanoparticles interaction with soil and transportation in plants. Image is mentioned in the title of the image.

Two methods exist for migrating inside the plant tissues after entering the roots. Apoplastic transport occurs outside the plasma membrane and xylem vessels [50]. The other method is called symplastic transport, which combines the improvement of water between the cytoplasm and sifter plates [51]. The usual circumstances have an impact on take-up. The roots' length and headway materials are both influenced by temperature. The root structure in the field is different from the root structure in the nursery. A novel material that is unmistakably a hyperaccumulator is essential to advancing phytoremediation and, to be more specific, phytoextraction, as shown in Figure 1 [52,53].

## 4. Nano-phytoremediation

Nano-phytoremediation combines phytoremediation and nanotechnology to improve the environment. Nanotechnology increases the efficacy of phytoremediation, and nanoparticles can also clean up soil and water that have been hazardous to metal, organic, and inorganic chemical contamination. Recent studies have shown that ordinary new chemicals like atrazine, molinate, and chlorpyrifos may be contaminated by zero-valent irons as tiny as a Nanometer. In protein-based bioremediation, phytoremediation can also be mixed with Nanoparticles [54]. The use of nanoparticles to clean up the environment is developing swiftly. Iron nanoparticles are widely used throughout the cycle of clean-up. Some researcher looks at whether organic contaminants (PCBs, PAHs, PPCPs, and organic solvents) in the soil may be decontaminated by nanomaterials. Combining nanotechnology and phytotechnology for TNT remediation from the soil is more efficient than either technology individually, clean of Nanoparticles [55-58].

### *4.1. Factors affecting contaminant nano-phytoremediation.*

These present factors can affect how a drug is absorbed and distributed by living plants. The mixtures' physical and chemical characteristics (e.g., water dissolvability, seethe pressure, and atomic weight). Typical characteristics (e.g., temperature, pH, standard matter, and soil dampness content). Aspects of the plant (e.g., sort of underground root advancement and kind of combinations) In Fig. 2, a schematic outline of the factors affecting nano-phytoremediation is shown.

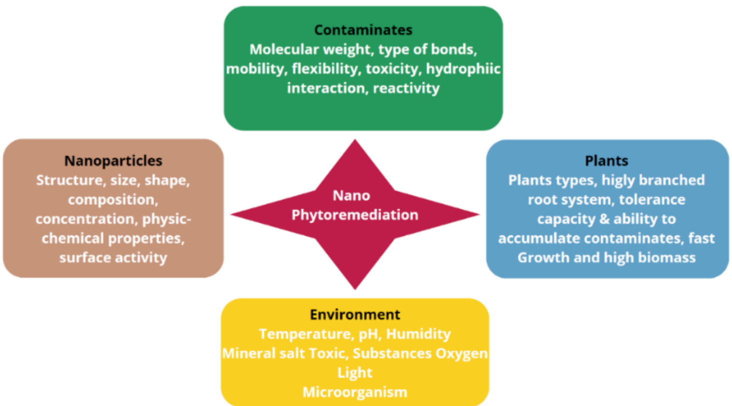


**Figure 2**. A schematic representation of the phytotechnology image is mentioned in the title of the image.

#### 4.1.1. Plants with the best properties for nano-phytoremediation.

Rapid plant growth and massive biomass production (improvement and productivity). Extended root surface district with high-level underground roots (wide, considerably fanned root establishment).The capacity to endure or accumulate debasements [59] (destructiveness obstruction limit). The more significant threshold for hyperaccumulating foreign compounds (inorganic, common, and deep metals), particularly in above-ground regions (sink potential). Simple to compile (considering the utility of the sink organ).Not suitable for human or animal consumption.

## 5. Choosing the Right Nanoparticles for Phytoremediation

The remediation of degraded soils may benefit from using a combined nano-and phytoremediation treatment (phyto-nano-treatment). To clean up contaminated areas, nano-phytoremediation propels (plant- and nanoparticle-based advances) use naturally occurring or genetically engineered plants [60]. Nanoparticles should not be hazardous to plants; increased biomass, root-shoot extension, plant level, and seedling development. Significantly increased plant production of Phyto enzymes, The ability to improve the chemicals used in plant growth, the capacity to link contaminants, and increased plant bioavailability. Using carefully chosen nanoparticles resulted in generally more advanced plant development, and nano augmentation enhanced phytoremediation capability, achieving gigantic pollutant removal from the soil environment [61]. Because they can develop plant advancement synthetic chemicals and help plants better absorb pollutants, many nanoparticles have also been acknowledged as plant improvement promoters. Additionally, it was discovered that several plant species benefited more from Nano treatment methods. Several studies have consistently zed the beneficial effects of metal and metal oxide nanoparticles on developing higher plants. Despite the potential benefits of nanocarbon, one obstacle to its use in soil remediation is its reasonable harm to plants and other soil life forms [62,63]. Application of nanomaterials is site-specific, and the effectiveness of this application is influenced by the poison type, concentration, size, charge/non-charge material, regular substance, and additional physical and manufactured soil properties, such as soil aggregates, surface, etc., close to the nanomaterial size. Different systems are employed to utilize nanomaterials in the soil during the remediation cycle [64-66]. These methods include hydrodynamics, pressure beat generation, circulation, and implantation under strain. Figure 3 provides a schematic outline of the application of nanoparticles in phytoremediation.

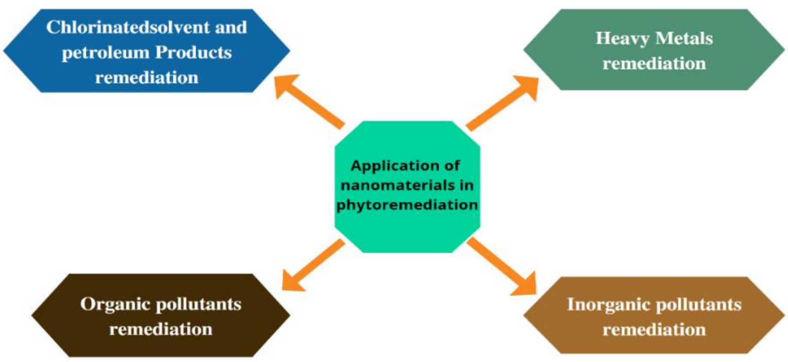


**Figure 3.** The application of nanomaterials in phytoremediation images is mentioned in the title of the image.

## 6. Pollutants in soil remediated by nano-phytotechnology

The combined use of nanoparticles and phytoremediation systems is essential for advancing nano-phytoremediation in the remediation of polluted soils. A significant step in the process of soil sanitization is the combination of phytoremediation and the usage of nanoparticles [67]. Numerous analyses have demonstrated that various nanoparticles or nanomaterials detoxify or repair the common, inorganic, and significant metal damages in soils. Bimetallic nanoparticles (Pd/Fe), magnetite nanoparticles ($nFe_3O_4$), and nanozerovalent iron (nZVI) can fast degrade conventional poisons such as chlorpyrifos, atrazine, lindane, pentachlorophenol, trichloroethylene (TCE), pyrene, polychlorinated biphenyls (PCBs), 2,4-dinitrotoluene, Nano $TiO_2$ ($nTiO_2$) reduces the half-lives of pyrene and phenanthrene in soil and degrades common hazardous chemicals (diuron, p,p′-DDT, pyrene, and phenanthrene) [68], via photocatalysis, redox reaction, and heated destruction while illuminated [69]. Persistent concentration also contributed to the significant contamination of atrazine advancements through PEI-copper nanoparticles retained on montmorillonite and sand [70]. The indirect impact on soil microorganisms may help explain various mixed effects that NPs applied to the soil have on both beneficial and harmful plants. The application of NPs of Ag (0.1–10 mg $kg^{-1}$) produced an unfavorable outcome, but positive responses of soil microorganisms have occasionally been addressed, especially in the case where 1 or 10 mg $kg^{-1}$ of NPs of FeO were given to the dirt [71]. The application of nano-phytoremediation has a significant impact on the release of soil damage. This invention has a strong capacity for plant uptake and can be utilized to remedy damages caused by heavy metals in atypical routine mixes. Nanomaterial-aided phytoremediation is very effective at removing common contaminations and repairing site damage. According to ongoing analyses, nanoparticles can also boost plants' ability to adapt to stress in both ex-situ and *in-situ* circumstances, enhancing their potential for phytoremediation [72,73].

**Table 1**. Utilization of engineered nanomaterials for remediation of contaminated soil.

| S.no | Nanomaterials | Pollutants | Major remediate mechanism | References |
|---|---|---|---|---|
| 1. | Nano-chlorapatite | Cd and Pb | Immobilization by precipitation as metal-phosphate compounds | [74] |
| 2. | Carbon nanotubes | Organochlorine pesticides | Organochlorine pesticides | [75] |
| 3. | Nano-hydroxyapatite | Cu and Zn | Stabilization by ion exchange, surface complexation, and precipitation as new metal phosphates | [76] |
| 4. | Nano-selenium | Cd | Immobilization of elemental mercury by forming insoluble mercuric selenide (HgSe) | [77] |
| 5. | Ferrous phosphate nanoparticles | Cd | Stabilization by the formation of cadmium phosphate through precipitation | [78] |
| 6. | Ni/Fe bimetallic nanoparticles | Polybrominated diphenyl ethers | Degradation by hydrogenation debromination reaction with Ni/Fe nanoparticles | [79] |
| 7. | Pd/Fe bimetallic nanoparticles | Polychlorinated biphenyls (PCBs) | Degradation by hydrogenation dech-lorination reaction with Pb/Fe nanoparticles | [80] |
| 8. | Magnetite nanoparticles | As | Stabilization by adsorption and coprecipitation | [81] |
| 9. | Fe-Mn binary oxide nanoparticles | Se | Immobilization by adsorptive immobilization | [82] |
| 10. | Fe/Cu bimetallic nanoparticles | Cr | Stabilization by the reductive transformation of Cr(VI) with Fe/Cu nanoparticles | [83] |
| 11. | nZVI | Cr | Stabilization by the reductive transformation of Cr(VI) into more stable and less toxic form | [84] |

## 7. Plant species-assisted remediation in contaminated soil using nanomaterials

It depends on the employment of nanoparticles and phytoremediation techniques (such as phytochange, phytoextraction, and phytodegradation) by using plants which plant species will be used in the nano-Phyto mechanical remediation (nano-phytoremediation) framework for cleaning dirty soil. This innovation has demonstrated a startling capability for cleaning accumulation and organic remediation of common damages. Plant species accelerated the release of poisons from the contaminated soil, which demands more effort than usual. Previous studies have shown that combining plant species and nanoparticles caused significant new chemicals to be released from contaminated soil [85,86]. To evaluate the effectiveness of new chemicals for nano-phytoremediation, various plant species and groups of nanoparticles are used. Their suitability for discharge is shown in Table 2. Nanoparticles interact with plants, causing many physiological and morphological changes. The response of the plants will unquestionably depend on the type, size, and speciation of the NPs, as well as the specific plant species used [87]. Their physical-compound game plan, size, shape, surface covering, reactivity, and especially the consideration on which they are solid, which alters starting with one plant then onto the next, lay out their reasonableness of not completely for all time [88,89]. Broadening evidence suggests that different nanoparticles increase plant advancement and improvement in varied assessments. On an incredibly fundamental level (>90 percent), silver nanoparticles expanded the production of ABA and GA phytohormones in plants, which helps plants endure stresses as well as increase the uptake of nutrients and water for improved growth [90,91]. Comparatively, salicylic-damaging nanoparticles advance plant growth and improve the ability of plants under arsenic (As) stress to phytoremediation [92]. After applying MnNP to the soil, Pradhan *et al*. observed beneficial effects on root and shoot expansion and nitrogen uptake, digestion, and handling of plant expansion. Incorporating nano-manures into nanoparticles in this way helps to increase soil structure discharge, accelerate soil efficiency, and advance plant enzymatic advancement, increasing chlorophyll content and seed germination [93].

**Table 2.** List plant species and nanoparticles used in a nano-phytoremediation system to remove pollutants.

| Plant species | Used NPs | Contaminants | Removal efficiency | References |
|---|---|---|---|---|
| *Alpinia calcarata* | nZVIs | Endosulfan | ≈100 (%) | [94] |
| *Ocimum sanctum* | nZVIs | Endosulfan | 76.28 ± 0.19 (%) | [94] |
| *Cymbopogon citratus* | nZVIs | Endosulfan | 86.16 ± 0.09 (%) | [94] |
| *Populus deltoides* | Fullerene (nC60) | Trichloroethylene | 82 (%) | [95] |
| *Isatis cappadocica* | SANPs | Arsenic | 705 ppm and 1188 ppm As accumulate in roots and shoots, respectively | [95] |

**Table 3.** A list of possible nanoparticles in process with plant species with the concentration of phytoremediation.

| S.no. | Nanoparticles | Plant species | Beneficiary concentration(s) | Effects | References |
|---|---|---|---|---|---|
| 1. | MnNPs | *Vigna radiata* | 50–1000 mg $L^{-1}$ | Expanded nitrogen take-up, root, and shoot prolongation | [96] |
| 2. | MWCNTs | *Lycopersicon esculentum* | 10–40 mg $L^{-1}$ | Upgraded the seed germination and development | [97] |
| 3. | AgNPs | *Zea mays L.* | | Expanded creation of ABA and GA phytochemicals | [94] |
| 4. | AgNPs | *Boswellia ovalifoliolata* | 10–30 g $mL^{-1}$ | Expanded germination and seedling development | [90] |
| 5. | SANPs | *Isatis cappadocica* | | Improve growth | [98-100] |

| S.no. | Nanoparticles | Plant species | Beneficiary concentration(s) | Effects | References |
|---|---|---|---|---|---|
| 6. | Aluminum oxide NPs | *Arabidopsis thaliana* | 400-4000 mg $L^{-1}$ | Root length | [101] |
| 7. | $CO_3O_4$ NPs | *Raphanus sativus L.* | 5 g $L^{-1}$ | Root elongation | [102] |
| 8. | $Fe_2O_3$ NPs | *Arachis hypogaea* | 2–1000 mg $kg^{-1}$ | Expanded root length, plant level, biomass. | [102-104] |
| 9. | MnOx NPs | *Lactuca sativa* | 10 mg $L^{-1}$ | Worked on the development of lettuce seedlings by upgrading root stretching | [105,106] |
| 10. | SWCNTs | *Allium cepa, Cucumis sativus* | 9, 56, 315, and 1750 mg $L^{-1}$ | Root elongation | [94] |
| 11. | Graphene oxide | *Vicia faba L.* | 400 and 800 mg $L^{-1}$ | Germination | [94] |
| 12. | ZnO NPs | *Arachis hypogaea* | 1000 ppm | Germination, stem, root development, and yield. | [107] |
| 13. | GNPs | *Arabidopsis thaliana* | 10 and 80 μg $mL^{-1}$ | Germination, shoot, and root development. | [108] |
| 14. | $TiO_2$ NPs Root | *Arabidopsis thaliana* | 400 mg $L^{-1}$ | Length | [109] |
| 15. | $SiO_2$ NPs | *Changbai larch* | 500 μL $L^{-1}$ | Expanded shoot level, root collar breadth, root length. | [110-113] |
| 16. | CuO NPs | *Common wheat* | 500 mg $kg^{-1}$ | Expanded biomass | [114] |

## 8. Challenges of nano-phytoremediation

Studies on phytoremediation aided by nanomaterials are incredibly scant. Since only microcosm experiments have been conducted so far, future research must incorporate more sensible assessments, and improved field knowledge is crucially needed. Long-term testing is anticipated to reveal the real effects of nanoparticles on the phytoremediation cycle and the status of the soil's richness. Nanomaterials can increase this and potentially decrease their transportability; thus, polymers or other coatings are intended to modify their bioavailability or adaptability. Analyzing the effects and success of applying nanomaterials to contaminated soil is necessary. Appropriately, environmentally stable nanomaterials should be considered since viable nano-phytoremediation largely depends on meteorological circumstances. Nano-phytoremediation is a valid method for problems with low pollution levels due to specious plant growth in extremely polluted soils. Growing agro-mining, which may be used to remove toxins even from harvestable plant biomass, will be supported by a general understanding of the poisons absorbed by plants from the soil.

## 9. Conclusions & FUTURE SCOPE

As mentioned above, nano phytoremediation technology is a relatively new field of environmental remediation processes. Most studies have been confined to laboratory scale and pot culture studies, and few studies have been performed at full scale. We observed different behavior between lab/pot cultivation experiments and field experiments due to differences in temperature, pH, soil type, nutrients, and soil moisture content that play a role in real field environments. This paper explains the latest discoveries and research on using nanomaterials to speed up the phytoremediation of polluted soil. Nanomaterials have the potential to remove pollutants, encourage plant development, and increase Phyto availability of pollutants, making it easier to carry out phytoremediation of polluted soils. Nanotechnology can provide green and eco-friendly alternatives for environmental clean-up and management without harming nature. Numerous plants, animals, and life forms that have a higher ability to accumulate very large metal associations have been identified and given the name "hyperaccumulators. "For the bioremediation of major metal-contaminated areas, several kinds of plant, parasite, and microbe species are of interest. Nanomaterials can be used in various ways to release pollutants into the atmosphere. These plant, parasite, and tiny animal species' nanoparticles were used to remove numerous important metals from contaminants to determine if nanomaterials significantly impact plants or the climate; it is necessary to comprehend the mechanism through which they affect the climate. The improvement of agronomic association for crucial standard clean-up methods necessitates the selection of suitable plant species and nanomaterials for the take-up of harmful contaminants. This field is seen as one of growing importance due to the abundance of anticipated open doors, the cross-disciplinary character, the possibility for advancement, the apparent history, and the impact of the conceivably positive effects of nanotechnology.

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## Conflicts of Interest

The authors declare no conflict of interest.

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