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REMOVAL OF CADMIUM FROM SOIL AND PLANT RHIZOSPHERE THROUGH BIOSYNTHESIZE NANOPARTICLES

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ABSTRACT

Cadmium pollution in soil and plant rhizosphere, resulting from industrial activity and agricultural practices, poses a substantial environmental and public health threat due to cadmium's toxicity and persistence in food chains. This review examines the environmentally sustainable synthesis of nanoparticles for cadmium remediation in soil, highlighting biosynthesized nanoparticles as viable alternatives to conventional remediation methods. The main aim is to consolidate recent developments in biosynthesized nanoparticles, particularly those originating from biological sources such as plants, bacteria, and fungi, emphasizing their efficacy in cadmium immobilization and environmental safety. This review thoroughly examines contemporary literature to examine diverse nanoparticle synthesis methods, cadmium adsorption and immobilization processes, comparative efficacy among nanoparticle kinds, and practical applications in the field. The review highlights significant trends, including biosynthesized nanoparticles' ecological advantages, while exposing deficiencies in standardization, long-term ecological effects, and practical implementation at field scale. The results highlight the capability of biosynthesized nanoparticles to improve cadmium cleanup while reducing environmental hazards, offering essential insights for future study and practical implementation. This review identifies the limits and inconsistencies in prior studies. It proposes targeted recommendations to enhance nanoparticle-based remediation technologies, promote sustainable agricultural practices, and refine regulatory frameworks for safe soil remediation methods.

Keywords: *Cadmium remediation, biosynthesized nanoparticles, plant rhizosphere and soil contamination, eco-friendly synthesis, sustainable agriculture, environmental impact, heavy metal removal.*

INTRODUCTION

Cadmium soil and plant rhizosphere pollution directly impacts the environment and agricultural production; in succession, food and public health worldwide are adversely affected (Zhang et al., 2021a). This heavy metal is regarded as a non-degradable substance because it bio-accumulates in the food chain owing to its industrial use and agricultural run-off caused by contaminated fertilizers. Badly disturbed ecosystems, particularly cadmium-contaminated soils and plants rhizosphere, are a long-term sustainability challenge in agricultural practice (Dutta et al., 2020). Numerous attempts have been made to develop remedial procedures for cadmium-contaminated soils, the majority of which could be impractical due to high costs or harm to the soil microbiome in the long run (Zulfiqar et al., 2023). The purpose of this review is to consolidate the latest findings related to cadmium oxychloride nanoparticles synthesized biosynthetically for soil purification, with an emphasis on green approaches.

Recent studies such as Zulfiqar et al. (2023), especially those observing biosynthesized nanoparticles and the role plants, fungi, and bacteria play in plant nutrient management, suggest promising outcomes since biosynthesized nanoparticles have a more environmentally friendly synthesis than their conventional counterparts. For instance, studies like Nair et al. (2010) mentioned using iron oxide and zinc oxide nanoparticles for cadmium adsorption and immobilization, drastically decreasing cadmium bioavailability in contaminated soils. However, while these studies illustrate the merits of employing biosynthesized nanoparticles, they point out vexing deficiencies in such areas, such as the need for uniform synthesis methods, the absence of comprehensive long-term effects studies, and the evaluation of biosynthesis under various soil conditions. These conditions have been identified because they are the very components that would enhance this field. After all, it would offer safer, ecologically acceptable alternatives for the large-scale use of cadmium in soils (Nizamov et al., 2023).

This review aims to bridge these gaps by reviewing the literature on biosynthesized nanoparticles for cadmium sequestration in depth. This review presents a new synthesis strategy for evaluating biosynthesized nanoparticles' functional and ecological safety in various surrounding environments by assessing contemporary developments and highlighting some of the weaknesses of earlier work. This approach brings new insights into nanoparticle-based remediation strategies. It underscores the importance of standardizing methods and evaluating their effects over time, which could change how sustainable soil reclamation is practised.

2. Eco-Friendly Synthesis of Nanoparticles for Heavy Metal Remediation

2.1 Green Synthesis Approaches for Metal Nanoparticles

As biological sources, plants, bacteria, and fungi are essential for the green synthesis of nanoparticles and are safer than chemical synthesis as shown in Figure 1 (Sandhya and Kalaiselvam, 2020). These organisms naturally possess reducing and stabilizing agents that allow non-toxic methods for nanoparticle fabrication. Such processes enable the use of biological substances that reduce toxicity, hazardous waste generation, and environmental pollution (Herlekar et al., 2014). Furthermore, biological synthesis methods often require less harsh conditions than conventional methods, saving energy. Other advantages include improved environmental protection, decreased ecological footprints, and the possibility of producing biocompatible nanoparticles, making such methods more promising in medicine and technology (Saif et al., 2016).

Biosynthesized nanoparticles provide several benefits over chemically synthesized nanoparticles, most importantly, their lower environmental burden and higher biocompatibility (Singh et al., 2016). In contrast to chemical methods, which often require harsh and toxic reagents, biosynthesis is performed by natural organisms, thus generating little harmful waste and being more environmentally friendly. As a result, these nanoparticles are generally more biocompatible and are, therefore, suitable for medical applications. Removing heavy metals from waste materials, such as biosynthesized nanoparticles, has excellent potential (Abdelbasir et al., 2020). Silver nanoparticles synthesized with plant extracts have effectively removed lead and cadmium from water resource sewage. Notably, heavy metals can be immobilized by iron oxide nanoparticles synthesized by bacteria, making them less toxic. These practical uses suggest that biosynthesized nanoparticles can safely and sustainably solve many ecological problems (Carlos et al., 2013).

Other biomolecules, such as enzymes and amines, are important molecular stabilizers for nanoparticle biosynthesis. They enable the controlled formation of nanoparticles as capping agents, which can minimize agglomeration, which is the elemental problem where particles group and reduce efficacy. Enzymes expedite reactions that give rise to a defined size and shape of the particles, leading to uniformity and stability. With their functional groups, amines induce electrostatic repulsion between particles and help reduce agglomeration (Dutta et al., 2009). In environmental applications, these stabilized nanoparticles are significant for heavy metal absorption because they have a larger surface area and are more reactive, allowing them to achieve maximum contaminant green chemistry. Overall, using biomolecules during nanoparticle synthesis not only provides better stability of the synthesized nanoparticles but also helps significantly in pollution control measures by enhancing the removal efficiency of pollutants (Nasrollahzadeh et al., 2019).

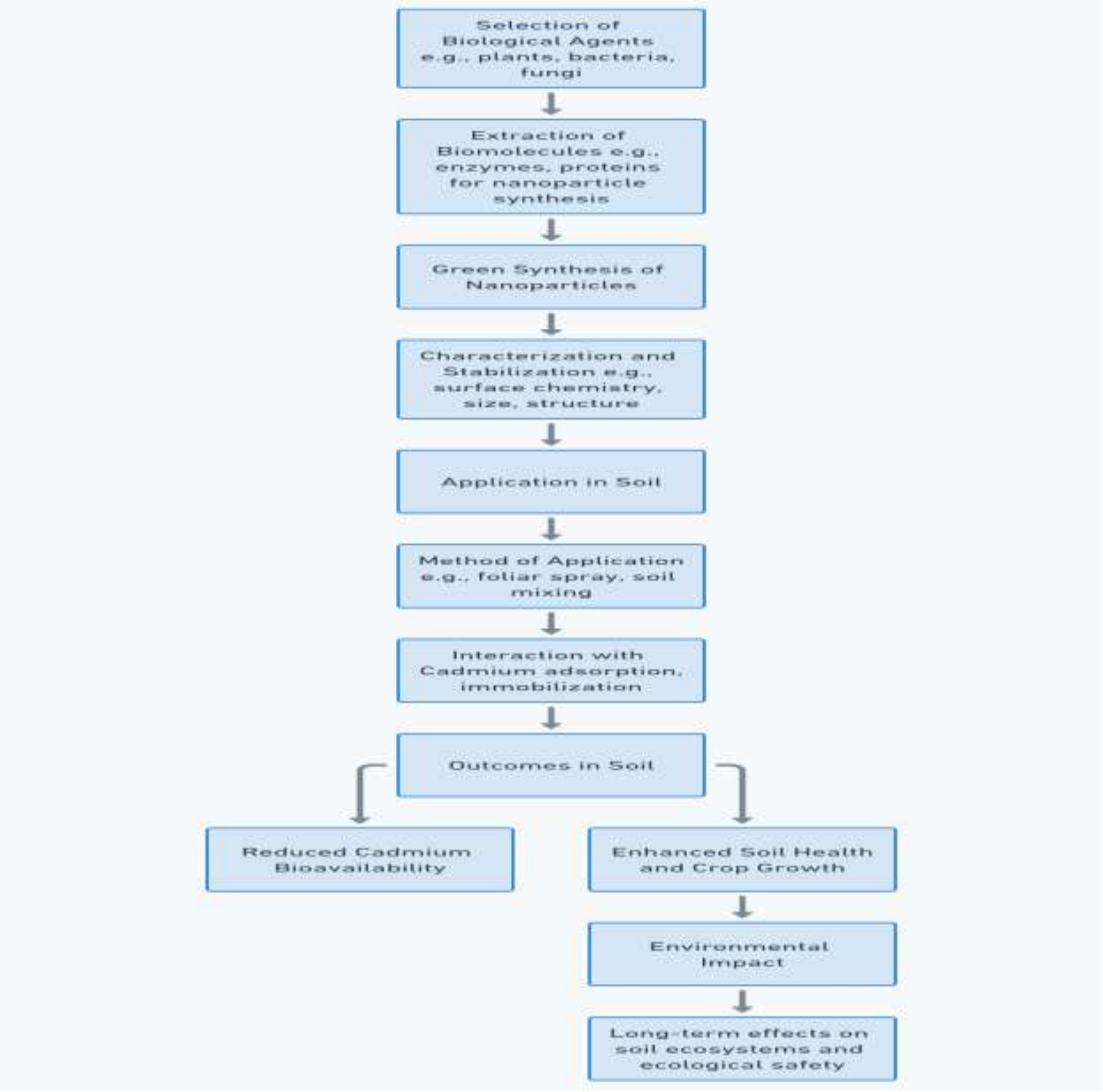

Figure 1: This flowchart delineates the process for developing and applying biosynthesized nanoparticles in cadmium cleanup. The process commences with the selection of biological agents such as plants, bacteria, or fungi, followed by the extraction of biomolecules (e.g., enzymes and proteins) crucial for nanoparticle creation. These nanoparticles are subjected to eco-friendly synthesis, subsequent characterization, and stabilization to guarantee optimal size, structure, and surface chemistry. Upon preparation, the nanoparticles are introduced to the soil using foliar sprays or soil mixing, where they engage with cadmium to adsorb and immobilize the metal. The objectives are to decrease cadmium bioavailability and boost soil health, resulting in improved crop growth. The approach evaluates long-term environmental effects on soil ecosystems and ecological safety.

2.2 Biosynthesized Nanoparticles for Environmental Applications

The nanomaterials produced biosynthetically have recently been developed to offer reasonable remediation solutions for heavy metals such as cadmium, lead, and arsenic. These nanoparticles, manufactured through biological processes, possess distinguishing features that make them more efficient regarding their environmental usage. They can adsorb heavy metals from water, making the treatment of contaminated water more efficient and minimizing its toxicity (Wong et al., 2016). Unlike typical chemical-based approaches that would create a secondary waste stream, biosynthesized nanoparticles are eco-friendly and biodegradable. Their large and active surfaces are adequate for the binding and immobilizing toxic materials/metals. Their use also reduces the chances of causing additional pollution, which is an advantage for any workable solution for environmental sustainability. This novel technique, therefore, enhances the effectiveness of remediation and, at the same time, utilizes sustainable alternatives, which makes it a credible substitute for environmental management practices (Braun et al., 2020).

The use of biosynthesized nanoparticles provides many advantages compared to the conventional method of remediating heavy metals, which uses chemicals or is physical in nature:

They are derived from natural processes, which ultimately help in reducing poison levels (Pattanayak et al., 2021).

Extra chemicals are not introduced with biosynthesized nanoparticles, as is the case for much of the conventional process, which could be more helpful. Such nanoparticles enable the binding of heavy metal substances, which makes it easier to extract them and, in some cases, recover them again. This type of nanoparticle also assists in protecting the environment as it lowers the energy necessary to execute the procedures used in other, more traditional remediation processes (Bhagat and Giri, 2021).

They improve the water quality in polluted systems by enhancing the bioavailability of pollutants, enhancing their degradation, and increasing the activity of the microbes in the system (Guerra et al., 2013).

In general terms, the use of biosynthesized nanoparticles offers a tremendous opportunity to resolve the issue of the remediation process's effectiveness and ensure that the ecosystem remains balanced and sustainable (Vázquez-Núñez et al., 2020).

Recent achievements in the use of stabilized nanoparticles to remove heavy metals have positively impacted the level of environmental toxicity. Modifying the surface of nanoparticles and coating them with polymers and stabilizing agents makes them more stable, inhibits agglomeration, and allows them to be homogenously distributed in polluted areas, making nanoparticles work optimally. These stabilizing techniques and methods increase the nanoparticles' working surface areas and reactivity, enabling them to extract and even deplete cadmium ions from both water and soil (Zhang et al., 2021b). Furthermore, such nanoparticles are less prone to leach and bioaccumulate, thus reducing their possible environmental hazard. Nanoparticles are, therefore, made safer, and because of this, these methods enhance the effectiveness of nanoparticles in remediating cadmium while offering environmentally friendlier practices that ensure that the use of nanotechnology does not threaten the environment (Bhandari, 2018).

3. Mechanisms of Cadmium Adsorption and Immobilization by Nanoparticles

3.1 Cadmium Adsorption Mechanisms in Soil Using Nanoparticles

In soils, Cd ions can interact with nanoparticles mostly via ionic and covalent bonding mechanisms. Regarding covalent bonding, cadmium ions can ionically bond with hydroxyl or carboxyl functional groups on the surface of the nanoparticles, creating a stable polynuclear linkage, as depicted in Figure 2 (Huang et al., 2020). Ionic cadmium bonding appears to have less impact; it is initiated by cadmium ions, which are positively charged, and ionic junctions on nanoparticles, which are negatively charged, thus allowing cadmium ions to bind reversibly with the nanoparticles. These types of bonding mechanisms are paramount for the reduction of Cd mobility in metal-contaminated soil (Dong et al., 2021). Thus, by encapsulating cadmium ions in the nanoparticle matrix, leaching into groundwater systems is reduced or eliminated, thus addressing bioavailability and ultimately assisting in remediating contaminated soils, benefiting the ecosystem. This immobimmobilizationssential is essential for effectively managing Cd pollution (Huang et al., 2016).

Cadmium ions found in contaminated soils can be adsorbed effectively through a particular focus on nanoparticle surface chemistry. For example, Carboxyl (-COOH) and hydroxyl (-OH) functional groups increase cadmium ions' binding substantially with the nanoparticles. Cd can be effectively captured through strong chelation bonds created by carboxyl groups. These groups increase the surface reactivity and, by extension, the general adsorption capacity of the nanoparticles (Miao et al., 2020). Similarly, cadmium ions are retained in the soil matrix because of the contribution of hydroxyl groups to the formation of hydrogen bonds and electrostatic interactions with cadmium ions. The existence of such surface functionalities, therefore, not only enhances the sorption of cadmium ions but also the stabilization and immobilization of the toxic metal, making them suitable for remediating cadmium-contaminated soils and mitigating the potential loss of ecotoxicity to the surrounding environments (Aşçı et al., 2007).

According to previous research, the biosynthesis of nanoparticles with iron oxide (FeO) and zinc oxide (ZnO) is not uniform in cadmium adsorption capacities within a soil matrix. The presence of ionic cadmium is favourable for binding due to the contribution of electrostatic forces and surface complexation with FeO nanoparticles, which possess high surface area and magnetic properties. This is because the porous structure of the FeO NPs increases the number of available adsorption sites (Lei et al., 2019). On the other hand, ZnO nanoparticles with different surface functional groups also effectively bond cadmium ions through oxygen chemisorption. The different fates of both nanomaterials' morphologies are tightly defined by their adsorption features; the magnetism of FeO allows for simple recovery, while ZnO provides effective cadmium encapsulation due to its intrinsic chemical character, making both practical but situational alternatives for remediation (Zhang and Elliott, 2006).

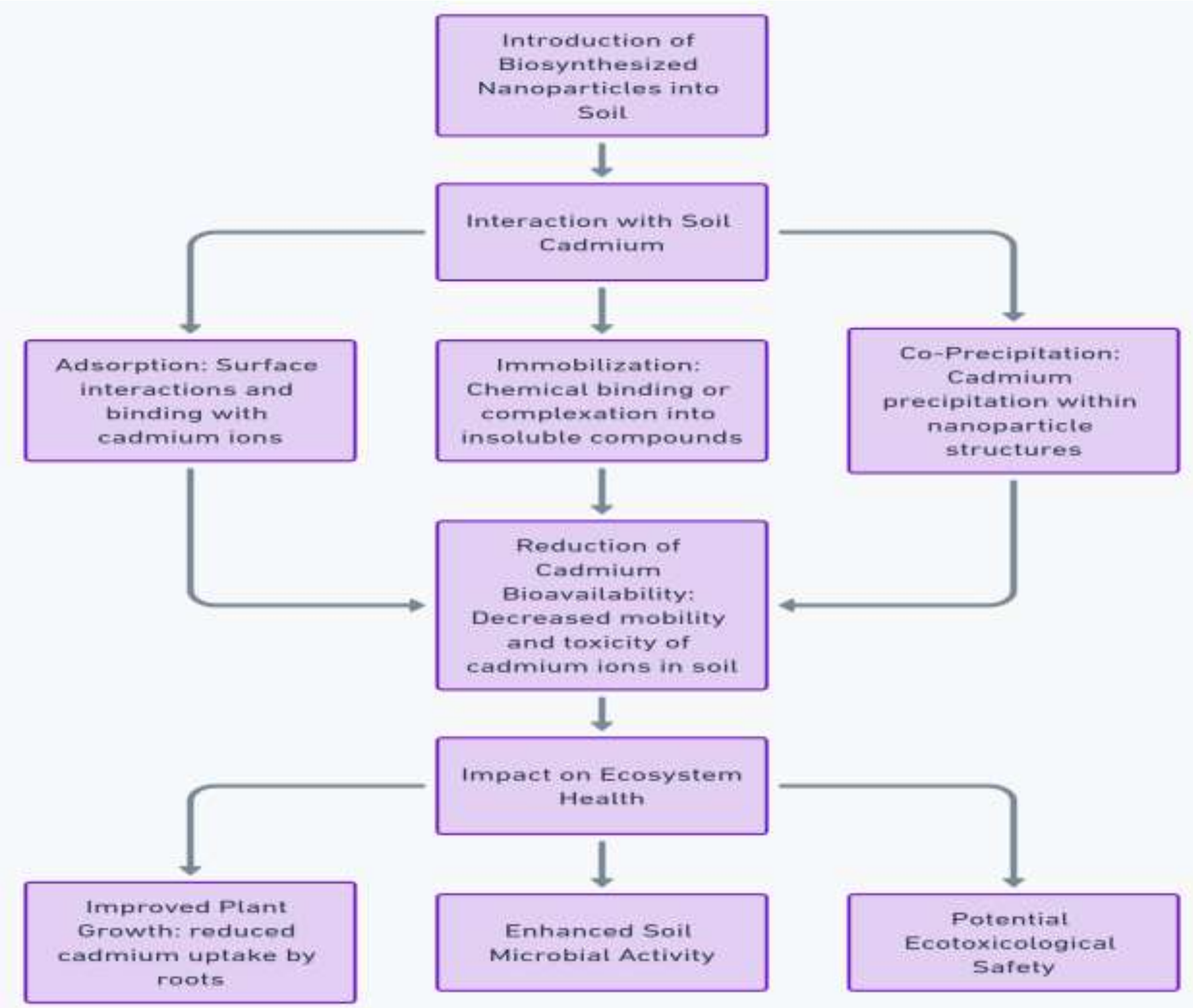

Figure 2: This flowchart depicts the process by which biosynthesized nanoparticles sequester cadmium ions in the soil, thereby diminishing their mobility and toxicity via three principal mechanisms: adsorption (binding cadmium to nanoparticle surfaces), immobilization (creating insoluble compounds with cadmium) and co-precipitation (integrating cadmium within nanoparticle structures). These interactions reduce cadmium bioavailability, fostering improved plant development, increased soil microbial activity, and safer ecological circumstances by alleviating the harmful effects of cadmium on the environment.

3.2 Biochemical and Molecular Interactions of Cadmium with Nanoparticles

Nanoparticles play a critical role in immobilizing the cadmium in the soils due to its vital molecular interactions: ligand complexation and co-precipitation. The formation of stable complexes between cadmium ions and functional groups on the surface of nanoparticles, whereby the cadmium ions are hindered in mobility, is known as ligand complexation. This interaction makes Cd less available for plant uptake or microbial action (Huang et al., 2020). Co-precipitation processes result in cadmium precipitation with other minerals or nanoparticles so that cadmium ions are encapsulated in a solid phase. These processes boost cadmium stabilization by decreasing its solubility, enabling no leaching of the cation into the groundwater (Lata and Kaur, 2022).

Among the factors that affect the efficiency of cadmium removal by nanoparticles, soil properties such as pH values, organic content, and cation exchange capacity (CEC) are pretty significant, as soil pH determines nanoparticles surface charge; at lower pH levels, hydrogen ion concentration increases, which itself boosts cadmium solubility, leading to higher cadmium attachment to nanoparticles (Zeng et al., 2020). A high organic content can help cadmium adsorption by offering more binding sites and helping nanoparticle stability. CEC also plays a significant role since it governs the number of cations that can be held by the soil, thus determining the amount of available cadmium and the extent to which it would compete with other cations for adsorption sites on the nanoparticle surfaces (Xia et al., 2019). Overall, all these parameters determine the interaction of Cd nanoparticles, hence determining the possible success of remediation techniques used to clean up contaminated soils. These interactions are essential for designing optimal remediation technologies involving nanoparticles (Cecchin et al., 2017).

Certain environmental conditions, such as toxic (high oxygen content) and anoxic (low oxygen content), strongly affect the efficiency of biosynthesized nanoparticles in cadmium immobilization within the soil. Cadmium in biosolid particles is believed to be oxidized in oxic environments, where nanoparticles are more stable and capable of fast oxidation, which promotes complexation with cadmium (Zeng et al., 2020). Cadmium, in turn, may be less efficiently retained by oxidizing bastnaesites in anoxic environments because diagenetic processes could modify the surface chemistry of nanoparticles (Tian et al., 2020). Furthermore, a lack of cadmium mobility in anoxic sediments decreases the capacity of cadmium to be retained in more binding forms, ultimately affecting the effectiveness of the nanoparticles. There are differences in reaction kinetics, which are determined by environmental factors. Hence, the biosynthesized particles cannot be relied on for Cd immobilization uniformly and concentrate different strategies for different soil conditions (Kolesnikov et al., 2021).

4. Comparative Effectiveness of Various Nanoparticles in Cadmium Soil Remediation

4.1 Effectiveness of Different Types of Nanoparticles for Cadmium Removal

The effectiveness of biosynthesized nanoparticles such as $Fe_3(PO_4)_2$, $FeHPO_4$, and $Fe(H_2PO_4)_2$ in reducing Cd bioavailability in soil has indeed been tested in some recent studies. Of these, $Fe_3(PO_4)_2$ is noted for its properties and efficiency in the soil, enhancing its effectiveness, including its higher surface area and soil stability. The phosphate groups on the surface allow cadmium to contact chemically because it can be bound and thus contain the metal (Satarug et al., 2003). Moreover, $Fe_3(PO_4)_2$ has been shown to have a high affinity towards cadmium ions, which interfere with the solubility of cadmium, creating stable complexes; hence, cadmium is rendered immobile (Cheng et al., 2020). In contrast, $FeHPO_4$ and $Fe(H_2PO_4)_2$ are less efficient because of their low binding efficiency and low solubility in water. Thus, $Fe_3(PO_4)_2$ is the best for Cd immobilization, which can assist in soil remediation (Dong et al., 2021).

Data on leachability and exchangeable Cd fractions, among others, have been relevant in determining the efficiency of biosynthesized nanoparticles in remediating soils. This considers how much of the Cd in its bioavailable form has been immobilized by the nanoparticles, thus reducing its toxicity (Lei et al., 2008). For instance, measures of the leachability of nanoparticles with high reduction suggest that they can bind cadmium and prevent its migration into groundwater (Zulfiqar et al., 2023). In addition, low exchangeable cadmium fractions indicate that the nanoparticles have bound cadmium in a more stable form that does not allow for easy uptake by plants and hence reduces ecological risk. The analysis of such data enables researchers to target specific types of nanoparticles that have demonstrated better results in Cd removal, enhancing the prospects of its use for formulating effective soil detoxification methods in the future. This type of evidence synthesis also improves the appreciation of how nanoparticles work in addressing the cleaning up of contaminated environments (Cecchin et al., 2017).

The immobilization of cadmium using biosynthesized nanoparticles has long-term stability and efficiency mainly determined by soil characteristics such as texture, pH, and contaminant levels, illustrated in Figure 1 (Zhang et al., 2021b). The soil texture determines the dispersal and contact of cadmium with the nanoparticles; smaller textures increase the contact of the nanoparticles with cadmium but may also cause them to aggregate. pH impacts nanoparticle dissolubility and possible activity; some nanoparticles may be dissolved in acidic media and hence be less valuable, while alkaline media can improve cadmium binding (Zhang et al., 2021b). Additionally, greater contaminant levels may exceed the immobilization potential of the nanoparticles and thus reduce their effectiveness. Such integrated remediation strategies also depend on factors such as nanoparticle formulations and application techniques to ensure that cadmium immobilization is effective and that potential environmental hazards are reduced. Further studies are needed to optimize these nanoparticles to work effectively in different types of soils and conditions (Dong et al., 2021).

4.2 Optimizing Nanoparticle Composition and Concentration

The composition of nanoparticles, especially iron (Fe) and zinc oxide (ZnO), reduces Cd uptake in maize (Zea mays) plants cultivated in sodic soils. It was pointed out that Fe nanoparticles can improve the soils and accelerate plant growth, thus enhancing Cd and heightening the plant's ability (González-Feijoo et al., 2023). Additionally, because ZnO nanoparticles exhibit antimicrobial properties, they can positively affect plant health, decreasing the stress response and, consequently, heavy metal uptake. As a result of the mixture of these nanoparticles with the components of soil, their reactivity changes, and accordingly, their ability to interact with the soil affects their efficiency in remediation. This plays a significant role in farming since it reduces refluxing patient content in plants and can be improved for safer crops in polluted environments (Saravanan et al., 2020). Optimizing the composition of multiple types of nanoparticles will improve these aspects. All of these must be considered in order to design adequate soil-cleaning methods (Usman et al., 2020).

The concentration, size, and surface area of nanoparticles are important structural features that determine the efficiency of cadmium removal from the soil. Using more significant nanoparticle concentrations improves cadmium retention, but excessively high concentrations cause overlap, reducing Availability. Less extended nanoparticles have a higher surface-to-volume ratio and can interact with cadmium ions more efficiently, leading to more efficient immobilization. The optimization of these properties is considered essential in the successful implementation of remediation procedures; in the case of the optimal distribution of nanostructures, they bond to cadmium sufficiently while minimizing the extent of clustering (Lei et al., 2019). Furthermore, the bioavailability of Cd is essential to control, prevent its uptake by plants and other organisms, and reduce the toxicity level within the ecosystem. Modifying nanoparticle properties may help improve their performance in immobilizing cadmium, and these strategies could further promote soil remediation approaches while protecting the environment (Lata and Kaur, 2022).

There are advantages and drawbacks to applying foliar and soil application methods of biosynthesized nanoparticles for cadmium removal. The foliar application technique makes it easier to deliver nanoparticles containing cadmium and other chemical agents through leaf stomata, thus improving the relative absorption (Faizan et al., 2021). However, it could be affected by environmental and leaf surface factors. On the opposite end of the spectrum is the application of the same onto the soil, which produces better results and more efficiency as there is a broader distribution of the nanoparticles in the root zone, which allows for direct contact with the soil that is interfered with. This strategy, on the other hand, may have a disadvantage, as it might experience limited bioavailability because of the adsorption processes by soil (Pérez-Hernández et al., 2020). As such, the efficacy of these strategies depends on the size of the nanoparticles, type of plant, and soil. In terms of practicality, it is different as foliar methods of application are more tedious, whereas soil methods can take a long time but require great attention to be successful (Worrall et al., 2018).

5. Environmental Impact and Safety Considerations in Nanoparticle-Based Remediation

5.1 Ecotoxicity of Nanoparticles in Soil Ecosystems

Biosynthesized nanoparticles are practical and have a broad spectrum of uses; however, they can cause toxicological risks to soil microbiota and plants in contaminated environments. Focus has been laid on how these nanoparticles have been used and can potentially be used while striking a balance between perturbations in soil microbial diversity and function (Du et al., 2018). For example, there is evidence that under some circumstances, specific nanoparticles have inhibited the growth of helpful soil bacteria, which has a detrimental effect on nutrient cycling and overall agricultural soil fertility. Such alterations in microbial community structure may also lead to hostile structures that curtail growth or even the ability of plants to withstand disease-causing organisms (Song et al., 2018). Results, however, indicate that while some nanoparticles could improve plant growth, they could undermine the activity of the soil microbiome, leading to other ecological impacts. Thus, there is a need for more studies to comprehend such interactions and avoid risks in contaminated environments (González-Feijoo et al., 2023).

The ecotoxic perturbations of nanoparticle-based cadmium sharks were evaluated using model organisms, such as Caenorhabditis elegans, which mount a robust immune response along multiple layers of immune cells for translational studies (Gonzalez-Moragas et al., 2017). These nematodes are widespread when testing non-target systems because of their uncomplicated structure, Availability of rapid generation times, and genetic modification possibilities, which make it feasible to see the action of nanoparticles on biological systems. Research on C. elegans further assesses nanomaterials and C. elegans-based ecotoxicological risk by investigating their toxicity, bioaccumulation, and potential soil ecosystem impact (Yao et al., 2022). As a result of humane exposure to cadmium-contaminated soils amended with nanoparticles, the growth of the organisms and subsequent reproduction and behaviours can be comprehensively examined in both short- and long-term exposure scenarios. This study sheds light on the risks of using nanoparticles in environmental remediation, in which caution is always taken to ensure that the fleets and techniques used do not adversely affect any organisms living in the soil or disrupt the ecological balance (Bone et al., 2020).

Nanoparticles synthesized using biological methods offer significant advances in environmental cleanup (Otto et al., 2008). However, their definitive fates differ in soil ecosystems and depend on factors such as degradation, persistence, and ecological interactions, among other fates. In this regard, some degradation rates may be driven by soil type, microbial level, or climatic factors; hence, the persistence levels may also differ. It is possible that some nanoparticles will be subject to degradation in a short period and thus will possess a low level of toxicity. On the other hand, some nanoparticles may be ingested by soil microorganisms, leading to bioaccumulation, which would negatively impact the soil microbiome. These aspects of behaviour must be well understood so that they can be safely applied (Loureiro et al., 2018). Other adverse effects could include disturbances to nutrient cycling or stress on non-target organisms due to contact with nanoparticles. There is also a need to have a clear understanding of the migration patterns of nanoparticles in the soil, as this would guide their use in remediation processes that have the least negative impacts on the environment. This contributes to the development of sustainable practices for the environment (Cecchin et al., 2017).

5.2 Safety and Environmental Regulations for Nanoparticle Use

Currently in use, regulatory systems for the biosynthesis of nanoparticles in environmental remediation mostly centre on safety studies, environmental effect evaluations, and application guidelines. European Chemicals Agency (ECHA) and Environmental Protection Agency (EPA) developed protocols for assessing the possible hazards associated with these compounds (Bregoli et al., 2013). However, there are difficulties, including the absence of uniform definitions and classifications for biosynthesized nanoparticles, which complicates procedures (Gwinn and Tran, 2010). Furthermore, impeding the proper evaluation of long-term ecological effects is a weakness in monitoring and reporting criteria. Harmonized international rules also help solve the cross-border character of environmental problems. Developing thorough safety rules and guaranteeing the responsible use of biosynthesized nanoparticles depends on improved cooperation among regulatory agencies and stakeholders (Delphine et al., 2009).

Evaluating the safety of biosynthesized nanoparticles for soil remediation offers various difficulties, mostly related to the need for more criteria and standardized testing techniques. Their variation complicates the evaluation of nanoparticle properties, including size, shape, and surface chemistry (Macé et al., 2006). Furthermore, interactions between nanoparticles and soil components can produce unexpected behaviour and toxicity profiles. Developing consistent safety procedures for cadmium cleanup based on nanoparticles is vital because it guarantees regulatory compliance and consistency in safety assessments (Hughes et al., 2018). Standard procedures would help improve public confidence, enable comparative research, and support the safe deployment of these novel materials in environmental remedial projects. A robust framework for safety assessment is required to maximize the use of biosynthesis-produced nanoparticles in sustainable soil management (Rajput et al., 2022).

Safely applying biosynthesis-generated nanoparticles in cadmium-contaminated soils depends on thorough risk assessments and environmental monitoring systems. These tests guarantee that the nanoparticles neither aggravate pollution nor generate new hazards, thereby helping to discover possible hazards to human health and ecosystems (Chen et al., 2021). Environmental monitoring helps to track interactions with soil components, the behaviour of nanoparticles, and how they affect soil microbiomes and plant life. Understanding the ongoing effects of nanoparticles over time depends on long-term research since short-term data could not show cumulative or delayed effects. By guiding safe use practices, regulating systems, and supporting sustainable remediation techniques, such studies help to ensure environmental integrity and public health while optimizing the advantages of nanotechnology (Dunphy Guzmán et al., 2006).

6. Field Application and Practical Challenges in Biosynthesized Nanoparticle Use

6.1 Application Techniques for Cadmium Remediation in Field Studies

Through several application techniques, biosynthesized nanoparticles provide creative ways to treat Cd-contaminated soils. Targeted delivery made possible by foliar spraying improves plant absorption of nanoparticles, although environmental factors and possible drift may restrict it. Although it might be labour-intensive and upset current soil structures, soil insertion directly improves soil characteristics and stimulates microbial activity (Nair et al., 2010). Although irrigation-based delivery systems provide consistent distribution and simplicity of use, soil type and moisture content might affect their performance. While each technique has unique benefits, such as lower toxicity and better bioavailability, it also has restrictions regarding practicality, environmental effects, and the possibility of nanoparticle leaching. Together, these techniques might maximize efforts to remediate soils contaminated by cadmium (Zhang et al., 2021b).

Achieving ideal distribution and efficient soil penetration of biosynthesis-produced nanoparticles in large-scale field applications involves many difficulties. Variation in soil textures and structures is a significant problem that could affect consistent nanoparticle dispersion (Wang et al., 2019). Furthermore, environmental parameters such as moisture content and soil pH influence nanoparticle behaviour and stability, influencing their reach to polluted areas. These difficulties can cause unequal remedial efficacy since some locations might receive insufficient nanoparticle treatment, affecting cadmium immobilization (Zhang et al., 2021b). Moreover, the possible aggregation of nanoparticles in soil can lower their Availability and reactivity, lowering their Cd binding efficacy. Thus, overcoming these difficulties is essential for improving the general effectiveness of bioremediation projects in polluted soils (Zulfiqar et al., 2023).

Several essential elements affect the success of biosynthesis-produced nanoparticles in agriculture, including soil type, level of pollution, and local meteorological circumstances. The soil type influences nanoparticle mobility and bioavailability; sandy soils may improve particle movement, while clay soils can better retain them (Bhardwaj et al., 2023). Contamination levels define how much nanoparticles can reduce harmful effects and hefty metals such as cadmium. Increased pollution might cause plants to absorb nanoparticles more actively, improving efficiency.

Local environmental factors, including temperature and humidity, also affect nanoparticles' plant physiology and stability (Rai et al., 2018). Perfect conditions can improve the performance of the nanoparticles, thereby lowering Cd absorption in plants. Optimizing the use of nanoparticles in polluted agricultural environments depends on an awareness of these factors (Rai et al., 2018).

6.2 Field Study Outcomes and Practical Implications

Field research on the biosynthesis of nanoparticles for Cd remediation has shown significant promise in lowering Cd absorption in crops and enhancing soil health. These findings show that often derived from plant extracts or microorganisms, nanoparticles improve the bioavailability of nutrients and help reduce harmful metal accumulation in plants (Dong et al., 2021). Observations point to a significant decrease in Cd levels in food-grade agricultural products, fostering food safety. Furthermore, using these NPs is associated with better soil microbial activity and nutrient cycling, thus promoting a better soil environment. These results imply that biosynthesized nanoparticles provide a valid, environmentally friendly method to solve cadmium pollution in agricultural and contaminated locations, thereby supporting sustainable agricultural methods and environmental rehabilitation (González-Feijoo et al., 2023).

Adopting biosynthesized nanoparticles for cadmium remediation encounters many challenges that impede their general application. Cost is a significant consideration, and the materials and techniques used to manufacture these nanoparticles can make them less desirable for large-scale use (Lata and Kaur, 2022). Scalability is another difficulty because techniques that are useful at the laboratory size cannot be applicable in real-world situations because they may not translate effectively to industrial levels (Bystrzejewska-Piotrowska et al., 2009). Furthermore, the technical knowledge needed for efficient deployment must be present in many areas, which calls for specific synthesis, application, and monitoring skills. These elements, taken together, form obstacles that affect the viability of nanoparticle-based remediation, thereby slowing down the flow from research into functional environmental solutions (Guerra et al., 2018).

Future studies on cadmium remediation based on nanoparticles should concentrate on several important areas to fill in the knowledge about environmental safety and long-term effectiveness. First, as environmental conditions may cause the efficacy of biosynthesized nanoparticles to fade over time, research on their longevity in different soil types is required (Rajput et al., 2022). Furthermore, significant hazards related to the possible leaching of these nanoparticles into groundwater require evaluation. The evaluation of the real-world effects of these nanoparticles on soil health, microbial populations, and general ecosystem dynamics depends on comprehensive field research (Pan and Xing, 2012). Knowing biosynthesized nanoparticles' long-term behaviour and interactions in contaminated soils can help guarantee environmental safety in the face of cadmium contamination and provide vital information for designing sustainable remedial plans (Zhang et al., 2021b).

7. Conclusion

Emphasizing their environmentally friendly synthesis, mechanistic interactions, and practical uses, this review summarizes present developments in the biosynthesis of nanoparticles for cadmium remediation in soil. Promising sustainable substitutes for conventional remediation techniques, findings suggest that nanoparticles produced from biological sources, including plant extracts, bacteria, and fungi, significantly reduce cadmium bioavailability by adsorption, immobilization, and complexation. Comparative research highlights these nanoparticles' efficiency, low environmental effect, and ability to lower cadmium absorption and enhance plant health. Nevertheless, standardizing nanoparticle manufacturing and application techniques, evaluating long-term ecological effects, and validating scalability in various soil environments still need to be improved. Future studies on environmental safety, uniformity in synthesis methods, and increased field applications to more significant, varied environments should all help to establish. By filling these gaps, the biosynthesis of nanoparticles' ecological feasibility will be more apparent, and more considerable agricultural use will be enabled. This study emphasizes the transforming possibilities of biosynthesis-based nanoparticles in sustainably regulating heavy metal contamination; however, it is limited by selection criteria and fast-changing research. Using focused research, these nanoparticles could significantly improve soil health, promote sustainable agriculture, and reduce public health hazards related to cadmium poisoning, thereby establishing their indispensable role in the future of environmental remediation.

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