**Nanobioremediation Approach to mitigate Soil Pollution: Nanotechnology**

1. **Introduction**

 Pollution of soil is mainly by the chemicals from a variety of sources, such as industrial and agricultural operations, the disposal of waste, and urbanization. Negative effects of soil pollution on agriculture, industry, cities, and the environment include altered soil biodiversity, decreased soil fertility, and water contamination. According to estimates, 24 billion metric tons of fertile soils are lost each year, and one-third of all land surfaces on the planet have some degree of degradation (Cherlet et al. 2018; unccd, ed. 1, 2017). Bioremediation refers to the exploitation of metabolism of microbiome and plants for the goodwill of the environmental health. This entails the controlled degradation of pollutants through biological means, reducing them to a harmless state or decreasing their concentration to levels sanctioned by regulatory bodies (Mueller et al., 1996)**.** Assisted by nanotechnology, a swiftly advancing scientific discipline dealing with synthetic particles measuring 100 nm or smaller in size (Fraceto et al. 2016), bioremediation emerges as a highly promising and cost-effective strategy for mitigating pollutants in contaminated environments. This approach is referred to as nanobioremediation. Nanobioremediation, which uses nanoparticles to speed up bioremediation as well as eradicate pollutants that are not possible with just bioremediation, aims to clean the environment. Degradation of pollutants incorporating a catalyst as nanoparticles is the fundamental idea behind nanobioremediation. Because nanoparticles (NPs) are smaller and have a bigger surface area, they can absorb pollutants above a wider surface area or function as catalysts. Zinc, silver, gold, copper, and various other nanoparticles (NPs) and nanomaterials have demonstrated their efficacy in neutralizing detrimental inorganic pollutants, thereby alleviating stress in contaminated environments (Ibrahim et al., 2021Vanlalveni et al., 2021; Hemlata et al., 2020). Extensive research, as indicated by studies like Deplanche et al., 2014 and Kharissova et al., 2013, has evaluated the catalytic attributes of diverse NPs along with their biological components to effectively mitigate harmful pollutants.

Therefore, innovative remediation approaches combine biological and nanotechnological remediation techniques, where the manipulation of nanoscale process facilitates the adsorption and degradation of contaminants (Rajput et al. 2022). This mind blowing concept will be explained in detail as we dive into the chapter.

1. **Soil pollution**

The natural ecosystem relies heavily on the soil, holding equal significance alongside flora, fauna, rocks, landforms, rivers, lakes, and animals. It profoundly impacts the distribution of various plant species and provides a habitat for a diverse array of organisms. Additionally, soil plays a pivotal role in governing the exchange of gases within the atmosphere and operates as a vital source and reservoir for water and chemical compounds, facilitating exchanges between the ground and the atmosphere. Though it may appear that soil is lifeless and motionless, this is not the case at all. It is ever-evolving and changing as time passes. In addition to the effects of man and land use, soil is constantly adapting to changes in environmental conditions. There will be some temporary and reversible modifications to the soil, while others will become a permanent part of it.

"Soil pollution" denotes the decline in soil productivity resulting from the presence of soil contaminants. This issue, which is of global concern, arises due to both natural and human-induced factors.There are different ways that soil can be polluted, such as:

* industrial waste products being thrown into the soil
* use of insecticides, herbicides, or fertilizer in excess
* Sedimentation from a landfill
* water contamination seeping into the ground

Due to urbanization, industrialization, and increased food consumption, a variety of compounds, chemicals, and chemical agents have been utilized, leading to the dispersion and accumulation of pollutants in the environment over time. Common pollutants found in soil include heavy metals, insecticides, and polycyclic aromatic hydrocarbons (PAHs) (Mirsal et al., 2008). Soil contamination occurs when these substances adhere to the soil, either through direct spills or contact with previously contaminated soil. As they degrade gradually due to microbial action in the soil and water, they accumulate in the soil. This accumulation has a detrimental impact on plant growth, inhibiting it and reducing fruit size and yield. The breakdown products of these pollutants may be taken up by plants, subsequently entering the food chain and potentially affecting animals and humans (Mishra et al., 2016).

On a global scale, soil contamination, particularly by inorganic pollutants such as toxic heavy metals, poses a significant and escalating issue that is compromising the quality and safety of food and feed while endangering agro-ecosystems. This rise in heavy metal contamination can be largely attributed to industrialization, intensive agricultural practices, and other human activities. The persistent nature of metals due to their non-degradative characteristics contributes to their prolonged presence in the environment, rendering them potentially harmful to human health and ecosystems (Saleem et al., 2022).

The contamination of soil with heavy metals can lead to two major concerns: alterations in the composition and functioning of soil microbiomes (Alsabhan et al., 2022; Du et al., 2021), as well as potential uptake by plants (Goyal et al., 2020; Malkowski et al., 2019), resulting in a loss of soil value. Additionally, there is a risk to human health in the vicinity of contaminated sites (Mitra et al., 2022; Zaynab et al., 2022). Effective measures, encompassing stringent governmental or private regulations and detoxification techniques, are essential for curtailing the release of heavy metals from diverse sources and consequently preventing or mitigating metal pollution. Regulatory limits for heavy metal concentrations in soil, established in different countries and varying across regions and metal types, serve as the foundation and guidelines for heavy metal remediation efforts.

The application of fertilizers not only enhances crop productivity but also induces changes in the physicochemical and biological attributes of the soil. However, the immediate effects of chemical fertilizers on soil may not be readily apparent, as observed in various research and studies (Savci, 2012). Nevertheless, consistent use of chemical fertilizers has been identified as a key factor contributing to the decline in agricultural soil quality and soil organic matter (SOM) content. The excessive utilization of chemical fertilizers has detrimental implications for the environment, including soil compaction, diminished fertility, soil and water pollution, air pollution, and a decrease in essential nutrients and minerals within the soil. The exclusive reliance on artificial fertilizers can also lead to reduced microbial activity within the cropping system (Pahalvi et al., 2021).

Pesticide toxicity is influenced by factors such as electrical characteristics, molecular structure, dosage, and exposure duration (Heard et al., 2017). Despite their potential environmental and human health risks, pesticides are used to control, eliminate, and manage hazardous pests. Excessive use of pesticides can contribute to elevated levels of pollutant substances in the environment. Over time, the World Health Organization has assessed the toxicity of pesticides and reported on their impacts on human health (WHO, 2019). Several pesticides with high toxicity have been banned in various countries due to their harmful effects. However, their production and use continue, particularly in underdeveloped nations. Given these concerns, implementing effective remediation strategies is crucial to reducing residual pesticide content in the soil.

The collective pollution sources contribute to the deterioration of land, a phenomenon characterized by the decline in essential ecosystem functions due to natural or human-induced processes that lead to the diminishment or elimination of inherent soil properties – physical, chemical, and biological (Montanarella and Sivakumar, 2007). The assessment of global land degradation is intricate and subject to disparities across different research studies (Figure 1).

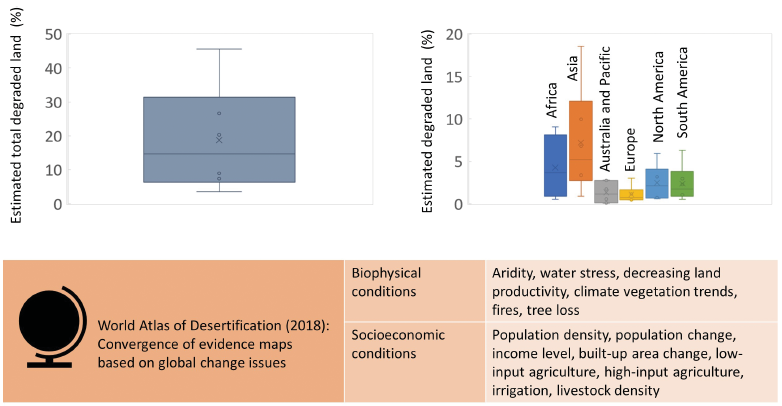
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Figure 1: Land degradation estimation (Coban et al., 2022): These graphs are based on data from Gibbs and Salmon (2015) and IPBES (2018) (177, 178).

Hence, it is imperative to minimize the presence of pollutants as extensively as achievable in order to enhance soil health, given that its condition significantly influences our overall quality of life.

1. **Nanobioremediation**

Nano-bioremediation, an approach employing nanoparticles as catalysts to accelerate bioremediation processes, is designed to purify the environment. These nanoparticles (NPs) can access contaminated areas that might be inaccessible to other agents. Consequently, nanobioremediation technologies offer a broader scope of applicability, giving them an advantage over alternative remediation methods (Shastri and Arunachalam, 2022 Ch-2). The process of nanobioremediation has been extensively researched and carbon- and metal-based nanoparticles have emerged as the most widely utilized (Gong et al., 2009; Chen et al., 2017). The nanobioremediation procedure involves two main steps: firstly, nanoparticles break down contaminants to a level conducive for subsequent bioremediation, undergoing various physicochemical processes and modifications; secondly, the pollutants undergo biodegradation (Cecchin et al., 2017). According to the findings of Singh et al. (2020), nano-bioremediation has been employed for the remediation of toxic substances using two distinct approaches. The initial approach involves a sequential technique, wherein the contaminants undergo treatment with nanoparticles before being exposed to microbes for subsequent degradation. The second method involves a combined approach, where the pollutants are simultaneously treated with both microbes and nanoparticles. Figure 2 visually illustrates the overall nanobioremediation process, particularly emphasizing biogenic nanoparticles.

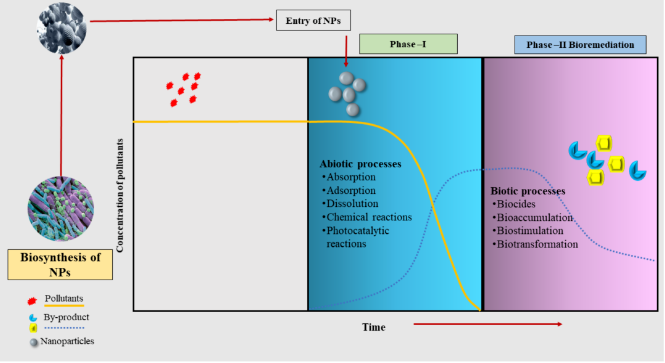


Figure 2: Outline of biogenic nanoparticle-assisted nanobioremediation processes (Rajput et al., 2022).

1. Top of Form

This approach offers an environmentally friendly and economically feasible solution for eliminating contaminants (Patra Shahi et al., 2021). The primary benefits of bioremediation in comparison to traditional methods encompass heightened efficiency, minimized generation of chemical and biological waste, selectivity, absence of additional nutrient requirements, potential for bio-sorbent regeneration, and the possibility of metal recovery (Juwarkar et al., 2010; Rizwan et al., 2014; Chauhan et al., 2020). Nano-bioremediation subcategories are distinguished based on the type of organism employed, namely microbial nanoremediation and nanophytoremediation involving the use of nanoparticles in conjunction with phytoremediation (Singh et al., 2020; Kumari et al., 2022; Figure 3).

Figure 3: Classification of Nanobioremediation (Singh and Saxena, 2022)

The interactions among nanoparticles (NPs), biotic components (microbes and phyto-), and contaminants are well-documented and are influenced by several factors. These factors include the size and shape of the NPs, their surface coating, and chemical composition. Moreover, the characteristics of the contaminants, the type of organism employed, the surrounding medium, pH, and temperature also play a significant role in shaping the process (Ibrahim et al., 2016; Tan et al., 2018). When NPs and biota interact, various processes may take place, including dissolution, apoplastic and symplastic transport, absorption, adsorption, biostimulation, and biotransformation (Kranjc and Drobne, 2019; Vázquez-Núñez et al., 2020).

1. **Microbiome-mediated nanobioremediation**

The utilization of microorganisms to detoxify various inorganic pollutants has yielded promising outcomes, as demonstrated by numerous researchers. There is a growing interest in leveraging the soil microbiome, particularly the bacterial, fungal, and algal communities, along with their secretory products or biomolecules, to produce novel environmentally friendly, commercially viable, and practically stable nanoparticles (NPs) with a wide range of applications, some of which are listed in Table 1. This trend has gained significant traction in recent years, encompassing various biogenic NPs (Mughal et al. 2021; Patil and Chandrasekaran, 2020). These biogenic NPs exhibit functionality in aerobic, anaerobic, and even extreme environmental conditions, rendering them highly suitable candidates for bioremediation processes. The soil microbiome is capable of synthesizing various NPs, contributing to the mitigation of inorganic soil pollutants as visually represented in Figure 4.

Bacteria are frequently employed in nanobioremediation techniques owing to their distinctive metal-binding capabilities. However, beyond bacteria, fungi and yeasts also play a significant role in this field of study (Pandey, 2018; Yadav et al., 2017). Fungi, in particular, are utilized in nanoparticle synthesis due to their notable enzymatic activity and protein content (Li et al., 2011; Patil et al., 2016; Guilger-Casagrande and Lima, 2019).

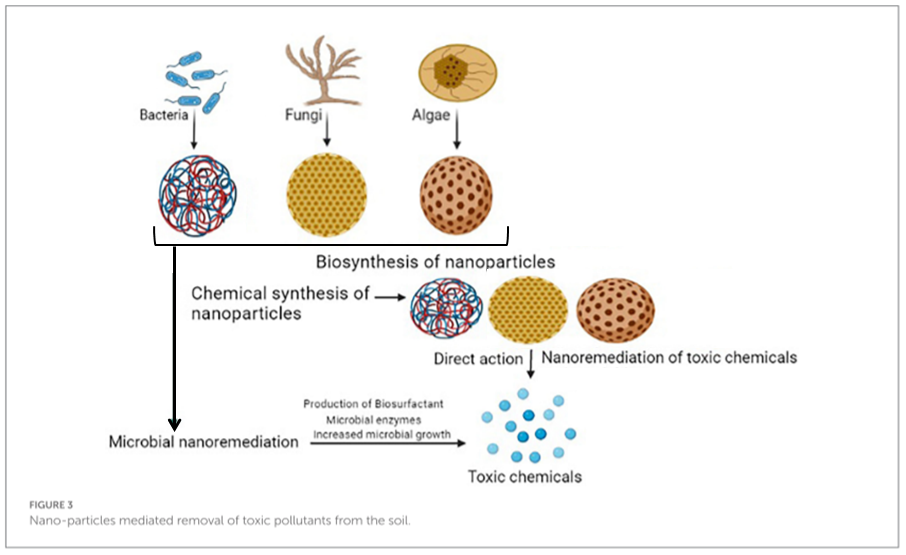


Figure 4: Utilization of nanoparticles for the removal of harmful pollutants from soil (Singh and Saxena, 2022).

Bacteria, among the heterogeneously distributed soil microbiome are regarded as valuable in nanobioremediation technology. This is because they have evolved protective mechanisms like biotransformation, biomineralization, bioreduction and secretion of extracellular polymeric substances (EPS) to reduce metal toxicity, and thereby could grow well at low pH and could multiply and ramify in environments containing toxic metals ((Rizvi et al., 2020; Narayanan and Sakthivel 2010), also the S-layers and bacterial cells' remarkable metal-binding properties. The soil microbiome boosts up the bioremediation process and concurrently detoxifies the pollutants by immobilizing, converting, or triggering the creation of microbial enzymes catalyzing the degradation/detoxification of toxicants. This process is capable of occurring either alone or in synergism (Saleem et al., 2022).

A variety of metal nanoparticles, including silver, palladium, and gold, have been successfully synthesized using algae from different groups such as Chlorophyceae, Cyanophyceae, Phaeophyceae, and Rhodophyceae. Algae constitute the largest group of photoautotrophic microorganisms, exhibiting the potential to function as nano-machineries for producing metallic nanoparticles. The process of fabricating nanoparticles from algae is notably time-efficient (Khanna et al., 2019). Algae possess several advantageous properties, including a high capacity for metal uptake, ease of handling and harvesting, cost-effectiveness, and low toxicity. These attributes render them well-suited to serve as nano-factories (Sharma et al., 2016).

Table1: Some Microbiome synthesis of nanoparticles (Miranda et al., 2022)

|  |  |  |  |
| --- | --- | --- | --- |
| **Microbe** | **Nanoparticle** | **Size (nm)** | **References** |
| *Fusarium oxysporium* | Au | 20-40 | Mukherjee et al., 2002 |
| *Thermomonospora* sp. | 8 | Ahmad et al., 2003 |
| *Colletotrichum* sp. | 20-40 | Shankar et al., 2003 |
| *Pseudomonas aeruginosa* | 15-30 | Husseiny et al., 2007 |
| *Chollera vulgaris* | 40-60 | Luangpipat et al., 2011 |
| *Rhodococcus* sp. | 5-15 | Mishra et al., 2012 |
| Algae | - | Costa et al., 2020 |
| Yeast | - | Krishnan et al., 2021 |
| *Pseudomonas stutzeri* | Ag | Up to 200 | Belliveau et al., 1987 |
| *Aspergillus flavus* | 8-10 | Vigneshwaran et al., 2007 |
| Yeast | - | Shu et al., 2020 |
| Algae | - | Chugh et al., 2021 |
| *M13 bacteriophage* | HAP | Hydroxyapatite fibrosis | He et al., 2010 |
| Tobacco mosaic virus | Silica | Various shapes | Fernandes et al., 2014 |
| *Escherichia coli* | CdS | 2-5 | Sweeney et al., 2004 |
| *Candida glabrata* | 2 | Gericke and Pinches, 2006 |
| *Clostridium thermocetium* | - | Prasad et al., 2010 |
| *Bacillus cereus* | - | Harikrishnan et al.,2014 |
| *Torulopsis* sp. | PbS | 2-5 | Kowshik et al., 2002 |
| *Desulfovibro desulfuricans* | - | Gomez-Bolivar et al., 2019 |
| Yeast | Zn3(PO4)2 | 10-80 X 80-100 | Yan et al., 2009 |

Fungi serve as biocatalysts and find application in bioremediation due to their adaptability to harsh conditions and ability to tolerate elevated concentrations of heavy metals (Dixit et al., 2015). In the realm of green nanotechnology, fungi are employed for synthesizing nanoparticles, playing a crucial role in eliminating toxic compounds and organic pollutants (Singh et al., 2018). Recently, the synthesis of metal nanoparticles from fungi has garnered substantial attention from researchers worldwide (Sunny et al., 2022). Metal nanoparticles synthesized through fungi offer numerous advantages, including a higher capacity for metal uptake, cost-effective and uncomplicated production, resistance to metal exposure, scalability, and remarkable stability (Yadav et al., 2015).

Enhancing the microbial community through the application of nanoparticles (NPs) offers an additional approach to mitigate and eliminate toxic pollutant loads. Silicon nanoparticles (Si NPs), for instance, have been documented to enhance microbial colonization and biomass, particularly benefiting rhizospheric microbes that play a role in enhancing soil health (Srivastava et al., 2021; Gajic et al., 2018).

1. **Nanophytoremediation**

Phytoremediation refers to the process in which plants are used to conduct bioremediation. This innovative technique employs various plant species to degrade, extract, confine, or immobilize contaminants present in soil and water, thereby aiding in environmental remediation (Sharma, 2012). The term "phytoremediation," rooted in Greek words signifying "restore" or "remedy through plants," captures its fundamental concept (Pandya et al., 2022). With the integration of nanotechnology, nanophytoremediation involves leveraging plants to absorb, store, or modify nanoparticles and nanomaterials, enhancing environmental cleanup initiatives, such as remediating pollutants in soil or water.

In recent times, research has increasingly focused on nanoparticle synthesis using chemical, physical, and green methods (Wang et al., 2007; Horwat et al., 2011). The shift is towards green synthesis, replacing physical and chemical approaches (Alsammarraie et al., 2018) due to concerns about energy consumption (Horwat et al., 2011), hazardous chemical releases (Hoag et al., 2009), and complex equipment usage (Baruwati et al., 2009; Saiqa Ikram, 2015). Green synthesis mainly involves microorganisms (fungi, bacteria, algae) (Subramaniyam et al., 2015; Arsiya et al., 2017) or extracts from plant leaves, flowers, roots, peelings, fruits, and seeds (Devi et al., 2019; Chahardoli et al., 2018; Leili et al., 2018; Thovhogi et al., 2016; Sone et al., 2020; Ehrampoush et al., 2015; Kumar et al., 2017; Dhand et al., 2016; Gao et al., 2016), Table 2. Engineered nanoparticles with tailored properties are synthesized by scientists to interact with specific pollutants. These synthesized nanoparticles can be absorbed by plants through roots or foliar application. Once inside the plant, they are transported through the vascular system, accumulating in various plant parts based on their characteristics. Interactions with pollutants include adsorption, catalysis of transformations, and aiding pollutant uptake. Combined with the plants' natural processes, synthesized nanoparticles enhance phytoremediation, where plants naturally mitigate pollutants. After the process, harvested plants, along with nanoparticles and pollutants, are disposed of in accordance with regulations.

Nanophytoremediation has demonstrated effectiveness in addressing diverse soil pollutants, spanning heavy metals to organic compounds. Plants function as natural detoxifiers by absorbing and detoxifying various substances. The success of nanophytoremediation is influenced by plant properties, such as growth rate, biomass, root development, tolerance to toxicity, accumulation capacity, non-palatability to animals, and genetic manipulability. To achieve optimal efficiency, plants should possess these attributes, ensuring high efficacy (Sajid et al., 2015).

Phytoremediation is recognized as a preferred and cost-effective method for the in-situ treatment of polluted soils, as emphasized by researchers (Liang et al., 2017). The nanophytoremediation approach has shown positive outcomes in addressing various soil contaminants, including heavy metals and organic compounds. Researchers such as Pillai and Kottekottil (2016) and Souri et al. (2017) have observed that the utilization of nanoparticles enhances plants' stress tolerance and simultaneously improves their contaminant absorption capacity. Nonetheless, phytoremediation has certain limitations, including the protracted duration of the remediation process and the generation of plant waste. The effectiveness of nanobioremediation is influenced by multiple factors, encompassing the physical and chemical attributes of compounds, their molecular weight, water solubility, soil conditions (pH, temperature, organic matter content), and plant characteristics (Gulzar and Mazumder, 2022).

**Table 2: Some plants synthesized nanoparticles** (Miranda et al., 2022)

|  |  |  |  |
| --- | --- | --- | --- |
| **Plant** | **Nanoparticle** | **Size (nm)** | **References** |
| *Pyrus* sp. | Au | 200-500 | Ghodake et al., 2010 |
| *Eucalyptus macrocarpa* | 20-100 | Poinern et al., 2013 |
| *Mangifera indica* | Ag | 20 | Philip, 2011 |
| *Citrullus colocynthis* | 31 | Satyavani et al., 2011 |
| *Psidium guajava* | 25-30 | Raghunandan et al., 2009 |
| *Rhododendron dauricum* | 25-40 | Mittal et al., 2012 |
| *Aloe vera* | Ag, Au | 50-350 | Chandran et al., 2006 |
| *Camelia sinensis* | 30-40 | Vilchis-Nestor et al., 2008 |
| *Aloe vera* | In2O3 | 5-50 | Maensiri et al., 2008 |
| *Curcuma longa* | Pd | 10-15 | Sathishkumar et al., 2009 |
| *Diospyros kaki* | Pt | 15-19 | Song et al., 2010 |

1. **Mitigation of contaminants of polluted soil**
2. **Heavy metals**

Nanoparticles, including bio-organic nanoparticles synthesized using biological organisms, have been employed for the purpose of removing heavy metals from soil. Bio-organic nanoparticles, exemplified by silver nanoparticles produced within *Morganella psychrotolerans*, have been utilized for heavy metal removal (Arif et al., 2016; Enez et al., 2018). Iron oxide nanoparticles coated with polyvinyl pyrrolidone (PVP) are applied in conjunction with *Halomonas* sp. (a gram-negative bacteria) for the bioremediation of lead and cadmium (Alabresm et al., 2018). Supported *by Spirulina platensis*, Pd NP managed to remove Pd in the range of 12% to 90% (Sayadi et al., 2018), while iron oxide nanoparticles based on *Geobacter sulfurreducens* exhibited complete removal of chromium from chromium-polluted soils (Watts et al., 2015).

A recent investigation into the removal of Cu, Cd, Cr, and Pb utilizing heavy metal-resistant bacteria, specifically B. *cereus* (PMBL-3) and L. *macroides* (PMBL-7), has effectively demonstrated that the application of ZnO nanoparticles (NPs) at a concentration of 5 mg L−1 leads to significant removal synergies. Specifically, the combination of ZnO NPs removed 60% of Cr, 70% of Cu, and 85% of Pb, as opposed to removal rates of 80% and 60% for B. *cereus*, and 55% and 50% for L. *macroides*, at a neutral pH (Baragano et al., 2020). Under neutral pH conditions, the surface of ZnO NPs carries negative charges that facilitate electrostatic interactions with metal cations. However, at lower pH levels, heavy metals precipitate as hydroxides, with hydrogen ions competing for binding with adsorbents (Xie et al., 2011).

Additionally, the strain XMCr-6 of *B. cereus* has been documented to reduce Cr6+ through an enzyme-mediated process. The reduced Cr3+ forms coordination bonds with functional groups on the surface of the bacterial cell wall, displaying a binding affinity to cells. Consequently, the by-product Cr2O3 NPs are formed on the cell surface (Laslo et al., 2022).

Certain fungi, like *Fusarium solani*, exhibit heightened tolerance towards specific heavy metals such as cadmium, nickel, and lead, and possess a remarkable capacity for nanoparticle synthesis (Rasha, 2017). Extremophilic fungi, due to their ability to endure harsh conditions, play a significant role in nanobioremediation of heavy metals, rendering them crucial for this purpose (Bahrulolum et al., 2021).

In the context of bio-organic nanoparticle synthesis, a strategy involves utilizing selective microbes to uptake heavy metal pollutants, subsequently removing them from the environment while generating value from waste. For instance, *Enterococcus faecelis* was employed for the removal and recovery of lead. Bacteria synthesized lead nanoparticles both extracellularly and intracellularly, with a particle size of approximately 10 nm. These nanoparticles exhibited high catalytic efficiency, effectively reducing 5.0 μmol Cr+6 within 12 hours (Cao et al., 2020).

Overall, this underscores the importance of the nanoparticle core and functional groups in such processes, as well as the valuable role of extremophilic fungi in nano-bioremediation.

The utilization of synthesized nanoparticles at a concentration of 20 ppm has been shown to mitigate the adverse effects of Cadmium by enhancing plant growth rate, photosynthesis, antioxidant enzymes, and iron absorption while reducing Cadmium content in plants (Prasad et al., 2021). In the context of remediating Cr(VI) contaminated soil, the study involving nZVI stabilized with sodium carboxymethyl cellulose revealed a substantial improvement in Chromium immobilization by reducing its bioaccessibility and leachability (Wang et al., 2014). However, this remediation approach hindered the growth of Chinese cabbage and rape plants due to the physicochemical properties of nZVI, which led to decreased root biomass and germination retardation (Zand et al., 2020). Nevertheless, after a month, a phytotoxicity test revealed an improvement in both plant cultures, suggesting that soil quality might be gradually restored through nZVI-based remediation.

Furthermore, a study investigated how wheat seedlings responded to the presence of citrate-coated magnetite nanoparticles when exposed to Cadmium(II) and Chromium(VI) toxicity (López-Luna et al., 2016). The nanoparticles were found to enhance the growth of wheat seedlings by mitigating the toxicity of these heavy metals, indicating their potential to alleviate the negative effects of heavy metal contamination on plant development.

The application of magnetite nanoparticles led to a significant reduction in the phytoavailability of Cadmium and Chromium, effectively diminishing their individual and combined toxicity. In the context of rice seedlings, a study investigated the impact of four different types of TiO2 nanoparticles in rutile and anatase forms on lead (Pb) bioaccumulation (Cai et al., 2017). While these nanoparticles successfully lowered lead bioaccumulation in rice tissues, they accumulated in rice roots by approximately 80%, raising potential concerns for food safety (Okoh et al., 2020).

Several studies have explored the interplay between nanoparticles and microorganisms in facilitating the bioremediation of contaminated land. Fe3O4 nanoparticles, when combined with soil-based microorganisms, exhibited enhanced potential for the degradation of the pesticide 2, 4-dichlorophenoxyacetic acid in soils (Fang et al., 2012). This highlights the synergistic effect of nanoparticles and microorganisms in enhancing the efficiency of bioremediation processes.

1. **Pesticides**

The exposure to nanotubes significantly reduced the bioavailability of pesticide residues, resulting in decreased contamination of edible lettuce tissues. Researchers found that pesticide uptake and accumulation ranged from 21 to 80 percent depending on the nanomaterial species used and their dosage. This study highlighted the varying impacts of nanomaterials on different plant species' ability to phytoremediate contaminated soil.

These aspects were further investigated in a different study involving the remediation of pesticides such as DDT, chlordane, and its metabolites (DDx). Nanowires and C60 were employed for this purpose across four plant species: S. *lycopersicum* (tomato), *Zea mays* (corn), G. *max* (soybean), and C. *pepo* (zucchini). The treatment involving C60 enhanced chlordane accumulation in tomato and soybean plants by 34.9 percent, while completely inhibiting DDx uptake in maize and tomato plants (Ramezani et al., 2021). This underscores the nuanced effects of nanomaterials on different plants' ability to remediate pesticide contamination.

1. **Chemical Fertilizers**
2. **Nanobiofertilizers and Bionanofertilizers**

The adoption of nanobiofertilizers (NFs) and bionanofertilizers as alternatives to chemical fertilizers holds the potential to enhance soil productivity sustainability and mitigate the impacts of soil pollution. NFs can serve as viable substitutes for traditional mineral fertilizers (depicted in Figure 5). NFs offer the advantage of controlled and sustained nutrient release, which can be tailored to meet the specific needs of different crops (Arora et al., 2022). Biological nanofertilizers are characterized by their non-toxicity and sustainable nature, distinguishing them from chemical or physical counterparts. These nanobiofertilizers are produced by bacteria in a medium containing metal compounds, which are then converted into nano-sized metals (El-Ghamry et al., 2018).

Copper, selenium, silicon, zinc, and other elements can all be organically synthesized into various types of nanofertilizers. The biological approach to nanoparticle synthesis involves the use of plant products, their extracts, isolates, and other microorganisms within the production process. This method is preferred for nanomaterial synthesis due to its lack of toxic chemicals, cost-effectiveness, scalability, and environmentally-friendly nature (Saravanan et al., 2021). These bio-based processes minimize nutrient loss resulting from soil leaching, gasification, erosion, and other factors (Al-Mamun et al., 2021). The bio-based synthesis of metallic nanoparticles, facilitated by plants or microbiomes, is deemed advantageous due to its rapid synthesis, controlled toxicity, desired morphologies, controlled size, cost-effectiveness, eco-friendliness, and ease of application (Singh et al., 2020).

Laboratory-scale production of NFs involves various biological and precursor materials, including bacteria, fungi, and plants (as illustrated in Figure 6). The key distinctions between bionanofertilizers and nanobiofertilizers are outlined in Table 3.

Table 3: Basic difference between Bionanofertilizers and nanobiofertilizers (Gade et al., 2023).

|  |  |  |
| --- | --- | --- |
| **Characteristic** | **Bionanofertilizers** | **Nanobiofertilizers** |
| Synthesis of NPs | Biological method | Biological, chemical, or Physical |
| Structure | Biologically synthesized NPs as  fertilizer | Nano-encapsulated Organic  Molecules as fertilizer |
| Encapsulation | Biomolecules from biological  materials | Nanomaterial |
| Core | Micro/macronutrient element | Inorganic and organic |
| Example | MgO , ZnO | Phosphorous-hydroxyapatite  NPs and Zn-Chitosan NPs |

Figure 5: The features and benefits of nanofertilizers (El-Ramady et al., 2022)

Figure 6: Illustration depicting the biological production process of nanofertilizers (Gade *et* al., 2023)

**3.3.4 Other toxic pollutants**

In addition to these primary pollutant categories, other harmful substances exist in the surroundings. The capability of Pseudomonas putida to effectively eliminate organic micropollutants through biogenic production of manganese oxide NPs was demonstrated (Furgal et al., 2015). Fullerene nanoparticles (NPs) have demonstrated the ability to increase the absorption of trichloroethylene in *Populus deltoides*. At concentrations of 2 and 15 mg/L, fullerene NPs enhanced uptake by 26% and 82%, respectively. Another study used *Plantago major* with activated charcoal and SiO2-synthesized Fe and Ag nanoparticles (*Ficus*-FeNPs, *Ipomoea*-Ag, *Brassica*-AgNPs) to remove chlorfenapyr, achieving removal rates of 93.7%, 91.30%, and 92.92%, respectively (Romeh and Saber, 2020).

A nanoremediation process mediated by *Bacillus licheniformis* involved bio-functionalizing Zn5OH8Cl2-modified Fe2O3 NPs with B. *licheniformis* to facilitate the natural degradation of crude oil into degradable compounds. Moreover, the potential of microbial bio-surfactants for efficient nanobioaugmentation of oil pollution was explored (El-Sheshtawy and Ahmed, 2017). Synergy between iron oxide NPs and *Alkaligenes faecalis* was found to enhance crude oil biodegradation in contaminated environments (Oyewole et al., 2019).

Hydrogen peroxide, frequently used in pharmaceuticals, also acts as an environmental pollutant. However, effective removal from industrial wastewater was achieved through electrocatalytic reduction using Pd nanoparticles synthesized from *Sargassum bovinum* (Momeni and Nabipour, 2015).

1. **Challenges in Nanobioremediation**

The introduction of nanoparticles into aquatic ecosystems, whether intentional or accidental, can potentially lead to detrimental impacts on various microorganisms such as bacteria, cyanobacteria, and algae. These microorganisms are highly sensitive to nanoparticle toxicity. Existing literature, including Li et al. (2010), has extensively examined nanoparticle toxicity towards microbes. In this context, the dosage of nanoparticles proves to be a critical factor within integrated systems for the degradation of toxicants. Evaluating the impacts and ensuring the safety of nanoparticle (NP) utilization in agriculture or contaminated soil is imperative. The viability of sustainable nanophytoremediation is closely tied to climatic conditions, which underscores the necessity of identifying inherently stable NPs in our investigation.

1. **Conclusion**

The emergence of nanobiotechnology as a research field presents prospects for the development of nanobioremediation methods aimed at rejuvenating contaminated soils. Empirical findings from various studies have underscored the potential of nanobioremediation in effectively removing diverse inorganic and organic contaminants from terrestrial environments. However, the high cost associated with nanoparticles has limited their application, particularly in economically disadvantaged and underdeveloped regions. Therefore, a crucial long-term objective should be the reduction of nanomaterial production costs, especially given the alarming escalation of pollutants contamination in densely populated nations like India, China, Africa, and other Southeast Asian countries. This would contribute to the broader accessibility and applicability of nanobioremediation strategies.

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