

NANOBIOREMEDIATION APPROACH TO MITIGATE SOIL POLLUTION: NANOTECHNOLOGY

Abstract

Agriculture, industry, and the environment are all negatively impacted by soil pollution, which is mostly brought on by chemicals from urban, industrial, and agricultural activities as well as waste disposal. Every year, almost 24 billion metric tons of rich soil are lost, causing soil deterioration throughout the world. Both human health and ecosystems are at risk from soil contamination, particularly from heavy metals. The quality and fertility of soil are also impacted by the use of chemical pesticides and fertilizers, which also contribute to soil degradation. Nano bioremediation is a cost-effective solution that combines biological and nanotechnological methods to use nanoparticles to accelerate the breakdown of contaminants. Microbial nano bioremediation and nano phytoremediation are two subcategories of nanobioremediation that show promise for soil detoxification. In conclusion, nanobioremediation holds significant promise as an innovative and environmentally friendly approach to addressing soil pollution by effectively harnessing the synergies between nanoparticles and biological processes for enhanced pollutant removal and soil restoration.

Keywords: Nanobioremediation, Soil pollution, Chemical Fertilizers

Author

Lajeni T Lajeo
Research Scholar
Division of Microbiology
IARI, New Delhi, India.

I. INTRODUCTION

Pollution of soil is mainly by the chemicals from various origins, encompassing industrial and agricultural activities, the disposal of waste, and urbanization. Adverse consequences of soil pollution on agriculture, industry, cities, and the environment include altered soil biodiversity, decreased soil fertility, and water contamination. According to estimates, every year, approximately 24 billion metric tons of fertile soil are depleted, 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 viable and economically efficient approach 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 are smaller and possess a larger surface area, allowing them to absorb pollutants above a wider surface area or function as catalysts. Zinc, silver, gold, copper, and various other nanoparticles and nanomaterials have demonstrated their efficacy in neutralizing detrimental inorganic pollutants, thereby alleviating stress in contaminated environments (Ibrahim *et al.*, 2021, Vanlalveni *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 Nanoparticles along with their biological components to effectively mitigate harmful pollutants.

Therefore, innovative remediation approaches combine biological and nano technological 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.

II. 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 central role in influencing 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 impacts of human activities and land utilization, 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, resulting in the gradual scattering and buildup of pollutants within the environment. Common pollutants found in soil include heavy metals, insecticides, and polycyclic aromatic hydrocarbons (Mirsalet *et al.*, 2008). Soil contamination happens when these substances attach to the soil, whether through direct releases 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 could potentially be absorbed by plants, leading to its incorporation into the food chain and potentially affecting animals and humans (Mishra *et al.*, 2016).

On a global scale, soil pollution, 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 methods, and various other human actions. 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 well-being and ecosystems (Saleem *et al.*, 2022).

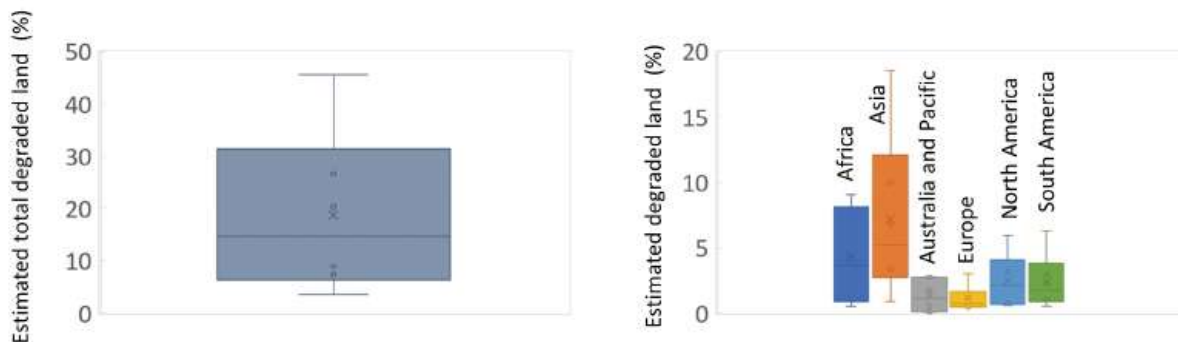
The contamination of soil with heavy metals can lead to two major concerns: alterations in the structure and functioning of soil microbiomes (Alsabhan *et al.*, 2022; Du *et al.*, 2021), and the possible absorption by plants (Goyal *et al.*, 2020; Malkowski *et al.*, 2019), resulting in a loss of soil value. Additionally, there is a risk to human well-being in the vicinity of polluted sites (Mitra *et al.*, 2022; Zaynab *et al.*, 2022). Effective measures, encompassing stringent governmental or proprietary guidelines and methods for detoxification, 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 alterations in the physical, chemical, 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 degradation of agricultural soil quality and soil organic matter levels. 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 can be shaped 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 polluting compounds in the environment. Over time, the World Health Organization has assessed the toxicity of pesticides and documented on their impacts on human health (WHO, 2019). Several pesticides with high toxicity have been prohibited in various nations because of their harmful effects. Nonetheless, the manufacturing and utilization of these substances 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 evaluation of worldwide land deterioration is intricate and subject to disparities across different research studies (Figure 1).




 <p>World Atlas of Desertification (2018): Convergence of evidence maps based on global change issues</p>	Biophysical conditions	Aridity, water stress, decreasing land productivity, climate vegetation trends, fires, tree loss
	Socioeconomic conditions	Population density, population change, income level, built-up area change, low-input agriculture, high-input agriculture, irrigation, livestock density

Figure 1: Land Degradation Estimation (Coban *et al.*, 2022): These Charts are Derived from Information Provided by Gibbs and Salmon in 2015 and IPBES in 2018 (References 177 and 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.

III. NANOBIOREMEDIATION

Nano-bioremediation, an approach employing nanoparticles as catalysts to accelerate bioremediation processes, is designed to purify the environment. These nanoparticles 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). 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.

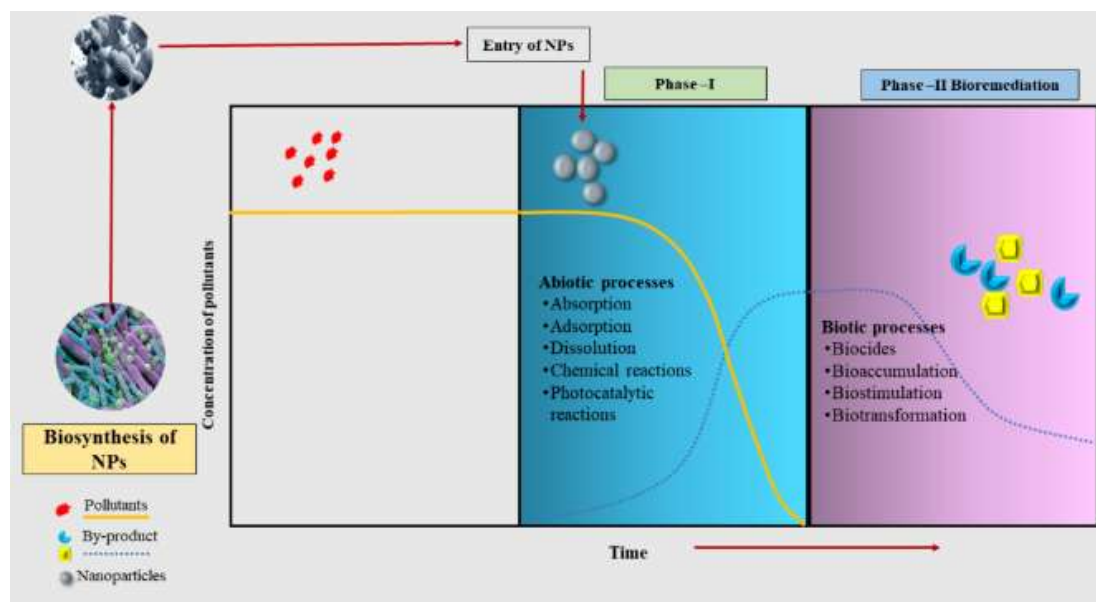


Figure 2: Outline of Biogenic Nanoparticle-Assisted Nanobioremediation Processes (Rajput *et al.*, 2022).

This approach provides an ecologically sustainable and cost-effective solution for eliminating pollutants (PatraShahi *et al.*, 2021). Principal advantages of bioremediation in comparison to traditional methods encompass heightened efficiency, minimized production of chemical and biological byproducts, 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). Nanobioremediation subcategories are distinguished based on the type of organism employed, namely microbial

nanobioremediation and nanophytoremediation involving the use of nanoparticles alongside phytoremediation (Singh *et al.* in 2020, Kumari *et al.* in 2022) as shown in Figure 3.

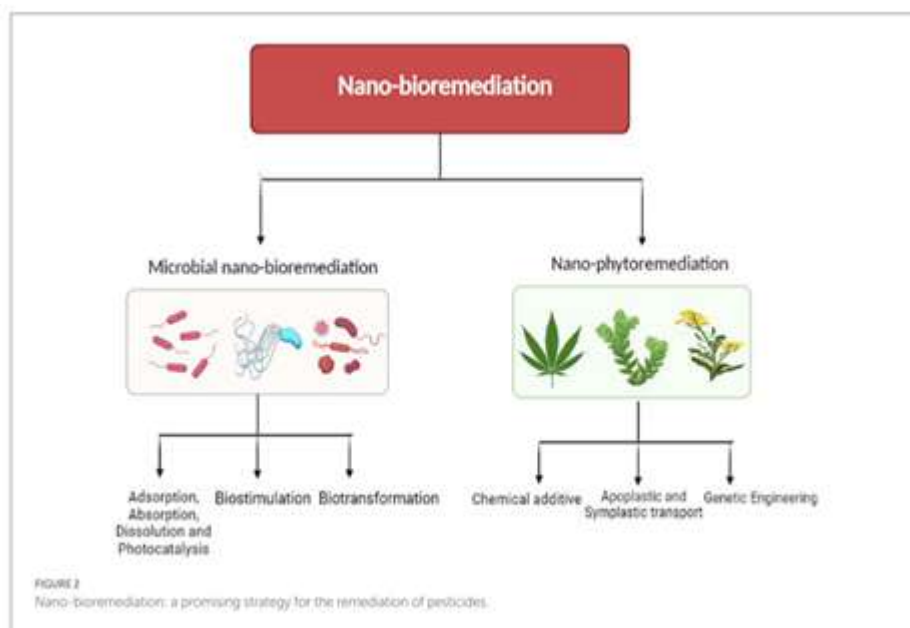


Figure 3: Classification of Nanobioremediation (Singh and Saxena, 2022)

The interactions among nanoparticles, biotic components (microbes and phyto-), and contaminants are well-documented and are influenced by several factors. These factors encompass the dimensions and shape of the nanoparticles, 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 Nanoparticles 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 communities of bacteria, fungi, and algae, along with their secretory substances or biomolecules, to produce novel environmentally friendly, commercially viable, and practically stable nanoparticles 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 nanoparticles (Mughal *et al.* 2021; Patil and Chandrasekaran, 2020). These biogenic Nanoparticles 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 Nanoparticles, 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).

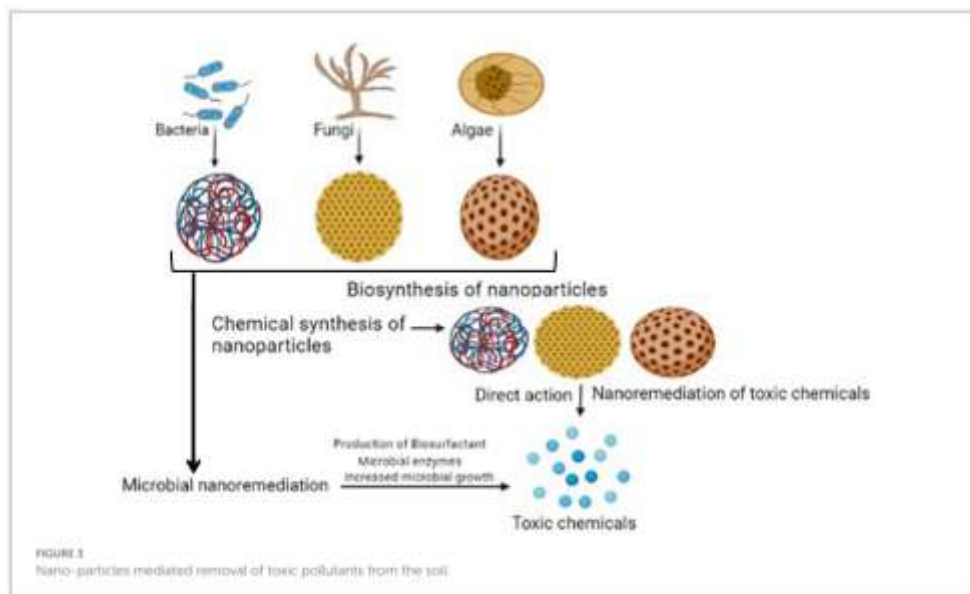


Figure 4: The Application of Nanoparticles for the Elimination of Noxious Contaminants from Soil (Singh and Saxena, 2022).

Bacteria, among the heterogeneously distributed soil microbiome are regarded as valuable in nanobioremediation technology. This is attributed to their development of defensive mechanisms like biotransformation, biomineralization, bioreduction and the production of extracellular polymeric substances to reduce metal toxicity, and thereby can thrive in low pH conditions and are capable of multiplying and ramifying 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 microbial community in soil boosts up the bioremediation process while simultaneously detoxifies the pollutants by immobilizing, converting, or triggering the creation of microbial enzymes that catalyze the breakdown and detoxification of harmful substances. 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 all been successfully synthesized using algae from various categories including Chlorophyceae, Cyanophyceae, Phaeophyceae, and Rhodophyceae. Algae constitute the most extensive category of photoautotrophic microorganisms, exhibiting the capability to function as nanoscale machinery for producing metal nanoparticles. The process of fabricating nanoparticles from algae is notably time-efficient (Khanna *et al.*, 2019). Algae possess several advantageous properties, including an ample capacity for metal absorption, ease of handling as well as harvesting, economic efficiency, and minimal

toxicity. These attributes render them well-suited to function as nano-production facilities (Sharma *et al.*, 2016).

Table1: Some Microbiome Synthesis of Nanoparticles (Miranda *et al.*, 2022)

Microbe	Nanoparticle	Size (nm)	References
<i>Fusarium oxysporium</i>	Au	20-40	Mukherjee <i>et al.</i> , 2002
<i>Colletotrichum</i> sp.		20-40	Shankar <i>et al.</i> , 2003
<i>Pseudomonas aeruginosa</i>		15-30	Husseiny <i>et al.</i> , 2007
<i>Chollera vulgaris</i>		40-60	Luangpipat <i>et al.</i> , 2011
<i>Rhodococcus</i> sp.		5-15	Mishra <i>et al.</i> , 2012
Algae		-	Costa <i>et al.</i> , 2020
Yeast		-	Krishnan <i>et al.</i> , 2021
<i>Aspergillus flavus</i>	Ag	8-10	Vigneshwaran <i>et al.</i> , 2007
Yeast		-	Shu <i>et al.</i> , 2020
Algae		-	Chugh <i>et al.</i> , 2021
<i>M13 bacteriophage</i>	HAP	Hydroxyapatite fibrosis	He <i>et al.</i> , 2010
Tobacco mosaic virus	Silica	Various shapes	Fernandes <i>et al.</i> , 2014
<i>Candida glabrata</i>	CdS	2	Gericke and Pinches, 2006
<i>Clostridium thermocetium</i>		-	Prasad <i>et al.</i> , 2010
<i>Bacillus cereus</i>		-	Harikrishnan <i>et al.</i> , 2014
<i>Torulopsis</i> sp.	PbS	2-5	Kowshik <i>et al.</i> , 2002
<i>Desulfovibrodieseluricans</i>		-	Gomez-Bolivar <i>et al.</i> , 2019
Yeast	Zn ₃ (PO ₄) ₂	10-80 X 80-100	Yan <i>et al.</i> , 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 production of metal nanoparticles using fungi has garnered substantial attention from researchers worldwide (Sunny *et al.*, 2022). Metal nanoparticles formed via 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 population by employing nanoparticles offers an additional approach to mitigate and eliminate pollution from toxic substances. Silicon nanoparticles, for instance, have been documented to enhance microbial colonization and biomass, particularly benefiting rhizospheric microbes that play a role in enhancing the health of the soil (Srivastava *et al.*, 2021; Gajic *et al.*, 2018).

- 2. 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 through chemical, physical, and green techniques (Wang *et al.*, 2007; Horwat *et al.*, 2011). The shift is towards green synthesis, substituting physical and chemical methods (Alsammaraie *et al.*, 2018) because of apprehensions regarding energy consumption (Horwat *et al.*, 2011), hazardous chemical releases (Hoag *et al.*, 2009), and complex equipment usage (Baruwati *et al.*, 2009; SaiqaIkram, 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; Sone *et al.*, 2020; 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 get taken up by plants via their 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 an economical approach for 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 pollutants, such as heavy metals and organic substances. Scientists like 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 as well as 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
<i>Pyrus</i> sp.	Au	200-500	Ghodake <i>et al.</i> , 2010
<i>Eucalyptus macrocarpa</i>		20-100	Poinern <i>et al.</i> , 2013
<i>Mangifera indica</i>	Ag	20	Philip, 2011
<i>Citrullus colocynthis</i>		31	Satyavani <i>et al.</i> , 2011
<i>Rhododendron dauricum</i>		25-40	Mittal <i>et al.</i> , 2012
<i>Aloe vera</i>	Ag, Au	50-350	Chandran <i>et al.</i> , 2006
<i>Cameliasinensis</i>		30-40	Vilchis-Nestor <i>et al.</i> , 2008
<i>Aloe vera</i>	In ₂ O ₃	5-50	Maensiri <i>et al.</i> , 2008
<i>Curcuma longa</i>	Pd	10-15	Sathishkumar <i>et al.</i> , 2009
<i>Diospyros kaki</i>	Pt	15-19	Song <i>et al.</i> , 2010

3. Mitigation of Contaminants of Polluted Soil:

- Heavy Metals:** Nanoparticles, which encompass bio-organic nanoparticles synthesized using biological organisms, have been employed for the purpose of heavy metal removal from soil. For instance, bio-organic nanoparticles like silver nanoparticles generated by *Morganellapsychrotolerans* have been employed in this context, as demonstrated by Arif *et al.* (2016) and Enez *et al.* (2018). Additionally, iron oxide nanoparticles coated with polyvinyl pyrrolidone (PVP) are utilized in conjunction with *Halomonas* sp., a gram-negative bacterium, aimed at the remediation of lead and cadmium contaminants, as shown in the research conducted by Alabresm *et al.* (2018). Supported by *Spirulinaplantensis*, Pd Nanoparticles managed to remove Pd in the range of 12% to 90% (Sayadi *et al.*, 2018), while iron oxide nanoparticles based on *Geobactersulfurreducens* exhibited complete elimination of chromium from soils contaminated with chromium Watts *et al.* (2015).

A recent investigation into the elimination of copper (Cu), cadmium (Cd), chromium (Cr), and lead (Pb) utilizing bacteria that are capable of withstanding heavy metal exposure, specifically *B. cereus* (PMBL-3) and *L. macroides* (PMBL-7), has effectively demonstrated that the application of ZnO nanoparticles at a concentration of 5 mg L⁻¹ leads to significant synergistic removal. Specifically, the combination of ZnO Nanoparticles 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 nanoparticles carries negative charges that facilitate electrostatic attraction to metal cations. However, when pH levels are lower, 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⁺ via an enzymatic-mediated mechanism. The reduced Cr³⁺, forms coordination bonds with functional groups found on the bacterial cell wall's surface, displaying a binding affinity to cells. Consequently, the by-product Cr₂O₃ nanoparticles 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 capacity to endure harsh conditions, exert a noteworthy role in nanobioremediation of heavy metals, rendering them crucial for this purpose (Bahrulolum *et al.*, 2021).

In the context of the synthesis of bio-organic nanoparticles, 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 faecalis* was utilized for the extraction and recuperation of lead. Bacteria synthesized lead nanoparticles both extracellularly and intracellularly, with a particle size of approximately 10 nm. These nanoparticles displayed exceptional catalytic efficiency, effectively reducing 5.0 $\mu\text{mol Cr}^{+6}$ within twelve 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 research conducted by Cai *et al.* (2017), examined the influence of four distinct variants of TiO_2 nanoparticles in rutile and anatase forms on lead (Pb) bioaccumulation. 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).

Numerous research investigations have delved into 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.

- **Pesticides:** The exposure to nanotubes significantly reduced the presence and accessibility of pesticide residues, resulting in decreased contamination of edible lettuce tissues. Researchers found that the absorption and buildup of pesticides ranged from 21 to 80 percent contingent upon 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.

- **Chemical Fertilizers**

- **Nanobiofertilizers and Bionanofertilizers:** The adoption of nanobiofertilizers (NFs) and bionanofertilizers as substitutes for synthetic fertilizers holds the potential for the purpose of improving 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 that can be customized to fulfill the distinct requirements of various 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 entails utilizing plant-derived 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 Nanoparticles Structure	Biological method Biologically synthesized Nanoparticles as fertilizer	Biological, chemical, or Physical Nano-encapsulated Organic Molecules as fertilizer
Encapsulation	Biomolecules from biological materials	Nanomaterial
Core	Micro/macronutrient element	Inorganic and organic
Example	MgO , ZnO	Phosphorous-hydroxyapatite Nanoparticles and Zn-Chitosan Nanoparticles

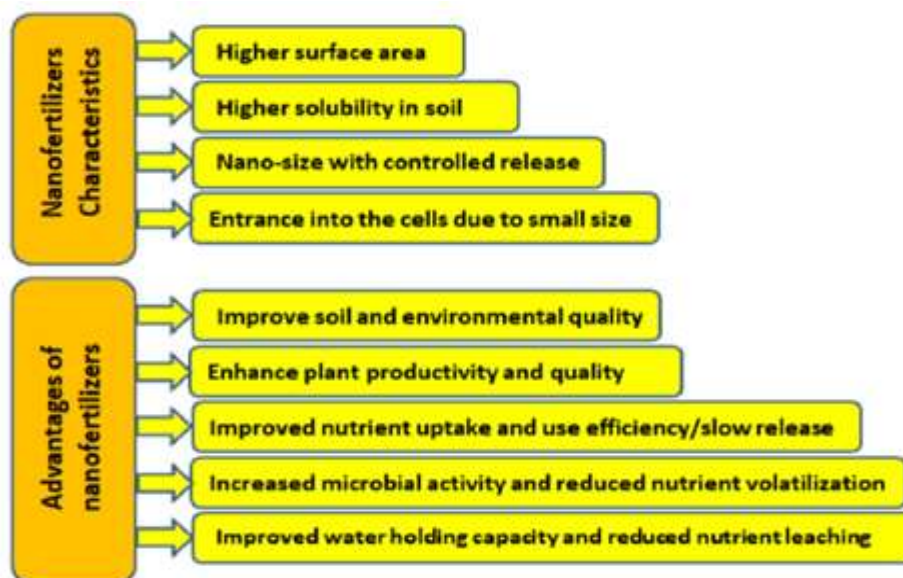


Figure 5: The Features and Benefits of Nanofertilizers (El-Ramady *et al.*, 2022)

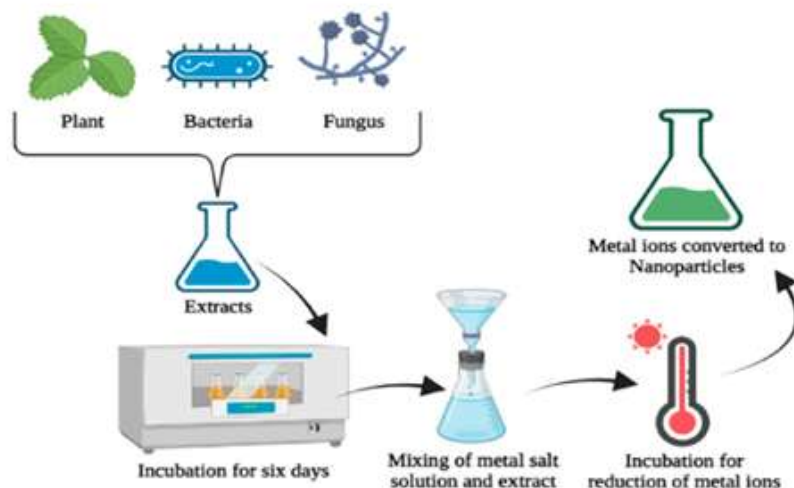


Figure 6: Illustration Depicting the Biological Production Process of Nanofertilizers (Gade *et al.*, 2023)

- **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 Nanoparticles was demonstrated (Furgal *et al.*, 2015). Fullerene nanoparticles have shown the capability to increase the absorption of trichloroethylene in *Populus deltoides*. Fullerene nanoparticles improved uptake by 26% and 82%, respectively, at concentrations of 2 and 15 mgL⁻¹. Another study used *Plantago major* with activated charcoal and SiO₂-synthesized Fe and Ag nanoparticles (*Ficus*-Fe nanoparticles, *Ipomoea*-Ag, *Brassica*-Ag Nanoparticles) to remove chlorfenapyr, thus achieved removal rates of 93.7%, 91.30%, and 92.92%, respectively, as reported by Romeh and Saber in 2020.

A nanoremediation process mediated by *Bacillus licheniformis* involved bio-functionalizing Zn₅OH₈Cl₂-modified Fe₂O₃ Nanoparticles with *B. licheniformis* to facilitate the natural degradation of crude oil into degradable compounds. Moreover, the potential of utilizing microbial biosurfactants to improve efficiency in nanobioaugmentation of oil pollution was explored (El-Sheshtawy and Ahmed, 2017). Synergy between iron oxide Nanoparticles and *Alkaligenes faecalis* was found to enhance the process of crude oil breaking down naturally in polluted 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).

IV. CHALLENGES IN NANOBIOREMEDIATION

The introduction of nanoparticles into aquatic ecosystems, whether intentional or accidental, can potentially lead to detrimental impacts on various microbes including

bacteria, cyanobacteria, and algae. These microorganisms are very responsive to the toxic effects of nanoparticles. 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 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 nanoparticles in our investigation.

V. 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.

REFERENCES

- [1] Ahmed, S., &Ikram, S. (2015). Silver nanoparticles: one pot green synthesis using Terminaliaarjuna extract for biological application. *J. Nanomed. Nanotechnol.*, 6(4), 309.
- [2] Al-Mamun, M.R.; Hasan, M.R.; Ahommed, M.S.; Bacchu, M.S.; Ali, M.R.; Khan, M.Z.H. Nanofertilizers towards sustainable agriculture and environment. *Environ. Technol. Innov.* **2021**, 23, 101658.
- [3] Alsabhan AH, Perveen K, Alwadi AS (2022) Heavy metal content and microbial population in the soil of Riyadh Region, Saudi Arabia. *J King Saud Univ-Sci* 34(1):101671.
- [4] Alsammaraie, F. K., Wang, W., Zhou, P., Mustapha, A., & Lin, M. (2018). Green synthesis of silver nanoparticles using turmeric extracts and investigation of their antibacterial activities. *Colloids and Surfaces B: Biointerfaces*, 171, 398-405.
- [5] Arif, N., Yadav, V., Singh, S., Singh, S., Ahmad, P., Mishra, R. K., & Chauhan, D. K. (2016). Influence of high and low levels of plant-beneficial heavy metal ions on plant growth and development. *Frontiers in environmental science*, 4, 69.
- [6] Arora S, GajiramMurmu, Koel Mukherjee, SumitSaha, DipakMaity D (2022). A comprehensive overview of nanotechnology in sustainable agriculture. *Journal of Biotechnology*, 355, 21-41.
- [7] Arsiya, F., Sayadi, M. H., & Sobhani, S. (2017). Green synthesis of palladium nanoparticles using *Chlorella vulgaris*. *Materials Letters*, 186, 113-115.
- [8] Bahrulolum, H., Nooraei, S., Javanshir, N., Tarrahimofrad, H., Mirbagheri, V. S., Easton, A. J., & Ahmadian, G. (2021). Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *Journal of Nanobiotechnology*, 19(1), 1-26.
- [9] Baragaño, D., Forján, R., Welte, L., & Gallego, J. L. R. (2020). Nanoremediation of As and metals polluted soils by means of graphene oxide nanoparticles. *Scientific reports*, 10(1), 1896.
- [10] Baruwati, B., Polshettiwar, V., & Varma, R. S. (2009). Glutathione promoted expeditious green synthesis of silver nanoparticles in water using microwaves. *Green chemistry*, 11(7), 926-930.
- [11] Cai, F., Wu, X., Zhang, H., Shen, X., Zhang, M., Chen, W., ...& Wang, X. (2017). Impact of TiO₂ nanoparticles on lead uptake and bioaccumulation in rice (*Oryzasativa L.*). *NanoImpact*, 5, 101-108.
- [12] Cao, X., Alabresm, A., Chen, Y. P., Decho, A. W., & Lead, J. (2020). Improved metal remediation using a combined bacterial and nanoscience approach. *Science of the Total Environment*, 704, 135378.

- [13] Cecchin, I., Reddy, K. R., Thomé, A., Tessaro, E. F., & Schnaid, F. (2017). Nanobioremediation: Integration of nanoparticles and bioremediation for sustainable remediation of chlorinated organic contaminants in soils. *International Biodeterioration & Biodegradation*, 119, 419-428.
- [14] Chahardoli, A., Karimi, N., & Fattahi, A. (2018). Nigella arvensis leaf extract mediated green synthesis of silver nanoparticles: Their characteristic properties and biological efficacy. *Advanced Powder Technology*, 29(1), 202-210.
- [15] Chandran, S. P., Chaudhary, M., Pasricha, R., Ahmad, A., & Sastry, M. (2006). Synthesis of gold nanotriangles and silver nanoparticles using Aloe vera plant extract. *Biotechnology Progress*, 22(2), 577-583.
- [16] Chauhan, A. K., Kataria, N., & Garg, V. K. (2020). Green fabrication of ZnO nanoparticles using Eucalyptus spp. leaves extract and their application in wastewater remediation. *Chemosphere*, 247, 125803.
- [17] Chen, C., Tsyusko, O. V., McNear Jr, D. H., Judy, J., Lewis, R. W., & Unrine, J. M. (2017). Effects of biosolids from a wastewater treatment plant receiving manufactured nanomaterials on *Medicago truncatula* and associated soil microbial communities at low nanomaterial concentrations. *Science of the Total Environment*, 609, 799-806.
- [18] Cherlet, M., Hutchinson, C., Reynolds, J., & Hill, J. S. Sommer, and von Maltitz, G. (eds.) (2018). *World atlas of desertification*.
- [19] Chugh, D., Viswamalya, V. S., & Das, B. (2021). Green synthesis of silver nanoparticles with algae and the importance of capping agents in the process. *Journal of Genetic Engineering and Biotechnology*, 19(1), 1-21.
- [20] Coban, O., De Deyn, G. B., & van der Ploeg, M. (2022). Soil microbiota as game-changers in restoration of degraded lands. *Science*, 375(6584), abe0725.
- [21] Costa, L. H., Hemmer, J. V., Wanderlind, E. H., Gerlach, O. M. S., Santos, A. L. H., Tamanaha, M. S., & Almerindo, G. I. (2020). Green synthesis of gold nanoparticles obtained from algae *Sargassum cymosum*: optimization, characterization and stability. *BioNanoScience*, 10, 1049-1062.
- [22] Deplanche, K., Bennett, J. A., Mikheenko, I. P., Omajali, J., Wells, A. S., Meadows, R. E., & Macaskie, L. E. (2014). Catalytic activity of biomass-supported Pd nanoparticles: influence of the biological component in catalytic efficacy and potential application in 'green' synthesis of fine chemicals and pharmaceuticals. *Applied Catalysis B: Environmental*, 147, 651-665.
- [23] Devi, H. S., Boda, M. A., Shah, M. A., Parveen, S., & Wani, A. H. (2019). Green synthesis of iron oxide nanoparticles using *Platanus orientalis* leaf extract for antifungal activity. *Green Processing and Synthesis*, 8(1), 38-45.
- [24] Dhand, V., Soumya, L., Bharadwaj, S., Chakra, S., Bhatt, D., & Sreedhar, B. (2016). Green synthesis of silver nanoparticles using *Coffea arabica* seed extract and its antibacterial activity. *Materials Science and Engineering: C*, 58, 36-43.
- [25] Dixit, R., Wasiullah, X., Malaviya, D., Pandiyan, K., Singh, U. B., Sahu, A., & Paul, D. (2015). Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. *Sustainability*, 7(2), 2189-2212.
- [26] Du Y, Zhang D, Zhou D, Liu L, Wu J, Chen H, Jin D, Yan M (2021) The growth of plants and indigenous bacterial community were significantly affected by cadmium contamination in soil-plant system. *AMB Express* 11(1):1-3.
- [27] El-Ghamry AM, Mosa AA, Alshaal TA, El-Ramady HR (2018). Nanofertilizers vs. Biofertilizers: New Insights. *Env. Biodiv. Soil Security* Vol. 2, 51 - 72. DOI:10.21608/jenvbs.2018.3880.1029
- [28] El-Ramady, H., Prokisch, J., El-Baily, S., Elasawi, T. H., Elmahrouk, M., Omara, A. E. D., ... & Brevik, E. (2022). Biological Nanofertilizer for Horticultural Crops: A Diagrammatic Mini-Review. *Environment, Biodiversity and Soil Security*, 6(2022), 339-348.
- [29] El-Sheshawy, H. S., & Ahmed, W. (2017). Bioremediation of crude oil by *Bacillus licheniformis* in the presence of different concentration nanoparticles and produced biosurfactant. *International Journal of Environmental Science and Technology*, 14, 1603-1614.
- [30] Enez, A., Hudek, L., & Bräu, L. (2018). Reduction in trace element mediated oxidative stress towards cropped plants via beneficial microbes in irrigated cropping systems: A review. *Applied Sciences*, 8(10), 1953.
- [31] Fang, G., Si, Y., Tian, C., Zhang, G., & Zhou, D. (2012). Degradation of 2, 4-D in soils by Fe₃O₄ nanoparticles combined with stimulating indigenous microbes. *Environmental Science and Pollution Research*, 19, 784-793.
- [32] Fernandes, F. M., Coradin, T., & Aimé, C. (2014). Self-assembly in biosilicification and biotemplated silica materials. *Nanomaterials*, 4(3), 792-812.

- [33] Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., and Bartolucci, C. (2016). Nanotechnology in agriculture: which innovation potential does it have? *Front. Environ. Sci.* 4, 20–21. doi: 10.3389/fenvs.2016.00020
- [34] Furgal, K. M., Meyer, R. L., & Bester, K. (2015). Removing selected steroid hormones, biocides and pharmaceuticals from water by means of biogenic manganese oxide nanoparticles in situ at ppb levels. *Chemosphere*, 136, 321-326.
- [35] Gade, A., Ingle, P., Nimbalkar, U., Rai, M., Raut, R., Vedpathak, M. & Abd-Elsalam, K. A. (2023). Nanofertilizers: The Next Generation of Agrochemicals for Long-Term Impact on Sustainability in Farming Systems. *Agrochemicals*, 2(2), 257-278.
- [36] Gajić, G., Djurdjević, L., Kostić, O., Jarić, S., Mitrović, M., & Pavlović, P. (2018). Ecological potential of plants for phytoremediation and ecorestoration of fly ash deposits and mine wastes. *Frontiers in Environmental Science*, 6, 124.
- [37] Gao, J. F., Li, H. Y., Pan, K. L., & Si, C. Y. (2016). Green synthesis of nanoscale zero-valent iron using a grape seed extract as a stabilizing agent and the application for quick decolorization of azo and anthraquinone dyes. *RSC advances*, 6(27), 22526-22537.
- [38] Gericke, M., & Pinches, A. (2006). Microbial production of gold nanoparticles. *Gold bulletin*, 39, 22-28.
- [39] Ghodake, G. S., Deshpande, N. G., Lee, Y. P., & Jin, E. S. (2010). Pear fruit extract-assisted room-temperature biosynthesis of gold nanoplates. *Colloids and Surfaces B: Biointerfaces*, 75(2), 584-589.
- [40] Gibbs, H. K., & Salmon, J. M. (2015). Mapping the world's degraded lands. *Applied geography*, 57, 12-21.
- [41] Gomez-Bolivar, J., Mikheenko, I. P., Macaskie, L. E., & Merroun, M. L. (2019). Characterization of palladium nanoparticles produced by healthy and microwave-injured cells of *Desulfovibrio desulfuricans* and *Escherichia coli*. *Nanomaterials*, 9(6), 857.
- [42] Gong, J. L., Wang, B., Zeng, G. M., Yang, C. P., Niu, C. G., Niu, Q. Y., ... & Liang, Y. (2009). Removal of cationic dyes from aqueous solution using magnetic multi-wall carbon nanotube nanocomposite as adsorbent. *Journal of hazardous materials*, 164(2-3), 1517-1522.
- [43] Goyal D, Yadav A, Prasad M, Singh TB, Shrivastav P, Ali A, Dantu PK, Mishra S (2020). Effect of heavy metals on plant growth: an overview. *Contaminants in agriculture* 79–101.
- [44] Guilger-Casagrande, M., & Lima, R. D. (2019). Synthesis of silver nanoparticles mediated by fungi: a review. *Frontiers in bioengineering and biotechnology*, 7, 287.
- [45] Gulzar, A. B. M., & Mazumder, P. B. (2022). Helping plants to deal with heavy metal stress: the role of nanotechnology and plant growth promoting rhizobacteria in the process of phytoremediation. *Environmental Science and Pollution Research*, 29(27), 40319-40341.
- [46] Harikrishnan, H., Shine, K., Ponmurugan, K., Moorthy, I. G., & Kumar, R. S. (2014). In vitro eco-friendly synthesis of cadmium sulfide nanoparticles using heterotrophic *Bacillus cereus*. *Journal of Optoelectronic and Biomedical Materials*, 6(1), 1-7.
- [47] He, T., Abbineni, G., Cao, B., & Mao, C. (2010). Nanofibrous bio- inorganic hybrid structures formed through self-assembly and oriented mineralization of genetically engineered phage nanofibers. *Small*, 6(20), 2230-2235.
- [48] Heard, M.S.; Baas, J.; Dorne, J.L.; Lahive, E.; Robinson, A.G.; Rortais, A.; Spurgeon, D.J.; Svendsen, C.; Hesketh, H. Comparative toxicity of pesticides and environmental contaminants in bees: Are honey bees a useful proxy for wild bee species? *Sci. Total Environ.* **2017**, 578, 357–365
- [49] Hemlata PR, Singh AP, Tejavath KK (2020) Biosynthesis of silver nanoparticles using cucumisprophetarum aqueous leaf extract and their antibacterial and antiproliferative activity against cancer cell lines. *ACS Omega* 5(10):5520.
- [50] Hoag, G. E., Collins, J. B., Holcomb, J. L., Hoag, J. R., Nadagouda, M. N., & Varma, R. S. (2009). Degradation of bromothymol blue by 'greener' nano-scale zero-valent iron synthesized using tea polyphenols. *Journal of Materials Chemistry*, 19(45), 8671-8677.
- [51] Horwat, D., Zakharov, D. I., Endrino, J. L., Soldera, F., Anders, A., Migot, S., ... & Pierson, J. F. (2011). Chemistry, phase formation, and catalytic activity of thin palladium-containing oxide films synthesized by plasma-assisted physical vapor deposition. *Surface and Coatings Technology*, 205, S171-S177.
- [52] Husseiny, M. I., Abd El-Aziz, M., Badr, Y., & Mahmoud, M. A. (2007). Biosynthesis of gold nanoparticles using *Pseudomonas aeruginosa*. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 67(3-4), 1003-1006.
- [53] Ibrahim S, Ahmad Z, Manzoor MZ, Mujahid M, Faheem Z, Adnan A (2021) Optimization for biogenic microbial synthesis of silver nanoparticles through response surface methodology, characterization, their antimicrobial, antioxidant, and catalytic potential. *Sci Rep* 11(1):1–8. El-Sheekh MM, El-Kassas HY, Shams El-Din NG, Eissa DI, El-

- [54] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, The IPBES Assessment Report on Land Degradation and Restoration (2018). doi: 10.5281/zenodo.3237393
- [55] Juwarkar, A. A., Singh, S. K., & Mudhoo, A. (2010). A comprehensive overview of elements in bioremediation. *Reviews in Environmental Science and bio/technology*, 9, 215-288.
- [56] Khanna, P., Kaur, A., & Goyal, D. (2019). Algae-based metallic nanoparticles: Synthesis, characterization and applications. *Journal of microbiological methods*, 163, 105656.
- [57] Kharissova, O. V., Dias, H. R., Kharisov, B. I., Pérez, B. O., & Pérez, V. M. J. (2013). The greener synthesis of nanoparticles. *Trends in biotechnology*, 31(4), 240-248.
- [58] Kowshik, M., Vogel, W., Urban, J., Kulkarni, S. K., & Paknikar, K. M. (2002). Microbial synthesis of semiconductor PbS nanocrystallites. *Advanced Materials*, 14(11), 815-818.
- [59] Kranjc, E., & Drobne, D. (2019). Nanomaterials in plants: a review of hazard and applications in the agri-food sector. *Nanomaterials*, 9(8), 1094.
- [60] Krishnan, S., Patel, P. N., Balasubramanian, K. K., & Chadha, A. (2021). Yeast supported gold nanoparticles: An efficient catalyst for the synthesis of commercially important aryl amines. *New Journal of Chemistry*, 45(4), 1915-1923.
- [61] Kumar, B., Smita, K., Cumbal, L., Debut, A., & Angulo, Y. (2017). Biofabrication of copper oxide nanoparticles using Andean blackberry (*Rubus glaucus* Benth.) fruit and leaf. *Journal of Saudi Chemical Society*, 21, S475-S480.
- [62] Kumari, A., Kumari, P., Rajput, V. D., Sushkova, S. N., and Minkina, T. (2022). Metal (loid) nanosorbents in restoration of polluted soils: geochemical, ecotoxicological, and remediation perspectives. *Environ. Geochem. Health* 44, 235–246. doi: 10.1007/s10653-021-00996-x
- [63] Laslo, V., Pinzaru, S. C., Zagula, G., Kluz, M., Vicas, S. I., & Cavalu, S. (2022). Synergic effect of selenium nanoparticles and lactic acid bacteria in reduction cadmium toxicity. *Journal of Molecular Structure*, 1247, 131325.
- [64] Leili, M., Fazlzadeh, M., & Bhatnagar, A. (2018). Green synthesis of nano-zero-valent iron from Nettle and Thyme leaf extracts and their application for the removal of cephalexin antibiotic from aqueous solutions. *Environmental technology*, 39(9), 1158-1172.
- [65] Li, T., Albee, B., Alemayehu, M., Diaz, R., Ingham, L., Kamal, S., ... & Whaley Bishnoi, S. (2010). Comparative toxicity study of Ag, Au, and Ag–Au bimetallic nanoparticles on *Daphnia magna*. *Analytical and bioanalytical chemistry*, 398, 689-700.
- [66] Li, X., Xu, H., Chen, Z. S., & Chen, G. (2011). Biosynthesis of nanoparticles by microorganisms and their applications. *Journal of nanomaterials*, 2011, 1-16.
- [67] Liang, L., Liu, W., Sun, Y., Huo, X., Li, S., & Zhou, Q. (2017). Phytoremediation of heavy metal contaminated saline soils using halophytes: current progress and future perspectives. *Environmental Reviews*, 25(3), 269-281.
- [68] López-Luna, J., Silva-Silva, M. J., Martínez-Vargas, S., Mijangos-Ricardez, O. F., González-Chávez, M. C., Solís-Domínguez, F. A., & Cuevas-Díaz, M. C. (2016). Magnetite nanoparticle (NP) uptake by wheat plants and its effect on cadmium and chromium toxicological behavior. *Science of the Total Environment*, 565, 941-950.
- [69] Luangpipat, T., Beattie, I. R., Chisti, Y., & Haverkamp, R. G. (2011). Gold nanoparticles produced in a microalga. *Journal of Nanoparticle Research*, 13, 6439-6445.
- [70] Maensiri, S., Laokul, P., Klinkaewnarong, J., Phokha, S., Promarak, V., & Seraphin, S. (2008). Indium oxide (In₂O₃) nanoparticles using Aloe vera plant extract: Synthesis and optical properties. *J Optoelectron Adv Mater*, 10(3), 161-165.
- [71] Małkowski E, Sitko K, Zieleźnik-Rusinowska P, Gieroń Ź, Szopiński M (2019). Heavy metal toxicity: Physiological implications of metal toxicity in plants. In *Plant metallomics and functional omics* (pp.53–301). Springer, Cham.
- [72] Miranda, M. H., Menezes, D. B., Vega-Baudrit, J. R., Ferreira, L. F. R., Bharagava, R. N., Iqbal, H. M., & Bilal, M. (2022). Nanobioremediation: An introduction. In *Nano-Bioremediation: Fundamentals and Applications* (pp. 3-22). Elsevier.
- [73] Mirsal, I.A. *Soil Pollution Origin, Monitoring & Remediation*, 2nd ed.; Springer-Verlag: Berlin/Heidelberg, Germany, 2008; ISBN 9783540707752
- [74] Mishra, A., Tripathy, S. K., & Yun, S. I. (2012). Fungus mediated synthesis of gold nanoparticles and their conjugation with genomic DNA isolated from *Escherichia coli* and *Staphylococcus aureus*. *Process Biochemistry*, 47(5), 701-711.
- [75] Mishra, R. K., Mohammad, N., & Roychoudhury, N. (2016). Soil pollution: Causes, effects and control. *Van Sangyan*, 3(1), 1-14.

- [76] Mitra S, Chakraborty AJ, Tareq AM, Emran TB, Nainu F, Khusro A, Idris AM, Khandaker MU, Osman H, Alhumaydhi FA, SimalGandara J (2022) Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *J King Saud Univ-Sci* 29:101865
- [77] Mittal, A. K., Kaler, A., & Banerjee, U. C. (2012). Free Radical Scavenging and Antioxidant Activity of Silver Nanoparticles Synthesized from Flower Extract of *Rhododendron dauricum*. *Nano Biomedicine & Engineering*, 4(3).
- [78] Momeni, S., & Nabipour, I. (2015). A simple green synthesis of palladium nanoparticles with *Sargassum* alga and their electrocatalytic activities towards hydrogen peroxide. *Applied biochemistry and biotechnology*, 176, 1937-1949.
- [79] Mueller, J. G., Cerniglia, C. E., & Pritchard, P. H. (1996). Bioremediation of environments contaminated by polycyclic aromatic hydrocarbons. *Biotechnology Research Series*, 6, 125-194.
- [80] Mughal, B., Zaidi, S. Z. J., Zhang, X., & Hassan, S. U. (2021). Biogenic nanoparticles: Synthesis, characterisation and applications. *Applied Sciences*, 11(6), 2598.
- [81] Mukherjee, P., Senapati, S., Mandal, D., Ahmad, A., Khan, M. I., Kumar, R., & Sastry, M. (2002). Extracellular synthesis of gold nanoparticles by the fungus *Fusarium oxysporum*. *ChemBioChem*, 3(5), 461-463.
- [82] Narayanan KB, Sakthivel N (2010) Biological synthesis of metal nanoparticles by microbes. *Adv Colloid Interface Sci* 156(1-2):1-13
- [83] Okoh, E., Yelebe, Z. R., Oruabena, B., Nelson, E. S., & Indiamawe, O. P. (2020). Clean-up of crude oil-contaminated soils: bioremediation option. *International Journal of Environmental Science and Technology*, 17(2), 1185-1198.
- [84] Oyewole, O. A., Raji, R. O., Musa, I. O., Enemanna, C. E., Abdulsalam, O. N., & Yakubu, J. G. (2019). Enhanced degradation of crude oil with *Alcaligenes faecalis* ADY25 and iron oxide nanoparticle.
- [85] Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Chemical fertilizers and their impact on soil health. *Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs*, 1-20.
- [86] Pandey, G. (2018). Prospects of nanobioremediation in environmental cleanup. *Oriental Journal of Chemistry*, 34(6), 2838.
- [87] Pandya, K., Rajhans, S., Pandya, H., and Mankad, A. (2022). Phytoremediation: an innovative perspective for reclaiming contaminated environment using ornamental plants. *World J. Adv. Res. Rev.* 13, 001-014. doi: 10.30574/wjarr.2022.13.2.0088
- [88] Patil S, Chandrasekaran R (2020) Biogenic nanoparticles: a comprehensive perspective in synthesis, characterization, application and its challenges. *J Genet EngBiotechnol* 18(1):1-23.
- [89] Patil, S. S., Shedbalkar, U. U., Truskewycz, A., Chopade, B. A., & Ball, A. S. (2016). Nanoparticles for environmental clean-up: a review of potential risks and emerging solutions. *Environmental Technology & Innovation*, 5, 10-21.
- [90] Philip, D. (2011). *Mangifera indica* leaf-assisted biosynthesis of well-dispersed silver nanoparticles. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 78(1), 327-331.
- [91] Pillai, H. P., and Kottekkottil, J. (2016). Nano-phytotechnological remediation of endosulfan using zero valent iron nanoparticles. *J. Environ. Prot. Sci.* 7, 734-744. doi: 10.4236/jep.2016.75066
- [92] Poinern, G. E. J., Chapman, P., Le, X., & Fawcett, D. (2013). Green biosynthesis of gold nanometre scale plates using the leaf extracts from an indigenous Australian plant *Eucalyptus macrocarpa*. *Gold Bulletin*, 46, 165-173.
- [93] Prasad, K., & Jha, A. K. (2010). Biosynthesis of CdS nanoparticles: an improved green and rapid procedure. *Journal of colloid and interface science*, 342(1), 68-72.
- [94] Prasad, S., Kannojiya, S., Kumar, S., Yadav, K. K., Kundu, M., & Rakshit, A. (2021). Integrative Approaches for Understanding and Designing Strategies of Bioremediation. In *Bioremediation Science* (pp. 37-56). CRC Press.
- [95] Rajput, V. D., Minkina, T., Upadhyay, S. K., Kumari, A., Ranjan, A., Mandzhieva, S., & Verma, K. K. (2022). Nanotechnology in the restoration of polluted soil. *Nanomaterials*, 12(5), 769.
- [96] Ramezani, M., Enayati, M., Ramezani, M., & Ghorbani, A. (2021). A study of different strategical views into heavy metal (oid) removal in the environment. *Arabian Journal of Geosciences*, 14, 1-16.
- [97] Rasha, F. M. (2017). Intracellular siderophore detection in an Egyptian, cobalt-treated *F. solani* isolate using SEM-EDX with reference to its tolerance. *Polish Journal of Microbiology*, 66(2), 235-243.
- [98] Rizvi A, Zaidi A, Ahmad B, Ameen F, Al Kahtani MDF, Khan MS (2020) Heavy metal induced stress on wheat: phytotoxicity and microbiological management. *RSC Adv* 10:38379-38403
- [99] Rizwan, M. D., Singh, M., Mitra, C. K., & Morve, R. K. (2014). Ecofriendly application of nanomaterials: nanobioremediation. *Journal of Nanoparticles*, 2014, 1-7.

- [100] Romeh, A. A., &Saber, R. A. I. (2020). Green nano-phytoremediation and solubility improving agents for the remediation of chlorfenapyr contaminated soil and water. *Journal of environmental management*, 260, 110104.
- [101] Sajid, M., Ilyas, M., Basheer, C., Tariq, M., Daud, M., Baig, N., &Shehzad, F. (2015). Impact of nanoparticles on human and environment: review of toxicity factors, exposures, control strategies, and future prospects. *Environmental Science and Pollution Research*, 22, 4122-4143.
- [102] Saleem, S., Rizvi, A., & Khan, M. S. (2022). Microbiome-mediated nano-bioremediation of heavy metals: a prospective approach of soil metal detoxification. *International Journal of Environmental Science and Technology*, 1-24.
- [103] Sathishkumar, M., Sneha, K., & Yun, Y. S. (2009). Palladium nanocrystal synthesis using Curcuma longa tuber extract. *Int J Mater Sci*, 4(1), 11-17.
- [104] Satyavani, K., Ramanathan, T., &Gurudeeban, S. (2011). Green synthesis of silver nanoparticles by using stem derived callus extract of bitter apple (Citrulluscolocynthis). *Dig J NanomaterBiostruct*, 6(3), 1019-1024.
- [105] Savci, S. (2012). An agricultural pollutant: chemical fertilizer. *International Journal of Environmental Science and Development*, 3(1), 73.
- [106] Sayadi, M. H., Salmani, N., Heidari, A., &Rezaei, M. R. (2018). Bio-synthesis of palladium nanoparticle using Spirulinaplatisensis alga extract and its application as adsorbent. *Surfaces and Interfaces*, 10, 136-143.
- [107] Shahi, M. P., Kumari, P., Mahobiya, D., &Shahi, S. K. (2021). Nano-bioremediation of environmental contaminants: applications, challenges, and future prospects. *Bioremediation for environmental sustainability*, 83-98.
- [108] Shankar, S. S., Ahmad, A., Pasricha, R., &Sastry, M. (2003). Bioreduction of chloroaurate ions by geranium leaves and its endophytic fungus yields gold nanoparticles of different shapes. *Journal of Materials Chemistry*, 13(7), 1822-1826.
- [109] Sharma, A., Sharma, S., Sharma, K., Chetri, S. P., Vashishtha, A., Singh, P., ...&Agrawal, V. (2016). Algae as crucial organisms in advancing nanotechnology: a systematic review. *Journal of applied phycology*, 28, 1759-1774.
- [110] Sharma, S. (2012). Bioremediation: features, strategies and applications. *Asian Journal of Pharmacy and Life Science*, 2231, 4423.
- [111] Shastri, D. V., &Arunachalam, K. D. (2022). Nanomaterials for biodeterioration: An introduction. In *Nano-Bioremediation: Fundamentals and Applications* (pp. 23-28). Elsevier.
- [112] Shu, M., He, F., Li, Z., Zhu, X., Ma, Y., Zhou, Z., &Zeng, M. (2020). Biosynthesis and antibacterial activity of silver nanoparticles using yeast extract as reducing and capping agents. *Nanoscale research letters*, 15, 1-9.
- [113] Singh E, Osmani RA, Banerjee R (2020). Nanobioremediation: an emerging approach for a cleaner environment. In *Microbial Bioremediation & Biodegradation* (pp. 309–363). Springer, Singapore.
- [114] Singh, J., Dutta, T., Kim, K. H., Rawat, M., Samddar, P., & Kumar, P. (2018). ‘Green’ synthesis of metals and their oxide nanoparticles: applications for environmental remediation. *Journal of nanobiotechnology*, 16(1), 1-24.
- [115] Singh, R., Behera, M., and Kumar, S. (2020). “Nano-bioremediation: an innovative remediation technology for treatment and management of contaminated sites,” in *Bioremediation of Industrial Waste for Environmental Safety*. eds. R. N. Bharagava and G. Saxena (Singapore: Springer), 165–182
- [116] Singh, Y., &Saxena, M. K. (2022). Insights into the recent advances in nano-bioremediation of pesticides from the contaminated soil. *Frontiers in Microbiology*, 13, 982611.
- [117] Sone, B. T., Diallo, A., Fuku, X. G., Gurib-Fakim, A., &Maaza, M. (2020). Biosynthesized CuO nanoparticles: physical properties & enhanced thermal conductivity nanofluidics. *Arabian Journal of Chemistry*, 13(1), 160-170.
- [118] Song, J. Y., Kwon, E. Y., & Kim, B. S. (2010). Biological synthesis of platinum nanoparticles using Diopyros kaki leaf extract. *Bioprocess and biosystems engineering*, 33, 159-164.
- [119] Souri, Z., Karimi, N., Sarmadi, M., and Rostami, E. (2017). Salicylic acid nanoparticles (SANPs) improve growth and phytoremediation efficiency of *Isatis cappadocica* Desv., under as stress. *IET Nanobiotechnol.* 11, 650–655. doi: 10.1049/iet-nbt.2016.0202
- [120] Srivastava, S., Shukla, A., Rajput, V. D., Kumar, K., Minkina, T., Mandzhieva, S., ...&Suprasanna, P. (2021). Arsenic remediation through sustainable phytoremediation approaches. *Minerals*, 11(9), 936.
- [121] Subramaniam, V., Subashchandrabose, S. R., Thavamani, P., Megharaj, M., Chen, Z., & Naidu, R. (2015). *Chlorococcum* sp. MM11—a novel phyco-nanofactory for the synthesis of iron nanoparticles. *Journal of applied phycology*, 27, 1861-1869.

- [122] Sunny, N. E., Kaviya, A., & Kumar, S. V. (2022). Mechanistic approach on the synthesis of metallic nanoparticles from microbes. In *Agri-Waste and Microbes for Production of Sustainable Nanomaterials* (pp. 577-602). Elsevier.
- [123] Tan, Y., Liu, L., Wang, Y., & Liu, J. (2018). pH- Regulated Surface Plasmon Absorption from Ultrasmall Luminescent Gold Nanoparticles. *Advanced Optical Materials*, 6(10), 1701324.
- [124] United Nations Convention to Combat Desertification, The Global Land Outlook (ed. 1, 2017); www.unccd.int/actions/global-land-outlook-glo.
- [125] Vanlalveni C, Lallianrawna S, Biswas A, Selvaraj M, Changmai B, Rokhum SL (2021) Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: a review of recent literature. *RSC Adv* 11(5):2804–2837
- [126] Vázquez-Núñez, E., Molina-Guerrero, C. E., Peña-Castro, J. M., Fernández-Luqueño, F., & de la Rosa-Álvarez, M. G. (2020). Use of nanotechnology for the bioremediation of contaminants: A review. *Processes*, 8(7), 826.
- [127] Vigneshwaran, N., Ashtaputre, N. M., Varadarajan, P. V., Nachane, R. P., Paralikar, K. M., & Balasubramanya, R. H. (2007). Biological synthesis of silver nanoparticles using the fungus *Aspergillus flavus*. *Materials letters*, 61(6), 1413-1418.
- [128] Vilchis-Nestor, A. R., Sánchez-Mendieta, V., Camacho-López, M. A., Gómez-Espinosa, R. M., Camacho-López, M. A., & Arenas-Alatorre, J. A. (2008). Solventless synthesis and optical properties of Au and Ag nanoparticles using *Camellia sinensis* extract. *Materials letters*, 62(17-18), 3103-3105.
- [129] Wang, Y., Maksimuk, S., Shen, R., & Yang, H. (2007). Synthesis of iron oxide nanoparticles using a freshly-made or recycled imidazolium-based ionic liquid. *Green Chemistry*, 9(10), 1051-1056.
- [130] Watts, M. P., Coker, V. S., Parry, S. A., Pattrick, R. A., Thomas, R. A., Kalin, R., & Lloyd, J. R. (2015). Biogenic nano-magnetite and nano-zero valent iron treatment of alkaline Cr (VI) leachate and chromite ore processing residue. *Applied Geochemistry*, 54, 27-42.
- [131] Xie, Y., He, Y., Irwin, P. L., Jin, T., & Shi, X. (2011). Antibacterial activity and mechanism of action of zinc oxide nanoparticles against *Campylobacter jejuni*. *Applied and environmental microbiology*, 77(7), 2325-2331.
- [132] Yadav, A., Kon, K., Kratosova, G., Duran, N., Ingle, A. P., & Rai, M. (2015). Fungi as an efficient mycosystem for the synthesis of metal nanoparticles: progress and key aspects of research. *Biotechnology letters*, 37, 2099-2120.
- [133] Yadav, K. K., Singh, J. K., Gupta, N., & Kumar, V. J. J. M. E. S. (2017). A review of nanobioremediation technologies for environmental cleanup: a novel biological approach. *J Mater Environ Sci*, 8(2), 740-757.
- [134] Yan, S., He, W., Sun, C., Zhang, X., Zhao, H., Li, Z., ...& Han, X. (2009). The biomimetic synthesis of zinc phosphate nanoparticles. *Dyes and Pigments*, 80(2), 254-258.
- [135] Zand, A. D., MikaeiliTabrizi, A., & Vaezi Heir, A. (2020). Application of titanium dioxide nanoparticles to promote phytoremediation of Cd-polluted soil: contribution of PGPR inoculation. *Bioremediation Journal*, 24(2-3), 171-189.
- [136] Zaynab M, Al-Yahyai R, Ameen A, Sharif Y, Ali L, Fatima M, Khan KA, Li S (2022) Health and environmental effects of heavy metals. *J King Saud Univ-Sci* 34(1):101653.