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

1. **Introduction**

 Nanotechnology is a rapid evolving scientific field that works with artificially created particles that are just 100 nm or smaller in size (Fraceto et al. 2016). When nanotechnology is used with the bioremediation procedure it’s known as Nanobioremediation. Nanobioremediation, which uses nanoparticles to speed up bioremediation, aims to clean the environment. Degradation of pollutants incorporating a catalyst as nanoparticles is the fundamental idea behind nanobioremediation. Because nano particles (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 other NPs/nanomaterials have been found to be useful in destroying harmful inorganic pollutants and making the contaminated environment stress-free (Ibrahim et al. 2021; El-Sheekh et al. 2021; Vanlalveni et al. 2021; Hemlata et al. 2020). According to numerous studies (Zhao et al., 1998; Kharissova et al., 2013), different NPs' catalytic characteristics as well as biological components have been evaluated to reduce 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).

1. **Soil pollution**

The natural ecosystem depends on the soil. It has equal importance to flora, fauna, rocks, landforms, rivers, lochs, and animals. It affects how different plant species are distributed and offers a habitat for a variety of critters. It regulates the exchange of gases in the atmosphere and serves as both a source and a sink for water and chemical compounds 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.

The term "soil pollution" refers to the decrease in soil productivity brought on by the presence of soil contaminants. An issue on a global scale, soil pollution has both natural and anthropogenic causes. Compounds, chemicals, and chemical agents have been used as a result of urbanization, industrialization, and rising food consumption, which over time have led to the dispersal and build-up of pollutants in the environment. Heavy metals, insecticides, and polycyclic aromatic hydrocarbons (PAHs) are typical pollutants found in soil (Mirsal et al. 2008).

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

The chemical that commonly causes soil pollution are the heavy metals, pesticides, insoluble compounds and petroleum hydrocarbons. When these substances stick to the soil, either directly through spills or through contact with previously contaminated soil, soil contamination occurs. As they slowly decay due to microbes in the soil and water, they build up in the soil. They consequently have a very detrimental influence on plant growth, suppressing it and lowering the production and size of fruit. Their decomposition byproducts may be ingested by plants, from which they pass via the food chain to reach animals and people (Mishra et al. 2016).

* 1. **Heavy Metals**

Globally, soil contamination, particularly which caused by inorganic pollutants such toxic heavy metals, is a severe issue that has steadily deteriorated the quality and safety of food and feed by endangering agro-ecosystems. Industrialization, intensive farming methods, and other anthropogenic activities are largely to blame for the worrisome rise in heavy metal contamination. Metals can be harmful to human health and the environment due to their non-degradative nature, which makes them persist in the environment for a longer period of time (Saleem *et al*., 2022).

In accordance to the data compiled in Table \_\_ from literatures (Phaenark *et al.* 2009; Singh *et al.* 2011; Tóth et al. 2016; Vodyanitskii 2016; Chen and Li 2018; Saleem *et al.* 2022), the soil concentration for several heavy metals varies. The availability of heavy metals in soil is nevertheless regulated by adsorption and desorption and is dependent on a number of physical and chemical characteristics of soils, including pH, the amount of organic matter present, the cation exchange capacity, the degree of oxidation-reduction, the presence of clay minerals, calcium carbonate, iron and manganese oxides, and so on.

Table 1: Heavy metal concentration in soil reported worldwide in literatures

|  |  |  |
| --- | --- | --- |
| Metals | Minimum concentration (mg kg−1) | Maximum concentration (mg kg−1) |
| As | 0.1 | 252.5 |
| Cd | 0 | 1458 |
| Cr | 0.05 | 10,000 |
| Cu | 0.1 | 1790 |
| Hg | 0 | 1800 |
| Ni | 0 | 5000 |
| Pb | 0.1 | 69,000 |
| Zn | 0.3 | 57012 |
| Mn | 3.0 | 42,600 |

Source: Chen and Li (2018)

The pollution of soils by the heavy metals is likely to result in two significant issues: loss of soil value through changes to the microbiome's composition and functioning (Alsabhan et al. 2022; Du et al. 2021) and through plants (Goyal et al. 2020; Malkowski et al. 2019), risk of human health around the contaminated sites (Mitra *et al.* 2022; Zaynab *et al.* 2022). Both stringent government or private regulations and detoxification techniques are crucial for controlling the release of heavy metals from various sources and, as a result, for preventing/eradicating metal pollution. In essence, the regulatory limits for heavy metal levels in soil established in various countries—which vary from area to region and metal to metal—provide as the foundation or serve as the rules for heavy metal removal. These standards also aid in the development of better heavy metal removal methods from contaminated sites.

* 1. **Chemical fertilizers**

Chemical fertilizer is crucial in order to increase agricultural output and soil fertility. Chemical fertilizers come in a variety of forms, including nitrogenous, phosphate, and potassium fertilizers. The use of fertilizers not only boosts crop productivity but also changes the physicochemical and biological characteristics of the soil. However, according to numerous researches and studies, the effects of chemical fertilizers on the soil is not immediately observed (Savci 2012) but regular use of chemical fertilizers is to blame for the loss in agricultural soil quality as well as the SOM (soil organic matter) content. The excessive use of chemical fertilizers damages the environment by making the soil harder, reducing its fertility, polluting the soil, water, and air, and reducing the amount of vital nutrients and minerals in the soil. The cropping system's limited microbial activity was caused by the sole use of artificial fertilizers (Pahalvi et al. 2021).

* 1. **Pesticides**

Pest control measures include chemical substances known as pesticides. They are substances, either chemical or biological, that render pests helpless or fatal. Insecticides, herbicides, rodenticides, bactericides, fungicides, and larvicides are some of the pesticides that can be categorized based on the sorts of pests they are intended to control. When pesticides are applied, some of them accumulate in the soil and have an impact on the soil's microbial inhabitants. Human exposure can happen when pesticides are used in jobs, agriculture, and homes, as well as when people ingest contaminated water and food and breathe contaminated air. The human body can be exposed to pesticides through the skin, mouth, eyes, and respiratory systems (Kim et al. 2017). Pesticide toxicity is influenced by the electrical characteristics, molecular structure, dosage, and duration of exposure (Heard et al. 2017).

In spite of their potential harm to the environment and human health, pesticides are used to prevent, eliminate, and control hazardous pests. High quantities of polluting compounds in the environment may result from their excessive use. The World Health Organization evaluated the toxicity of the pesticides over time and reported on how they affected human health (WHO 2019). Due to their extreme toxicity, a number of pesticides have been prohibited throughout time in several nations. However, its manufacturing and use are still ongoing today, particularly in underdeveloped nations. Due to these factors, it is imperative to employ efficient remediation strategies to lower the residual pesticide content in the soil.

2.3.1 Classification of Pesticides

By the functions they perform and the kinds of pests they target, pesticides can be categorized. The five primary categories are bactericides, fungicides, insecticides, and rodenticides.

2.3.1.1 Herbicides

The use of herbicides is to manage and get rid of weeds and undesired vegetation. It is derive from the Latin words herbs and caedo. In order to increase crop yield, these chemicals are primarily sprayed to agricultural soils before or during cultivation. As well as in forests, in urban and suburban settings, herbicides are utilized in the management of weeds.

Table 2: Classification of the most common herbicides used in agricultural soil.

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Pesticide Class** | **Chemical Structure** | **Mode of Action** |
| Glyphosate | Organophosphate |  | Disruption of Shikimic acid pathway through inhibition of the enzyme 5-enolpyruvylshikimate-3-phosphate synthase. |
| Atrazine | Organochlorine |  | Inhibition of the photosynthetic pathway, specifically the photosystem II. |
| 2,4-D | Organochlorine |  | Imitation of plant growth hormone auxin and uncontrolled cell division in vascular tissue, leading to uncontrolled growth and eventually death of plants. |
| Trifluralin | Organophosphate |  | Inhibition of cell mitosis, acting on the meristems and tissues of underground organs. |
| Dicamba | Organochlorine |  | Imitation of plant growth hormone auxin and uncontrolled cell division in vascular tissue, leading to uncontrolled growth and eventually death of plants. |

Source: Raffa and Chiampo (2021)

2.3.1.2 Fungicides

Fungicides are chemical compounds that are used to kill parasitic fungi or their spores. Fungi can seriously hurt agriculture, leading to significant losses in productivity, quality, and profit. Fungicides are used to treat fungal infections in animals as well as in crops by interfering with various biochemical processes within the cytoplasm and mitochondria (Thind an Hollomon 2018).

2.3.1.3 Insecticides

Insecticides are chemical compounds that are used to kill insects at all stages depending on the target category of the insecticide. Insecticides are thought to have played a significant role in the rise in agricultural output during the 20th century. But a large majority of pesticides have the potential to drastically affect ecosystems; many of them are hazardous to people and/or animals; some concentrate as they move up the food chain. The groups of carbamates, pyrethroids, and organophosphates contain the most often used insecticides. They affect the victims' neurological systems, resulting in respiratory failure, spasms, and/or death (Raffa and Chiampo 2021). Some of which are listed in Table 3.

Table 3: Classification of the most common insecticides used in agricultural soil.

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Pesticide Class** | **Chemical Structure** | **Mode of Action** |
| DDT | Organochlorine |  | Interaction with sodium ion channels in neuron, causing their inactivation, which leads to spasms and eventual death. |
| Cyfluthrin | Pyrethroid |  | Interference with nerve signalling by inhibition of the membrane sodium channel systems. |
| Tefluthrin | Pyrethroid |  | Interruption of functioning of the nervous system, interfering with sodium channels. |
| Aldicarb | Carbamate |  | Inhibition of cholinesterase prevents the breakdown of acetycholine in the synapse. It leads to respiratory failure. |

Source: Raffa and Chiampo (2021)

2.3.1.4 Rodenticides

Rodenticides are used for the sole purpose of reducing the population of rodents by mixing with the baits. These are chemical compound that has high toxicity when ingested in lethal dosage. When such compounds are not managed properly, it may end up in the soil which ultimately causes pollution.

1. **Nanobioremediation & its approaches**

Nano-bioremediation, which uses nanoparticles to speed up bioremediation, aims to clean the environment. Two more subgroups of nano-bioremediation are identified as follows: microbial nanoremediation and nanophytoremediation of nanoparticles with phytoremediation (Singh et al. 2020; Kumari et al. 2022; Figure 1).

Figure 1 Source: Singh and Saxena (2022)

1. **Microbiome-mediated nanobioremediation**

The application of microbes to detoxify various inorganic pollutants has shown promising results by numerous researchers. The interest in using the soil microbiome, particularly the bacterial, fungal, and algal communities and their secretary products, or biomolecules, for the generation of novel NPs that are environmentally friendly, commercially viable, and practically stable with broader applications has alarmingly increased in recent years among many biogenic NPs (Mughal et al. 2021; Patil and Chandrasekaran, 2020). Bacteria, among the heterogeneously distributed soil microbiome are regarded as valuable in nanobioremediation technology. This is because they have evolved protective mechanisms like biotrans-formation, 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).

The microbiome of the soil synthesises a number of NPs that leads to mitigation of inorganic soil pollutants.

1. **Nanophytoremediation**

The Greek word "phytoremediation" means "restore/remedy through plants" (Pandya et al., 2022). However, phytoremediation has some drawbacks, including a lengthy remediation process and plant waste.

Utilizing manufactured nanoparticles from plants, nano-hytoremediation is a technique for cleaning up toxins and pollutants. Because they absorb many types of substances and detoxify them, plants are the soil's natural detoxifiers. Numerous soil contaminants, including heavy metals and organic compounds, responded well to the nanophytoremediation approach. According to Pillai and Kottekottil (2016) and Souri et al. (2017), the use of nanoparticles boosted the ability of plants to withstand stress while simultaneously increasing their ability to absorb contaminants.

1. **Nanobiofertilizers and Bionanofertilizers**

The use of nanobiofertilizers and bionanofertilizers as an alternative replacement of the chemical fertilizers can lead to sustainability of soil productivity and reduce the impact of soil pollution. NFs have been considered to be an alternative to traditional or mineral fertilizers (Figure 2). The release of nutrients from nanofertilizers (NFs) can be slowed down and sustained, and they can be customized to meet the demands of various crops (Arora *et al.* 2022). Biological nanofertilizers are non-toxic and sustainable when compared to chemical or physical nanofertilizers. Nanobiofertilizers are produced by bacteria in media that has been supplied with metal compounds, which are then transformed into nano-metals (El-Ghamry *et al*. 2018). Copper, selenium, silicon, zinc, and other elements can all be organically synthesized into various types of nanofertilizers. Utilizing plant products, their isolates, extracts, and other microorganisms in the production system is essential to the biological method of creating nanoparticles. This is appropriate for Nano Materials (NMs) synthesis because it is toxic-chemical-free, economical, scalable, and environmentally benign (Saravanan *et al.* 2021). They minimize nutrient loss due to soil leaching, gasification, erosion, etc (Al-Mamun *et al.*). Because of its ease of fast synthesis, precise toxicity, desired morphologies, and controlled size, as well as its low cost, eco-friendliness, and ease of application, the bio-based (plants/microbiome) synthesis of metallic NPs is generally regarded as profitable (Singh et al. 2020). At the laboratory scale, NFs are produced by using various biological and precursor materials, such as bacteria, fungi, and plants (Figure 3). The basic differences between Bionanofertilizers and nanobiofertilizers are described in Table 4.

Table 4: Basic differences between Bionanofertilizers and nanobiofertilizers

|  |  |  |
| --- | --- | --- |
| **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 |

Source: Gade *et al.* 2023

Figure 2: The characteristics and advantages of nanofertilizers (El-Ramady *et al.* 2022)

Figure 3: Schematic diagram for biological synthesis of nanofertilizers (Gade *et al.* 2023)

1. **Conclusion**

The emergence of nanobiotechnology as a research area opens up opportunities for the creation of nanobioremediation techniques for the regeneration of polluted soils. The experimental results of several studies demonstrated the potential of nanobioremediation for the elimination of different inorganic and organic contaminants from terrestrial ecosystems. Nanoparticles are expensive, which has hampered their use in impoverished and underdeveloped countries. A cost decrease in the production of nanomaterials should be the long-term objective given the worrying rise in heavy metal contamination across densely populated nations including India, China, Africa, and other Southeast Asian countries.

1. **References**

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.

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.

Arora S, Gajiram Murmu, Koel Mukherjee, Sumit Saha, Dipak Maity D (2022). A comprehensive overview of nanotechnology in sustainable agriculture. Journal of Biotechnology, 355, 21-41. [https://doi.org/10.101 6/j.jbiotec.2022.06.007](https://doi.org/10.101%206/j.jbiotec.2022.06.007).

Chen W, Li H (2018) Cost-effectiveness analysis for soil heavy metal contamination treatments. Water Air Soil Pollut 229:1–13

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.

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

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

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.

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.

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

Hemlata PR, Singh AP, Tejavath KK (2020) Biosynthesis of silver nanoparticles using cucumis prophetarum aqueous leaf extract and their antibacterial and antiproliferative activity against cancer cell lines. ACS Omega 5(10):5520.

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-

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.

Kim, K.H.; Kabir, E.; Jahan, S.A. Exposure to pesticides and the associated human health effects. *Sci. Total Environ.* **2017**, *575*, 525–535.

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

Małkowski E, Sitko K, Zieleźnik-Rusinowska P, Gieroń Ż, Szopiński M (2019). Heavy metal toxicity: Physiological implications of metal toxicity in plants. In Plant metallomics and functional omics (pp.53–301). Springer, Cham.

Mirsal, I.A. *Soil Pollution Origin, Monitoring & Remediation*, 2nd ed.; Springer-Verlag: Berlin/Heidelberg, Germany, 2008; ISBN 9783540707752

Mishra, R. K., Mohammad, N., & Roychoudhury, N. (2016). Soil pollution: Causes, effects and control. *Van Sangyan*, *3*(1), 1-14.

Mitra S, Chakraborty AJ, Tareq AM, Emran TB, Nainu F, Khusro A, Idris AM, Khandaker MU, Osman H, Alhumaydhi FA, Simal Gandara 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

Narayanan KB, Sakthivel N (2010) Biological synthesis of metal nanoparticles by microbes. Adv Colloid Interface Sci 156(1–2):1–13

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.

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.

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

Patil S, Chandrasekaran R (2020) Biogenic nanoparticles: a comprehensive perspective in synthesis, characterization, application and its challenges. J Genet Eng Biotechnol 18(1):1–23.

Phaenark, C., Pokethitiyook, P., Kruatrachue, M., & Ngernsansaruay, C. (2009). Cd and Zn accumulation in plants from the Padaeng zinc mine area. International Journal of Phytoremediation, 11, 479–495.

Pillai, H. P., and Kottekottil, 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

Raffa, C. M., & Chiampo, F. (2021). Bioremediation of agricultural soils polluted with pesticides: A review. *Bioengineering*, *8*(7), 92.

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.

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

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.

Saravanan A, Kumar PS, Karishma S, Vo DVN, Jeevanantham S, Yaashikaa PR, George CS (2021). A review on biosynthesis of metal nanoparticles and its environmental applications. Chemosphere, 264, Article 128580.

Savci, S. (2012). An agricultural pollutant: chemical fertilizer. *International Journal of Environmental Science and Development*, *3*(1), 73.

Sherbiny BA (2021) Green synthesis, characterization applications of iron oxide nanoparticles for antialgal and wastewater bioremediation using three brown algae. Int J Phytoremed 23(14):153852

Singh E, Osmani RA, Banerjee R (2020). Nanobioremediation: an emerging approach for a cleaner environment. In Microbial Bioremediation & Biodegradation (pp. 309–363). Springer, Singapore.

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

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.

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

*The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2019*; World Health Organization: Geneva, Switzerland, 2020; ISBN 924154663

Thind, T.S.; Hollomon, D.W. (2018). Thiocarbamate fungicides: Reliable tools in resistance management and future outlook. Pest Manag. Sci., 74, 1547–1551.

Tóth G, Hermann T, Da Silva MR, Montanarella LJEI (2016) Heavy metals in agricultural soils of the European Union with implications for food safety. Environ Int 88:299–309

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

Vodyanitskii YN (2016) Standards for the contents of heavy metals in soils of some states. Ann Agrar Sci 14(3):257–263

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.