World Journal of Pharmaceutical and Life Sciences
WJPLS
www.wjpls.org
SJIF Impact Factor: 7.409

NANOBIOREMEDIATION: A COMPREHENSIVE REVIEW ON ADVANCING OR ATTAINING SUSTAINABLE ENVIRONMENTAL SOLUTIONS

Navneet Swami*[1], Payal Verma[2]

Smt. Mohari Devi Taparia Kanya Mahavidyalaya, Jaswantgarh, Rajasthan, India.

***Corresponding Author: Navneet Swami**
Smt. Mohari Devi Taparia Kanya Mahavidyalaya, Jaswantgarh, Rajasthan, India.
DOI: https://doi.org/10.5281/zenodo.17225239

Article Received on 12/08/2025 **Article Revised on 02/09/2025** **Article Accepted on 22/09/2025**

ABSTRACT
This review paper provides an overview of the contribution of nanobioremediation to achieving sustainable environmental goals. Nanobioremediation is an emerging interdisciplinary field that integrates nanotechnology with bioremediation to tackle complex environmental contamination issues. Due to its unique properties, nanotechnology can potentially enhance bioremediation processes. Nanobioremediation leverages the synergy between biological processes and the properties of nanoparticles to facilitate the eradication of contaminants from the environment. This review explores the potential of nanobioremediation to advance sustainable environmental goals, including resource conservation, ecosystem restoration, and pollution management. Nanobioremediation offers a promising approach to mitigating environmental degradation by increasing the efficacy and regulation of traditional bioremediation techniques. It is essential to comprehensively evaluate the potential risks and long-term effects of nanomaterials on ecosystems and human health. As emphasized in this review, further evaluation of the safety, stability, biodegradability, and bioaccumulation potential of nanoparticles is crucial. Additionally, to ensure the secure and widespread application of nanobioremediation technologies, the development of regulations, standards, and guidelines is crucial.

KEYWORDS: Nanobioremediation, Nanotechnology, Nanoparticles, Environmental goals, Sustainable.

INTRODUCTION
Recently, researchers have received much attention to nanotechnology due to its benefits in related scientific fields such as ecology and environmental health. In 1952, Feynman introduced the concept of nanotechnology, which has since become one of the most prominent research areas (Yadav et al. 2017). The simplest definition of nanotechnology is "technology at the nanoscale" The rapidly developing discipline of nanotechnology is based on the precise synthesis, utilization, and application of materials at the nanoscale (10 _9m) (Drexler and Peterson, 1989, Balzani, 2005). Eric Drexler contributed to the growing popularity of nanomaterials research in the 1980s as nanotechnology entered a new era. Numerous industries, including the food, pharmaceutical, medical, agricultural, and environmental sectors, have discovered nanotechnology for themselves. Rapid development and modernization have increased the unsustainable burden on the environment. The environmental pollution load became increasingly unsustainable with the fast pace of modernization and industrialization (Singh et al., 2020). Toxic pollutants, rising at a concerning rate, are undermining ecosystem health and posing significant risks to human well-being. The Global Agenda 2015 highlights that the escalating pollution levels in India represent the third most prominent global trend (Councils, 2015, Vara and Karnena, 2021). As a result, numerous research teams have developed many methods to clean up the polluted region on a larger scale. However, due to their high energy requirements, high operating and maintenance costs, and other disadvantages, these technologies have not been widely used. In recent decades, nanotechnology has become increasingly important in many areas of our daily lives, including environmental remediation. The currently available literature on nanotechnology makes it clear that it will solve numerous problems and improve the possibilities of remediation technologies. The use of nanotechnology has expanded across various sectors of daily life over the past few decades, with notable advancements in the field of environmental remediation (Chauhan et al., 2020, Chauhan et al., 2022).

In recent years, sustainable remediation methods have become increasingly important. Their main aim is to reduce dangerous concentrations of pollutants to a safe level without further harming the environment. In bioremediation processes, microorganisms eliminate contaminants from soils and water (Singh et al., 2020, Ramezani et al., 2021). Compared to physicochemical methods, bioremediation offers several advantages, such as lower energy consumption, specificity, and cost efficiency. One of the disadvantages of these methods is the fact that it can take months or even years for the toxic or resistant materials in the soil to decompose. The effectiveness of these technologies is restricted when contaminated sites contain elevated concentrations of hazardous chemicals (Konni et al., 2021, Kahraman et al., 2022). However, these problems could be solved by combining these strategies with other strategies. Through this interdisciplinary collaboration, pollution can be tackled more effectively and efficiently by utilizing the expertise of both fields (Hemalatha et al., 2022).

Nanobioremediation to enhance pollutant removal in a more efficient, environmentally sustainable, and time-effective manner. By leveraging the advantages of both nanotechnology and bioremediation, this method offers a more effective, sustainable, and cost-efficient solution to environmental pollution, which is essential for advancing environmental sustainability objectives (Carata et al., 2017). This review paper offers a comprehensive overview of nanotechnology and nanobioremediation, detailing their interactions and possible use in the removal of environmental pollutants. It also explores their role in achieving and advancing environmental sustainability objectives.

Key Properties and Significance of Nanoparticles:- With diameters of 1 to 100 nanometers (nm), nanoparticles are typically incredibly small particles of materials (Khan et al., 2019). The nanoscale represents a captivating region of the dimensional scale, where nanostructures are positioned at the interface between the smallest engineered devices and the largest biological molecules. The following key properties and their significance are listed: -

1. The high surface-to-volume ratio of nanoparticles enhances surface interactions, which can result in improved performance, increased reactivity, and elevated catalytic activity. These properties are particularly beneficial in applications like chemical energy storage and drug delivery.
2. Nanoparticles can exhibit both unique optical behavior and remarkable mechanical properties.
3. The low electrical conductivity and high thermal conductivity of nanoparticles can be advantageous for heat control.
4. The self-assembly of nanoparticles into ordered structures, driven by nanoscale intermolecular forces, enables the fabrication of sophisticated nanostructures and nanocomposites.

For these important properties and attributes, nanoparticles are extremely valuable and flexible in various sectors such as materials technology, electronics, environmental science, and medicine.

Methodology of Nanoparticle Biosynthesis: -The biosynthesis of nanoparticles primarily involves two main approaches: (1) top-down and (2) bottom-up synthesis. In the traditional top-down method, bulk materials are progressively broken down or fragmented into nanoscale dimensions. Common techniques used in the top-down approach include electro-explosion, grinding, and milling. These methods involve the mechanical or physical manipulation of larger particles to achieve nanometer-sized structures. In the bottom-up approach, conversely, a nanoparticle is assembled atom by atom and molecule by molecule to achieve the desired properties. This category includes sedimentation and reduction techniques, including spinning, template support synthesis, biological synthesis, biochemical synthesis, etc (Khan et al., 2019).

Nanoparticles can be synthesized through biosorption and bioreduction processes. Metal interacts with cell wall components to generate stable nanoparticles. Complexation, physisorption, ion exchange, and precipitation are the main mechanisms leading to the biosorption of metals on microbial surfaces (Saravanan et al., 2021). Although reported by some to occur during the stationary phase, these bioreduction strategies usually take place during the growth phase of the microbial culture. Microbial enzymes isolated from the growing culture can also produce them extracellularly. The biogenic production of nanoparticles, which is also used in bioremediation, is one of the green ways to maintain an environmentally friendly environment. When it comes to cost, environmental impact, and human health, biogenic nanoparticles are a preferable alternative to physicochemical ones (Kumari et al., 2019).

The Role of Nanobioremediation in Attaining or Advancing Sustainable Environmental Goals:- Nanobioremediation involves the use of nanotechnology to address environmental pollution, including the removal of heavy metals and other harmful contaminants. Biogenic nanoparticles, synthesized by biological systems such as plants, bacteria, and fungi, offer a promising approach for the effective remediation of contaminated environments. These nanoparticles significantly enhance the uptake, transformation, and immobilization of pollutants, facilitating their removal or detoxification from the environment. Nanobioremediation is gaining increasing interest as a flexible technology for environmentally friendly remediation (Koul and Taak, 2018). Incineration, bioremediation, chemical and physical remediation are the most advanced technologies available for the remediation of contaminated environments (Singh, 2006). Three main methods are used in bioremediation: enzymatic remediation, plant-based bioremediation, and the use of microbes.

In recent years, nanotechnology and nanomaterials have emerged as promising alternatives to conventional remediation techniques due to their potential for enhanced efficiency, reduced costs, and greater environmental sustainability. These properties make them a viable solution for addressing various challenges in environmental remediation and other industrial applications (Dastjerdi and Montazer, 2010). An innovative method of environmental remediation is the combination of nanotechnology and bioremediation, sometimes referred to as nanobioremediation. It tackles pollution more effectively and efficiently by combining biological systems (such as bacteria or plants) with the special capabilities of nanomaterials. Bioremediation leverages natural biological systems to degrade, transform, or remove environmental contaminants. Nanotechnology offers innovative tools to enhance the efficiency and efficacy of these bioremediation processes. Due to its potential to enhance the effectiveness, speed, and affordability of conventional bioremediation processes, this new field is crucial to achieving environmentally sustainable goals. The following (Fig-1) are several ways in which nanobioremediation contributes to environmental sustainability and the advancement of its diverse applications:-

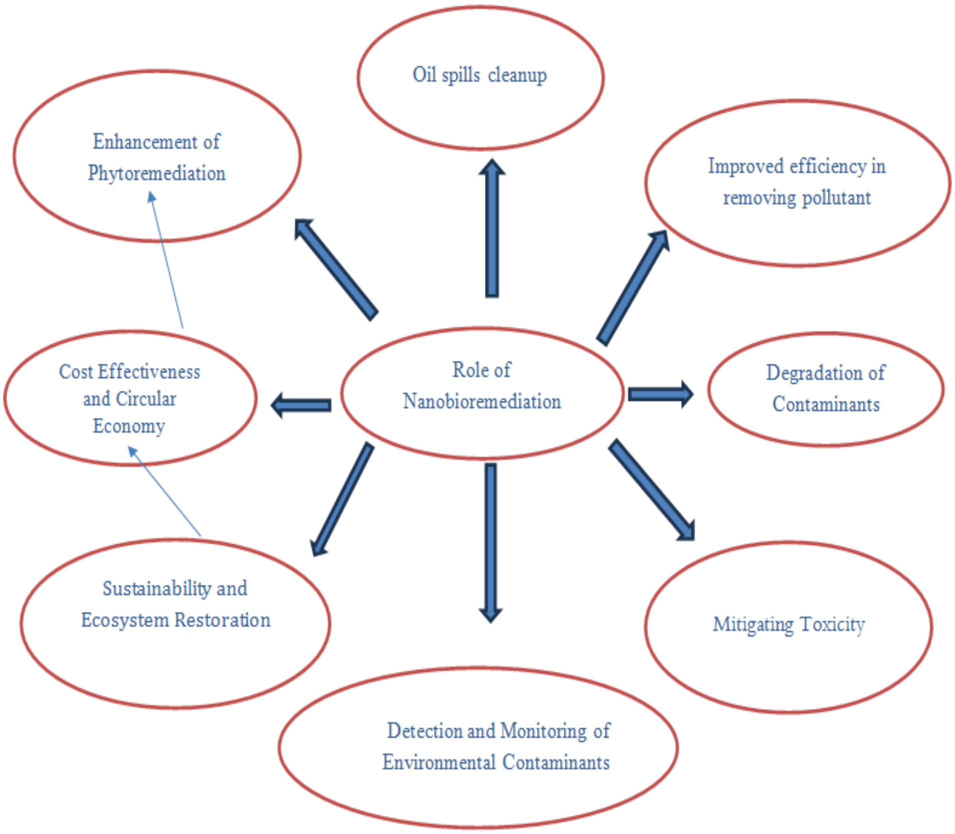

Figure 1:- Role of Nanobioremediation to achieve environmental sustainability goals.

1. Improved efficiency in removing pollutants: - By significantly increasing the surface area and reactivity of materials used in bioremediation, nanomaterials can improve their ability to encapsulate or trap contaminants, including pesticides, heavy metals, and toxins. In contrast to conventional methods, nanoparticles such as zero-valent iron (ZVI) exhibit enhanced efficacy in degrading and neutralizing pollutants like chlorinated hydrocarbons in groundwater, leading to faster and more complete remediation (Ghormade et al., 2011).

2. Enhanced degradation of Contaminants:- Nano-sized carriers are more effective at supplying microorganisms involved in biodegradation with nutrients, oxygen, or other necessary components than larger particles. In environments with high pollutant concentrations or delayed microbial activity due to environmental variables, this could accelerate the breakdown of pollutants. By combining biological systems with nano-catalysts, chemical breakdown processes can be accelerated, reducing the overall cleanup time (Zhu et al., 2019).

3. Mitigating Toxicity Through Advanced Nanotechnology:- Nanotechnology offers a promising solution for transforming toxic compounds into less hazardous or entirely non-toxic forms. For example, nanoparticles can aid in the transformation of hazardous pollutants like lead, mercury, and arsenic into less toxic forms, thereby reducing their long-term health risks to both humans and ecosystems. One prominent application is the use of zero-valent iron nanoparticles (ZVI), which efficiently mitigate the toxicity of metal contaminants and chlorinated organic compounds (Boente et al., 2018). Moreover, biologically integrated nanomaterials can enhance the activity of microbes that degrade pollutants, enabling the conversion of hazardous substances into harmless byproducts like water and carbon dioxide (Xiu et al., 2010).

4. Enhanced Detection and Monitoring of Environmental Contaminants:- Nanotechnology enhances the sensitivity and precision of sensors and biosensors, significantly improving their effectiveness in monitoring environmental pollution. These advanced nano sensors enable real-time tracking of pollution levels and the assessment of bioremediation efforts. By detecting even trace aggregate of contaminants in soil, water, and air, nano sensors facilitate faster and more accurate responses to environmental damage, promoting timely interventions and better management of ecological health (Singh et al., 2020).

5. Sustainability and Ecosystem Restoration:- Ecosystems damaged by environmental pollution can be effectively restored through nano-bioremediation, a technology that cleans contaminated soil, water, and air while supporting biodiversity and ecological sustainability (Green, 2017). Nano-bioremediation utilizes nano-encapsulated nutrients and nanoparticle-based systems to enhance microbial activity, facilitating the breakdown and degradation of pollutants with minimal intervention. This approach promotes the natural recovery of ecosystems and contributes to biodiversity conservation. Additionally, nanoparticles play a key role in mineralizing and detoxifying pollutants by converting harmful substances into non-toxic compounds, such as water and carbon dioxide. This process ensures long-term environmental remediation, making nano-bioremediation a promising solution for restoring and sustaining natural ecosystems (Otto et al., 2008). Nanobioremediation promotes sustainable practices by minimizing chemical usage, reducing energy consumption, and generating less waste during remediation processes.

6. Cost-Effectiveness, Environmental Sustainability and Circular Economy:- Nano-bioremediation presents a more cost-effective and environmentally sustainable alternative to traditional remediation techniques, such as chemical treatments and physical removal methods. By enhancing microbial activity or promoting the neutralization of pollutants, nano-bioremediation minimizes the need for costly chemicals and labour-intensive physical interventions, thereby offering a more efficient and eco-friendly approach to pollutant management. This approach line up with the concept of a circular economy by enhancing resource efficiency, reducing waste, and decreasing energy consumption. In doing so, it supports sustainable environmental management and contributes to the long-term goal of minimizing ecological impact (Lateef, 2023). By mitigating environmental damage and optimizing resource efficiency, nanobioremediation contributes to long-term sustainability and the preservation of ecological balance.

7. Enhancement of Phytoremediation:- Phytoremediation, a plant-based technology for the uptake, detoxification, and removal of environmental pollutants, can be significantly enhanced through the integration of nanomaterials. Nanoparticles increase the regulation of phytoremediation by stimulating plant growth, enhancing the bioavailability of contaminants, and aiding in the translocation of pollutants from soil into plant tissues (Raskin et al., 1997). This accelerated remediation process makes nanomaterial-assisted phytoremediation a promising and effective strategy for environmental cleanup. For example, iron oxide nanoparticles increase the regulation of plants in remediating contaminated soils by facilitating the uptake of heavy metals such as lead and arsenic. These nanoparticles also promote the release of organic acids from plant roots, which aids in the solubilization of metals, making them more bioavailable for absorption. This dual mechanism significantly improves the overall effectiveness of phytoremediation (Prakash, 2023).

8. Nanobioremediation in oil spill cleanup:- Nanobioremediation significantly enhances the biodegradation of hydrocarbons during oil spill remediation by augmenting microbial activity (Basak et al., 2020). Nanomaterials, such as nanoparticles and nano-encapsulated nutrients, increase the bioavailability of oil pollutants, making them more accessible to oil-degrading microorganisms. Furthermore, these nanomaterials promote microbial growth and enhance microbial activity, thereby accelerating the breakdown of complex hydrocarbons into benign byproducts such as carbon dioxide and water. This process significantly improves the efficiency of hydrocarbon degradation in contaminated environments (Karan et al., 2009). By facilitating faster and more efficient remediation, nano-bioremediation provides a sustainable and environmentally friendly solution to reduce the impact of oil spills on both terrestrial and marine ecosystems. This approach enhances the natural processes of pollutant degradation, promoting ecological recovery in contaminated environments.

Challenges and Considerations in Nanobioremediation:- Nanomaterials have the potential to enhance bioremediation processes significantly. However, poorly designed, inadequately monitored, or unrestricted use of nanoparticles may introduce new environmental risks. The prolonged consequence of nanomaterials on ecosystems and human health remains uncertain, with potential impacts on humans, plants, and animals. Additionally, raising the production of nanoparticles while maintaining cost efficiency poses a significant challenge. Ongoing research aims to enhance the productivity, affordability, and scalability of these technologies for wider application. Additional research is necessary to examine the stability, biodegradability, and potential for bioaccumulation of these materials. To ensure safety and effectiveness, nanobioremediation processes require well-defined regulations, standards, and guidelines. Developing comprehensive frameworks is essential for achieving widespread acceptance.

CONCLUSION

Nanobioremediation offers an effective and sustainable solution to complex environmental contamination challenges. By enhancing traditional bioremediation methods, it contributes to environmental sustainability goals, including pollution control, resource conservation, and ecosystem restoration. However, a thorough assessment of the potential environmental risks and long-term impacts of nanomaterials is crucial. While nanobioremediation significantly contributes to global sustainability goals, further research is making sure to secure, efficient, and environmentally benign use of nanomaterials in the long term. With continued research, nanobioremediation has the potential to become a vital tool in the global pursuit of sustainability and the mitigation of environmental damage. The capacity of this technology to enhance pollutant degradation could significantly contribute to addressing critical environmental challenges.

REFERENCES

1. Balzani, V. Nanoscience and nanotechnology: a personal view of a chemist, 2005; 1(3): 278-283.
2. Basak, G., Hazra, C., and Sen, R. Biofunctionalized nanomaterials for in situ clean-up of hydrocarbon contamination: A quantum jump in global bioremediation research. *Journal of environmental management*, 2020; *256:* 109913.
3. Boente, C., Sierra, C., Martínez-Blanco, D., Menéndez-Aguado, J. M., and Gallego, J. R. Nanoscale zero-valent iron-assisted soil washing for the removal of potentially toxic elements. *Journal of Hazardous Materials*, 2018; *350:* 55-65.
4. Carata, E., Panzarini, E., and Dini, L. Environmental nanoremediation and electron microscopies. *Nanotechnologies for Environmental Remediation: Applications and Implications*, 2017; 115-136.
5. Chauhan, G., González-González, R. B., and Iqbal, H. M. Bioremediation and decontamination potentials of metallic nanoparticles loaded nanohybrid matrices–a review. *Environmental Research*, 2022; *204:* 112407.
6. Chauhan, R., Yadav, H. O., and Sehrawat, N. Nanobioremediation: A new and a versatile tool for sustainable environmental clean up-Overview. *J. Mater. Environ. Sci.*, 2020; *1*(4): 564-573.
7. Councils, G. A. (2015). Outlook on the global Agenda 2015. In *World economic forum*.
8. Dastjerdi, R., and Montazer, M. A review on the application of inorganic nano-structured materials in the modification of textiles: focus on anti-microbial properties. *Colloids and surfaces B: Biointerfaces*, 2010; *79*(1): 5-18.
9. Drexler, K. E. and Peterson, C. Nanotechnology and enabling technologies. *Foresight Briefing*, 1989; 2.
10. Feynman, R. P. There's plenty of room at the bottom. Engineering and Science, 1960; 23(5): 22–36. ISSN 0013-7812.
11. Galdames, A., Ruiz-Rubio, L., Orueta, M., Sánchez-Arzalluz, M. and Vilas-Vilela, J. L. Zero-valent iron nanoparticles for soil and groundwater remediation. *International journal of environmental research and public health*, 2020; 17(16): 5817.
12. Ghormade, V., Deshpande, M. V., and Paknikar, K. M. Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnology advances*, 2011; *29*(6): 792-803.
13. Green, A. E. S. 1 Bioremediation. *Environmental Pollutants and their Bioremediation Approaches*, 2017; 1.
14. Hemalatha, I., Harika, D., and Karnena, M. K. Sustainable Nano-Bioremediation Approaches for the Treatment of Polluted Soils. *Nature Environment & Pollution Technology*, 2022; *21*(4).
15. Kahraman, B. F. and Altın, A. Treatment of Pb–naphthalene co–contamination in soils by zero-valent iron nanoparticles (NZVI) and bioremediation. *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, 2022; *27*(1): 57-70.
16. Karn, B., Kuiken, T., and Otto, M. Nanotechnology and in situ remediation: a review of the benefits and potential risks. *Environmental health perspectives*, 2009; *117*(12): 1813-1831.
17. Khan, I., Saeed, K. and Khan, I. Nanoparticles: Properties, applications, and toxicities. *Arabian journal of chemistry,* 2019; 12(7): 908-931.
18. Konni, M., Mukkamala, S. B., Srikanth Vemuri, R. S. S. and Karnena, M. K. Sustainable Approaches for the Treatment of Industrial Wastewater Using Metal-Organic Frame Works. *Water Safety, Security and Sustainability: Threat Detection and Mitigation*, 2021; 463-493.
19. Koul, B. and Taak, P. (2018). *Biotechnological strategies for effective remediation of polluted soils*. Springer.
20. Kumari, S., Tyagi, M. and Jagadevan, S. Mechanistic removal of environmental contaminants using biogenic nano-materials. *International Journal of Environmental Science and Technology*, 2019; 16(11): 7591-7606.
21. Lateef, A. Cola nitida: Milestones in catalysis, biotechnology and nanotechnology for circular economy and sustainable development. *Biocatalysis and Agricultural Biotechnology*, 2023; 102856.
22. Otto, M., Floyd, M., and Bajpai, S. Nanotechnology for site remediation. *Remediation Journal: The Journal of Environmental Cleanup Costs, Technologies & Techniques*, 2008; *19*(1): 99-108.
23. Prakash, Priyanka. "Nano-phytoremediation of heavy metals from soil: a critical review." *Pollutants*, 2023; 3(3): 360-380.
24. Ramezani, M., Rad, F. A., Ghahari, S., Ghahari, S. and Ramezani, M. Nano-bioremediation application for environment contamination by

microorganism. *Microbial Rejuvenation of Polluted Environment*, 2021; 2: 349-378.

25. Raskin, I. and Ensley, B. D. (2000). *Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment*. Wiley.
26. Raskin, I., Smith, R. D., and Salt, D. E. Phytoremediation of metals: using plants to remove pollutants from the environment. *Current opinion in biotechnology*, 1997; *8*(2): 221-226.
27. Saravanan, A., Kumar, P. S., Karishma, S., Vo, D. V. N., Jeevanantham, S., Yaashikaa, P. R. and George, C. S. A review on biosynthesis of metal nanoparticles and its environmental applications. *Chemosphere*, 2021; *264:* 128580.
28. Singh, B. K., and Walker, A. Microbial degradation of organophosphorus compounds. *FEMS microbiology reviews*, 2006; *30*(3): 428-471.
29. Singh, P. M., Tiwari, A., Maity, D. and Saha, S. Recent progress of nanomaterials in sustainable agricultural applications. *Journal of Materials Science*, 2022; 57(24): 10836-10862.
30. Singh, R., Behera, M., and Kumar, S. Nano-bioremediation: an innovative remediation technology for treatment and management of contaminated sites. *Bioremediation of Industrial Waste for Environmental Safety: Volume II: Biological Agents and Methods for Industrial Waste Management*, 2020; 165-182.
31. Vara, S. and Karnena, M. K. Fungal enzymatic degradation of industrial effluents–A review. *Current Research in Environmental and Applied Mycology (Journal of Fungal Biology),* 2020; *10*(1): 417-442.
32. Xiu, Z. M., Gregory, K. B., Lowry, G. V., and Alvarez, P. J. Effect of bare and coated nanoscale zerovalent iron on tceA and vcrA gene expression in Dehalococcoides spp. *Environmental science & technology*, 2010; *44*(19): 7647-7651.
33. Yadav, K. K., Singh, J. K., Gupta, N., and Kumar, V. J. J. M. E. S. A review of nanobioremediation technologies for environmental cleanup: a novel biological approach. *J Mater Environ Sci.*, 2017; *8*(2): 740-757.
34. Zhu, Y., Xu, F., Liu, Q., Chen, M., Liu, X., Wang, Y., and Zhang, L. Nanomaterials and plants: Positive effects, toxicity and the remediation of metal and metalloid pollution in soil. *Science of the Total Environment*, 2019; *662:* 414-421.