BioThink, Vol -2, Issue -1
ISSN: 3048-7943

Environmental Quality Management Employing Nanobiotechnology - A Sustainable Solution For Nature

SUMIT JANI[1], R.Y. HIRANMAI[2], GANESH KUMAR[2]

[1] School of Nanoscience, [2] School of Environment and Sustainable Development
Central University of Gujarat, Gandhinagar-382030, India.
***E-mail :** ganesh24cug@gmail.com

Introduction

Environmental degradation has become one of the most pressing challenges of the 21st century. Rapid industrialization, urbanization, and deforestation have led to air, water, and soil pollution, severely affecting ecosystems and human health all over the world. (1). Traditional methods of environmental remediation often fall short in terms of efficiency, cost, and sustainability. As a result, there is a growing demand for innovative and sustainable solutions to address environmental challenges. (2). Nano biotechnology, a multidisciplinary and interdisciplinary field combining nanotechnology and biotechnology, has emerged as a promising solution for environmental management (3). Nano biotechnology utilizes nano materials, biological entities, and biomolecules to develop new approaches for environmental quality management. These technologies offer significant advantages due to their unique properties, such as high surface area, target to specific molecule reactivity, and specificity. Furthermore, integrating biological systems into nanotechnologies for example. (4) Nano particles Synthesis via green route methods are now in trend due to more effective results than other methods and eco friendly in nature, enhances the sustainability and eco-friendliness of the methods. Applications of nano biotechnology in environmental remediation include the removal of toxic pollutants, heavy metals, and hazardous chemicals from water, soil, and air, as well as the monitoring and restoration of ecosystems. These solutions are not only efficient but also reduce the environmental footprint of traditional techniques (5)

Several studies have highlighted the potential of nano biotechnology to offer more sustainable and effective solutions for waste management, pollution control, and resource recovery. For instance, nano materials, such as nano particles, carbon

BioThink, Vol -2, Issue -1
ISSN: 3048-7943

nano tubes, and nano composites, have demonstrated remarkable abilities to absorb and neutralize contaminants in various environmental matrices (6-7). Additionally, bioremediation strategies using genetically engineered microorganisms or plant systems, in conjunction with nanomaterials, can provide a dual-action approach to environmental cleaning (8). Moreover, the use of biosensors and nanodiagnostics facilitates real-time monitoring of environmental pollutants, enabling timely interventions and more informed decision-making.

The integration of nanobiotechnology into environmental management systems represents a sustainable solution that can address the limitations of conventional methods while contributing to the protection and restoration of ecosystems. This review explores the role of nanobiotechnology in environmental quality management, its applications in pollution control, and the potential benefits it offers for a sustainable future (9).

Nanobiotechnology in Environmental Quality Management

Nanobiotechnology involves the use of nanomaterials and biological agents for environmental management. Nanomaterials possess unique properties due to their size, surface area, and reactivity, while biological systems—such as microorganisms, enzymes, and plants—can be enhanced or engineered at the nanoscale to perform specific tasks. The combination of these two domains enables efficient and targeted solutions for a wide range of environmental challenges. (10-11)

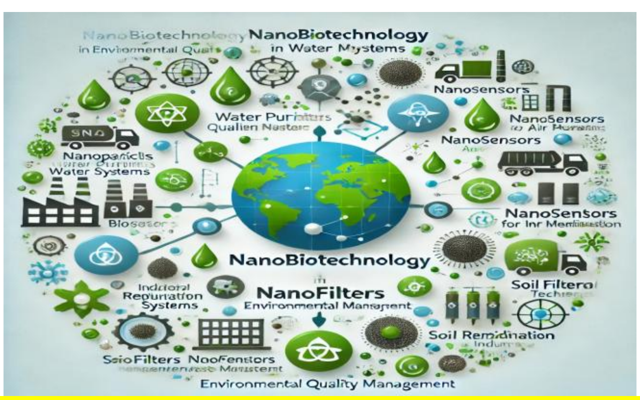

Fig. 1. Shows the various Application of Nanobiotechnology in Environmental Quality Management

Key Applications of Nanobiotechnology in Environmental Management

1. Water Quality Management: Water pollution is a critical issue affecting ecosystems and human health worldwide. NBT offers innovative solutions for water purification and management:

Nanofiltration and Adsorption: Nanoparticles such as carbon nanotubes (CNTs) and silver nanoparticles have shown significant efficacy in removing heavy metals, bacteria, and organic pollutants from water sources. Their high surface area and reactivity make them ideal for contaminant removal.(12)

Bioremediation Enhancement:

By integrating nanomaterials with microorganisms, NBT can enhance the bioremediation of water by Sfacilitating the degradation of harmful compounds like pesticides and petrochemicals. Nanoparticles can help deliver nutrients to bacteria, increasing their efficiency in degrading pollutants. (13)

2. Air Quality Control: Air pollution, particularly from industrial emissions and vehicular exhaust, has harmful effects on human health and the environment. NBT provides solutions to reduce airborne contaminants:

Photocatalysis:

Nanomaterials, especially titanium dioxide (TiO_2), are effective in breaking down pollutants in the air through photocatalytic reactions under UV light. This technology can degrade volatile organic compounds (VOCs), nitrogen oxides (NO_x), and particulate matter (PM). (14-15)

Nanostructured Filters:

The development of advanced filters using nanomaterials allows for the capture of fine particulate matter and hazardous gases from the air. These filters are particularly effective at removing ultrafine particles, which are not captured by traditional filtration methods. (16-17)

3. Soil Remediation: Contaminated soils, resulting from industrial activities, agriculture, and waste disposal, are a significant environmental challenge. NBT offers innovative ways to restore soil health:

Nanomaterial-Based Adsorbents:

Nanoparticles, such as iron oxide nanoparticles, are used for the removal of heavy metals, oils, and organic pollutants from soil. These materials have high adsorption capacities, which makes them effective in cleaning up contaminated soils.(18-19)

Bio-Nanotechnology

The application of genetically engineered microorganisms or enzymes at the nanoscale can improve the bioremediation of polluted soils. These organisms can be designed to target specific pollutants, such as herbicides, pesticides, and petroleum hydrocarbons, for degradation.(20)

4. Waste Management and Recycling:

NBT plays a significant role in improving waste management practices:

Nanocomposites for Waste Degradation:

Nanomaterials can accelerate the degradation of non-biodegradable plastics and other waste products. For instance, nano-structured materials such as biodegradable polymers or nanocatalysts can be employed to break down plastics in landfills. (21-22)

Recycling and Waste Sorting:

NBT can also enhance recycling processes by providing advanced methods for sorting and processing waste materials. Nanomaterials may be used to selectively capture and separate valuable materials from waste streams, such as metals from electronic waste. (23)

Environmental Benefits of Nanobiotechnology

The integration of nanotechnology and biological systems provides numerous environmental benefits:

Efficiency and Precision:

Nanobiotechnology enables highly efficient and precise environmental management by targeting specific pollutants at the molecular level. This reduces the overall resource consumption and energy required for remediation. (24)

Sustainability

NBT uses naturally occurring biological processes, making it an environmentally sustainable approach to pollution control and resource recovery. It also minimizes the use of harmful chemicals, reducing the environmental impact of conventional methods. (25)

Cost-Effectiveness

The ability to utilize smaller quantities of materials for large-scale environmental remediation and management makes NBT a cost-effective solution compared to traditional methods. The scalability of NBT applications also allows for economic implementation at various levels, from local communities to industrial-scale projects. (26)

Challenges and Limitations

Despite the promising potential of NBT, there are several challenges to its widespread adoption in environmental quality management:

Toxicity and Environmental Impact

The potential toxicity of nanoparticles to both ecosystems and human health remains a concern. The long-term effects of nanoparticles on living organisms and their persistence in the environment must be studied thoroughly to ensure their safety. (27)

Regulatory and Ethical Issues

The rapid development of nanobiotechnology has outpaced the creation of regulatory frameworks. Governments and organizations must establish clear guidelines and standards to ensure the safe use of nanomaterials in environmental applications. (28)

Scalability and Cost

While laboratory-scale studies have demonstrated the effectiveness of NBT, scaling up these technologies for large-scale applications remains a challenge. Additionally, the production costs of some nanomaterials can be high, which may limit their commercial viability. (29)

Future Directions

The future of nanobiotechnology in environmental quality management looks promising, with ongoing research aimed at overcoming current limitations:

Multifunctional Nanomaterials

Future developments will likely focus on creating multifunctional nanomaterials that can target multiple pollutants simultaneously, enhancing the efficiency of environmental management efforts.

Biodegradable Nanomaterials:

Research into developing biodegradable and environmentally friendly nanomaterials will address concerns about the potential accumulation of synthetic nanoparticles in the environment.

Integration with Artificial Intelligence: The combination of NBT with artificial intelligence (AI) and machine learning could optimize the monitoring and management of environmental quality, making it easier to track pollution levels and predict future trends.(30)

Nanobiotechnology in Bioremediation

Nanobiotechnology involves the use of nanomaterials (such as nanoparticles) and biological entities (like microorganisms, enzymes, or plant systems) to address environmental pollutants. Nanoparticles possess unique properties such as large surface area, high reactivity, and the ability to interact with biological systems at the molecular level. These characteristics make them highly effective in enhancing bioremediation processes.(31)

In bioremediation, nano biotechnology can improve pollutant removal through several mechanisms:

Nanoparticle-Microbe Interactions: Nanoparticles can enhance microbial activity by increasing the bioavailability of contaminants and providing a larger surface area for microbial attachment.

Nanomaterial-Enhanced Enzyme Activity: Nanoscale materials can facilitate the action of enzymes that break down organic pollutants, improving the rate and extent of bioremediation.

Facilitating Nutrient Delivery: Nanoscale materials can help deliver nutrients and growth factors to microorganisms, boosting their capacity to degrade pollutants.

Accelerating Pollutant Degradation: Nanomaterials can be engineered to directly degrade pollutants through chemical reactions, complementing microbial processes in bioremediation.(32-33)

Applications of Nanobiotechnology in Bioremediation

Bioremediation of Soil

Soil contamination, especially from heavy metals, pesticides, petroleum products, and other toxic compounds, is a significant environmental challenge. Nanobiotechnology offers various ways to enhance soil remediation:

Heavy Metal Removal: Nanomaterials such as magnetic nanoparticles (e.g., Fe_3O_4) have been used to capture and remove heavy metals like lead, cadmium, and mercury from contaminated soil. These nanoparticles can adsorb metals effectively and facilitate microbial degradation of the adsorbed contaminants.

Petroleum Hydrocarbon Degradation: Hydrocarbon-contaminated soils, commonly from oil spills, can benefit from nanobiotechnology. Nanoparticles can accelerate the degradation of petroleum hydrocarbons by promoting microbial activity. For example, zinc oxide (ZnO) nanoparticles have been shown to enhance the microbial degradation of hydrocarbons in soil, making the bioremediation process faster and more efficient.

Pesticide and Herbicide Breakdown: NBT can also address contamination from agricultural chemicals such as pesticides and herbicides. Nanoparticles can increase the bioavailability of these chemicals to microorganisms, aiding in their biodegradation. For instance, nanoparticles of titanium dioxide (TiO_2) have photocatalytic properties that can degrade pesticide residues in soil when exposed to light.(35-36)

Bioremediation of Water:

Water pollution, especially from industrial effluents, agricultural runoff, and sewage, presents a major threat to freshwater ecosystems and human health. Nanobiotechnology offers advanced methods to clean contaminated water:

Oil Spill Cleanup: Nanoscale materials such as hydrophobic nanoparticles have been explored for oil spill bioremediation. These nanoparticles can effectively absorb and concentrate oil from water surfaces, allowing microorganisms to break down the oil. Nano-bioreactors—systems combining nanoparticles with microorganisms—have been developed to enhance oil biodegradation in aquatic environments.

Heavy Metal Contamination: Water bodies contaminated with heavy metals can be remediated using nanoparticles like zero-valent iron (ZVI) and chitosan-based nanoparticles. These particles can adsorb heavy metals such as arsenic, lead, and cadmium from water. Furthermore, nanoparticles can also be engineered to release bacteria or enzymes capable of breaking down organic pollutants, further enhancing the bioremediation process.

Nutrient Delivery for Microbial Growth: In polluted water, nutrient availability can be a limiting factor for microbial degradation. NBT can provide a novel solution by delivering nutrients or enhancing microbial survival. For instance, nanoparticles can be used to encapsulate nutrients, releasing them slowly to stimulate the growth of indigenous microorganisms that degrade pollutants in the water. (37)

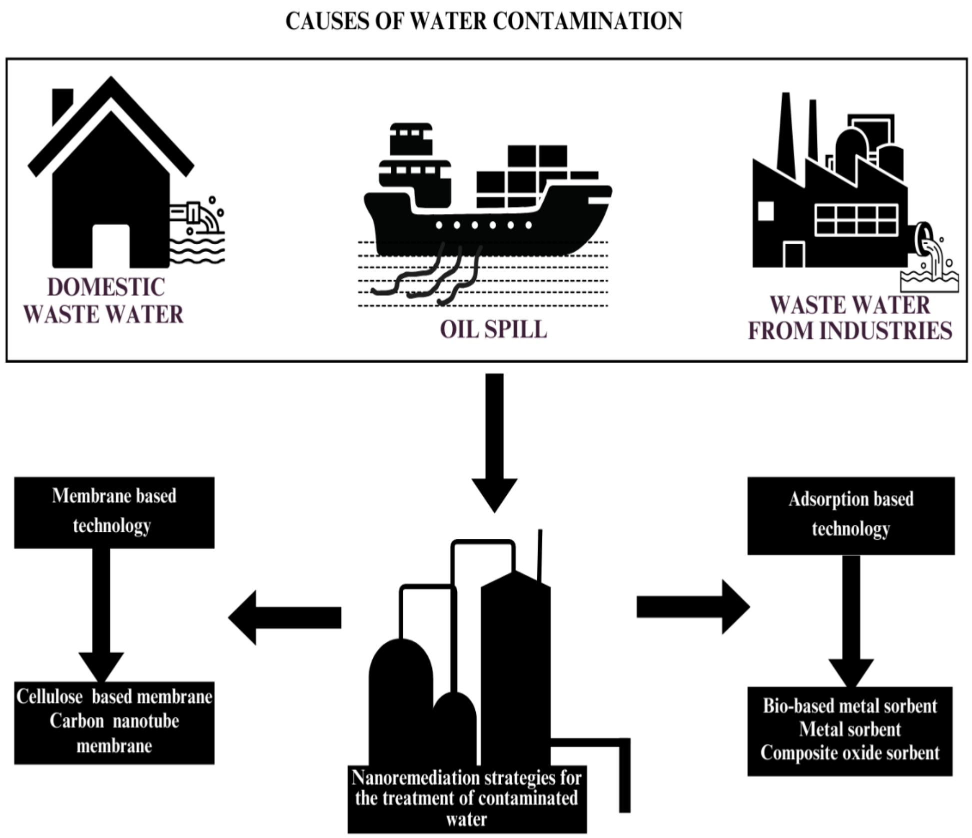

Fig. 2. Shows the various nano remediation strategies for the treatment of contaminated water

Advantages of Using Nanobiotechnology for Bioremediation

Enhanced Pollutant Removal Efficiency

NBT significantly improves the efficiency of bioremediation by increasing the rate of pollutant degradation. The unique properties of nanoparticles, such as their large surface area, reactivity, and ability to interact with microorganisms, contribute to faster and more complete pollutant removal.

Eco-friendly and Sustainable

NBT promotes the use of natural processes for environmental cleanup. By enhancing the biodegradation capabilities of microorganisms, nanobiotechnology provides a sustainable alternative to chemical treatments, which can have harmful side effects on ecosystems.

Targeted Approach

Nanomaterials can be tailored to interact specifically with certain pollutants. This targeted approach makes NBT more efficient compared to traditional bioremediation methods, which may lack specificity and require longer times to achieve the desired outcomes.

Versatility

Nanobiotechnology can be applied to a wide range of pollutants in both soil and water. This versatility makes it an ideal solution for various types of environmental contamination, including toxic metals, organic pollutants, and hydrocarbons.(38-39)

Challenges and Limitations

While the potential of NBT for bioremediation is significant, several challenges need to be addressed:

Toxicity of Nanoparticles

The environmental and health impacts of nanoparticles, especially their toxicity to aquatic organisms and soil biota, remain a concern. More research is needed to evaluate the long-term effects of nanoparticles on ecosystems and ensure their safe application in bioremediation.

Cost and Scalability

The production of nanoparticles can be expensive, and scaling up laboratory-based NBT applications to field-level operations

ISSN: 3048-7943

remains a significant challenge. Research into more cost-effective methods of nanoparticle synthesis and application is necessary for the widespread use of NBT in environmental cleanup.

Regulatory and Ethical Concerns

As NBT continues to advance, regulatory frameworks are needed to ensure the safe and ethical use of nanomaterials in environmental applications. Policies regarding the production, use, and disposal of nanomaterials will play a critical role in ensuring the responsible deployment of NBT technologies (40-41).

Sustainability for Environment Management

Sustainability being a concept for future considers every biotic and abiotic part of the environment. Global functioning of soil ecosystem is of high significance as it is vital for food production and environment management. Quality of soil is depicted in terms of its capacity to function in the ecosystem. The managed ecosystem or natural conditions are to be balanced to maintain air, water and living organisms. Soil is influenced by natural and anthropogenic activities that modifies the characteristics of soil. Soil quality is influenced by multicomponent approaches that depends on climatic variations, physico chemical and biological characters, agriculture pattern, and land use. Sustainable land management practices are required for improving the productivity by identifying the SDGs with suitability. Sustainability of land management practices are possible by translating science and technology into practice in harmony with nature (42).

Soil health has been broadly defined as the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (42-43).

More simply stated by Tom Franzen, a midwestern farmer in the USA, “a sustainable agriculture — sustains the people and preserves the land”. Sustainability management practices are achieved by translating the knowledge acquired by scientists are applied effectively. It requires assessing the production-based problems, variation in air and water quality monitoring, formulation of policies for real time application in agriculture. Safe and clean environment are to be attained by the practices of sustainability. Major sustainable development goal scan be achieved by soil management practices (44).

The Sustainable Development Goal 15 of the 2030 Agenda for Sustainable Development is devoted to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss"(https://sdgs.un.org/topics/biodiversity-and-ecosystems). The Sustainable Development Goals (SDGs) proposed for water and sanitation (SDG 6) and ecosystems (SDG 15) have targets for restoring and maintaining ecosystems to provide waterrelated services. The targets mention the need to integrate ecosystem values into planning, development processes, and strategies for reducing poverty. Ecosystem services are integral to the functioning of water infrastructure. Although their effectiveness has been questioned, schemes in which local communities are paid to safeguard important ecosystem services are increasingly being promoted. Ecosystems also underpin the achievement of Goal 3, 'Good Health and Well-being.' Natural environments play a pivotal role in regulating air quality and reducing pollution, thereby promoting public health. Additionally, the psychological benefits of interaction with nature contribute to overall mental wellbeing. Thus, ecosystem services not only provide tangible resources but also have the potential to alleviate poverty (Goal 1) and inequality (Goal 10) through the equitable distribution of these benefits.

Consequently, recognizing and integrating the value of ecosystem services into socio-economic policies and decisions is crucial to accomplish the 2030 Agenda for Sustainable Development. Approaches like 'nature-based solutions' can strike a balance between development and conservation, optimizing the use of ecosystem services without depleting them. By understanding and promoting the linkages between ecosystem services and SDGs, we can foster a symbiotic relationship between humanity and nature, ensuring a sustainable and equitable future for all. (45)

Socio economic resource development using natural resources and their conservation. Nanotechnology with an interdisciplinary approach is applicable for sustainable practices in agro industry sector. Applicability of nanopriming and treatment using nanomaterials are eco friendly methods that are of benefit to farmers (46). Sustainable packaging materials can reduce the dumping of non-degradable wastes. Nanopackaging materials are safe to environment and biodegradable as they are prepared from bionanomaterials with their commitment to sustainability (47). Traditional packaging materials that are non degradable can be replaced by biodegradable nanomaterials (48).

Sustainable production and balanced agroecosystem are claimed by application of various forms of NPs whereas few studies also reported the adverse effects. There is a need to create the optimum dosage and materials that could be ecofriendly and benefit the ecosystem balance.

Challenges

1. Challenges in utilising nanomaterials is their entry into food chain and food web and bioaccumulation leading to nano toxicity.
2. Cell viability in living organisms get reduced due to the cyto and geno toxicity.
3. Changes are induced in microbes and plants by engineered nanoparticles.
4. Variation in toxicity occurs in nature due to different conditions in natural environment compared to the controlled laboratory condition.
5. Many times the nanoparticles adversely affects the cells by disrupting cell membranes, production of ROS and toxic compounds.
6. Production of stress influences the functioning and damaging the secondary metabolism.(49-50).

Opportunities

1. Utilisation of locally available resources for sustainable management practices.
2. Development of new technological solution for maintaining environmental quality.

3. Eco friendly and economic methods of remediation.
4. Practicing SDGs
5. Sustainable solution for Soil and water quality.

Reduction in agriculture production, nutritional deficiency, contamination in soil and climate change are some of the biggest challenges agriculture sector faces today. Rise in food insecurity causes economic and ecological instability. Present food production need to be increased approximately 50-70% in order to meet the future demand of food (51). Soil quality, food productivity and nutritional value in food is continuously decreasing. Use of synthetic chemicals, agrochemicals and herbicides leads to contamination in agricultural soil and water. Due to anthropogenic activities global temperarture is increased carbon dioxide level in atmosphers is also increases which critically changes the patterns of rainfall as a result of this overall crop production will be reduced (52). All these factors were responsible for causing contamination in agricultural soil and water, reduces nutrients cycling and impacts autochthonous microbial diversity in soil (53). Development of sustainable agriculture strategies needs to be adapted. Nanobiofertilizers is a mixture of nanotechnology and biotechnology. Use of nanobiofertilizers in agriculture sector is a promising strategy for the removal of contaminants and increasing crop yield. Nanobiofertilizers are the substances which are made up of biofertilizers and nanoformulations both are enclosed in suitable nanomaterial covering and final product is synthesized (54). These fertilizers increases the quality and fertility of soil by various processes such as conserve moisture content, reduces the concentration of heavy metals by producing iron chelators makes them less toxic to plants, produces protective solutes and plant hormones. Nanobiofertilizers plays a crucial role in mitigating biotic and abiotic stress in plants and increases the nutrients uptake efficiency in crops(55-56).Encapsulation of nanomaterials with biofertilizers increases the efficacy of nanobiofertilizers which leads to the controlled and slow release in the root zone thus reduces the loss of nutrients through leaching and mitigates the chances of contamination in ground water aquifers(57).The mechanism of action of nanobiofertilizers gives better results when applied to plants these initiates various processes which plays significant role in the growth and development of plants. These fertilizers reduces the impacts of reactive oxygen species on plants, produces stress related proteins and increases the production of hormones(58-59). Nanobiofertilizers also increases the chances of growing crops in adverse environmental conditions these fertilizers decreases the production of stress hormones and increases the level of various growth hormones (60).Nanobiofertilizers helps in increasing the quality and quantity of agricultural crops. Even lower concentration of these fertilizers gives better results as compared to synthetic fertilizers also their chances of accumulation in environment is very less because these fertilizers works effectively without deteriorating the quality of agricultural system (61). For sustainable production of agriculture nanobiofertilizers applicability in agricultural system is a promising and environmental friendly approach without causing any harmful impacts to agroecosystem (62).

Conclusion

In conclusion, nanobiotechnology holds significant promise for advancing environmental quality management by providing sustainable solutions for water, air, soil, and waste management. By integrating nanomaterials with biological systems, this technology can enhance pollutant removal, resource efficiency, and ecosystem restoration. While challenges such as toxicity, scalability, and regulatory concerns remain, the potential benefits of nanobiotechnology in addressing environmental issues are immense. Future research and interdisciplinary collaboration will be crucial in overcoming these challenges and ensuring that nanobiotechnology contributes to a cleaner, greener, and more sustainable future for our planet. Nanobiotechnology offers transformative solutions to some of the most pressing environmental challenges, such as pollution, waste management, and resource depletion. By leveraging the unique properties of nanomaterials and biological systems, nanobiotechnology can enhance water, air, and soil quality management, fostering sustainability. However, to realize its full potential, future research must address safety, scalability, and regulatory concerns, ensuring that nanobiotechnology serves as a viable and eco-friendly solution for a cleaner, greener future.

Acknowledgments

The authors would like to express their sincere gratitude to all those who have contributed to the completion of this review. Special thanks to **Sumit Jani**, Laboratory Assistant at the School of Nano Sciences, Central University of Gujarat, for his valuable support in research and technical assistance. We also extend our appreciation to **R.Y. Hiranmai**, Professor and Dean of the School of Environment and Sustainable Development, Central University of Gujarat, for his expert guidance and encouragement. Lastly, we acknowledge **Ganesh Kumar**, Ph.D. Scholar at the Central University of Gujarat, for his insightful contributions and review and assistance their collective efforts of this work.

References

1. Ajith, M.P., Aswathi, M., Priyadarshini, E. and Rajamani, P., 2021. Recent innovations of nanotechnology in water treatment: A comprehensive review. *Bioresource technology*. **342**: 126000.

2. Akhtar, N.; Ilyas, N.; Meraj, T.A.; Pour-Aboughadareh, A.; Sayyed, R.Z.; Mashwani, Z.-R.; Poczai, P. Improvement of Plant Responses by Nanobiofertilizer: A Step towards Sustainable Agriculture. Nanomaterials (2022). **12**: 965.

3. Alao, M.B., Bamigboye, C.O. and Adebayo, E.A., (2022). Microbial Nanobiotechnology in Environmental Pollution Management: Prospects and Challenges. *Biotechnological Innovations for Environmental Bioremediation*. 25-51.

4. Ali Mansoori, G., Bastami, T.R., Ahmadpour, A. and Eshaghi, Z., 2008.. Environmental application of nanotechnology. *Annual review of nano research*. 439-493.

5. Ali, S.S.; Darwesh, O.M.; Kornaros, M.; Al-Tohamy, R.; Manni, A.; El-Shanshoury, A.E.-R.R.; Metwally, M.A.; Elsamahy, T.; Sun, J. Nano-biofertilizers: Synthesis, advantages, and applications. In Biofertilizers; Woodhead Publishing: Cambridge, MA, USA, 2021; pp. 359–370.

6. Beni, A. A., and Jabbari, H. (2022). Nanomaterials for environmental applications. *Results in Engineering*, *15*, 100467.

7. Benjamin, S.R., Lima, F.D., Florean, E.O.P.T. and Guedes, M.I.F., 2019. Current trends in nanotechnology for bioremediation. *International Journal of Environment and Pollution*, *66*(1-3), 19-40.

8. Bhat, S.A., Sher, F., Hameed, M., Bashir, O., Kumar, R., Vo, D.V.N., Ahmad, P. and Lima, E.C., (2022). Sustainable nanotechnology based

wastewater treatment strategies: achievements, challenges and future perspectives. *Chemosphere*, *288*, 132606.

9. Bhawana, P., and Fulekar, M. (2012). Nanotechnology: remediation technologies to clean up the environmental pollutants. *Res J Chem Sci ISSN*, *2231*, 606X.

10. Bhushan, B. (2017). Introduction to nanotechnology. *Springer handbook of nanotechnology*. 1-19.

11. Bibi, F.; Ilyas, N.; Arshad, A.; Khalid, A.; Saeed, M.; Ansar, S.; Batley, J. Formulation and efficacy testing of bio-organic fertilizer produced through solid-state fermentation of agro-waste by Burkholderia cenocepacia. Chemosphere 2022. **291**: 132762.

12. Biswas, J. K., and Rai, M. (2024). Nanotechnology for Environmental Management.

13. Boisseau, P., and Loubaton, B. (2011). Nanomedicine, nanotechnology in medicine. *Comptes Rendus Physique*. **12**(7): 620-636.

14. Bora, T., and Dutta, J. (2014). Applications of nanotechnology in wastewater treatment—a review. *Journal of nanoscience and nanotechnology*. **14**(1): 613-626.

15. Callegari, A.; Bolognesi, S.; Cecconet, D.; Capodaglio, A.G. Production Technologies, Current Role, and Future Prospects of Biofuels Feedstocks: A State-of-the-Art Review. Crit. Rev. Environ. Sci. Technol. 2020. 50: 384–436.

16. Chakraborty, R., Karmakar, S., and Ansar, W. (2022). Advances and applications of bioremediation: network of omics, system biology, gene editing and nanotechnology. *Environmental Informatics: Challenges and Solutions*. 167-199.

17. Chaudhary, P., Ahamad, L., Chaudhary, A., Kumar, G., Chen, W. J., and Chen, S. (2023). Nanoparticle-mediated bioremediation as a powerful weapon in the removal of environmental pollutants. *Journal of Environmental Chemical Engineering*. 11(2): 109591.

18. Doran, J.W., Liebig, M.A., Santana, D.P., 1998. Soil health and global sustainability. In: Proceedings of the 16th World Congress of Soil Science. Montepellier, France, 20–26 August 1998.

19. Doran, J.W., Sarrantonio, M., Liebig, M., 1996. Soil health and sustainability. In: Sparks, D.L. (Ed.), Advances in Agronomy, Vol. 56, Academic Press, San Diego, CA, USA, pp. 1–54.

20. Doran. J W. (2024). Soil health and global sustainability: translating science into practice. *Agriculture, Ecosystems and Environment.* **88** (2002) :119–127

21. El-Kady, M.M., Ansari, I., Arora, C., Rai, N., Soni, S., Verma, D.K., Singh, P. and Mahmoud, A.E.D., 2023. Nanomaterials: A comprehensive review of applications, toxicity, impact, and fate to environment. *Journal of Molecular Liquids*. **370**: 121046.

22. El-Sayed, S. M., & Youssef, A. M. (2023). Ecofriendly biodegradable nanocomposite materials and their

recent use in food packaging applications: a review. Sustainable Food Technology. **1**(2): 215- 227.

23. Emerich, D. F., and Thanos, C. G. (2003). Nanotechnology and medicine. *Expert opinion on biological therapy*. **3**(4): 655-663.
24. Fang, Y., and Guo, Y. (2018). Copper-based non-precious metal heterogeneous catalysts for environmental remediation. *Chinese Journal of Catalysis*, *39*(4), 566-582.
25. Fazelian, N., and Yousefzadi, M. (2022). Nano-biofertilizers for enhanced nutrient use efficiency. In Nano-enabled Agrochemicals in Agriculture (pp. 145-158). Academic Press.
26. Gaur, N., Flora, G., Yadav, M., and Tiwari, A. (2014). A review with recent advancements on bioremediation-based abolition of heavy metals. Environmental Science: Processes & Impacts, 16(2), 180-193.
27. Guerra, F. D., Attia, M. F., Whitehead, D. C., and Alexis, F. (2018). Nanotechnology for environmental remediation: materials and applications. *Molecules*. *23*(7): 1760.
28. Guerra, F.D., Attia, M.F., Whitehead, D.C. and Alexis, F., (2018). Nanotechnology for environmental remediation: materials and applications. Molecules. **23**(7): 1760.
29. Iavicoli, I., Leso, V., Ricciardi, W., Hodson, L. L., and Hoover, M. D. (2014). Opportunities and challenges of nanotechnology in the green economy. *Environmental health*. **13**: 1-11.
30. Ibrahim, R. K., Hayyan, M., AlSaadi, M. A., Hayyan, A., and Ibrahim, S. (2016). Environmental application of nanotechnology: air, soil, and water. *Environmental Science and Pollution Research*. **23**: 13754-13788.
31. Kaphle, A., Nagaraju, N., and Daima, H. K. (2018). Contemporary developments in nanobiotechnology: applications, toxicity, sustainability, and future perspective. In *Nanobiotechnology* (pp. 1-34). CRC Press.
32. Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61, 4–10.
33. Karn, B., Kuiken, T., and Otto, M. (2009). Nanotechnology and in situ remediation: a review of the benefits and potential risks. *Environmental health perspectives*. **117**(12): 1813-1831.
34. Khin, M. M., Nair, A. S., Babu, V. J., Murugan, R., and Ramakrishna, S. (2012). A review on nanomaterials for environmental remediation. *Energy & Environmental Science*. **5**(8): 8075-8109.
35. Kishore, S., Malik, S., Shah, M.P., Bora, J., Chaudhary, V., Kumar, L., Sayyed, R.Z. and Ranjan, A., 2024. A comprehensive review on removal of pollutants from wastewater through microbial nanobiotechnology-based solutions. *Biotechnology and Genetic Engineering Reviews*. **40**(4): 3087-3112.

36. Kour, D., Khan, S.S., Kumari, S., Singh, S., Khan, R.T., Kumari, C., Kumari, S., Dasila, H., Kour, H., Kaur, M. and Ramniwas, S., 2024.Microbial nanotechnology for agriculture, food, and environmental sustainability: Current status and future perspective. *Folia Microbiologica*, 1-30.

37. Kumar, S. R., and Gopinath, P. (2017). Nano-bioremediation applications of nanotechnology for bioremediation. *Handbook of advanced industrial and hazardous wastes management*. 27-48.

38. Mallikarjunaiah, S., Pattabhiramaiah, M., and Metikurki, B. (2020). Application of nanotechnology in the bioremediation of heavy metals and wastewater management. *Nanotechnology for food, agriculture, and environment*. 297-321.

39. Mathur, S., Singh, D., and Ranjan, R. (2022). Remediation of heavy metal (loid) contaminated soil through green nanotechnology. *Frontiers in Sustainable Food Systems*. **6**: 932424.

40. McNeil, S. E. (2005). Nanotechnology for the biologist. *Journal of leukocyte biology*. **78**(3): 585-594.

41. Mukhopadhyay, R., Sarkar, B., Khan, E., Alessi, D.S., Biswas, J.K., Manjaiah, K.M., Eguchi, M., Wu, K.C., Yamauchi, Y. and Ok, Y.S., (2022). Nanomaterials for sustainable remediation of chemical contaminants in water and soil. *Critical Reviews in Environmental Science and Technology*. **52**(15): 2611-2660.

42. Nasrollahzadeh, M., Sajadi, S. M., Sajjadi, M., and Issaabadi, Z. (2019). An introduction to nanotechnology. In *Interface science and technology* (Vol. 28, pp. 1-27). Elsevier.

43. Otto, M., Floyd, M., & Bajpai, S. (2008). Nanotechnology for site remediation. *Remediation Journal: The Journal of Environmental Cleanup Costs, Technologies & Techniques*. **19**(1): 99-108.

44. Pachchigar, K. P., Dharajiya, D. T., Jani, S. N., Songara, J. N., and Dave, G. S. (2022). Mechanisms and Applications of Nanopriming: New Vista for Seed Germination. *Miniaturized Analytical Devices: Materials and Technology*, 261-277.

45. Sangeetha, J., Mundaragi, A., Thangadurai, D., Maxim, S.S., Pandhari, R.M. and Alabhai, J.M., 2019. Nanobiotechnology for agricultural productivity, food security and environmental sustainability. *Nanotechnology for Agriculture: Crop Production & Protection*, 1-23.

46. Shafiei-Masouleh, S.-S. Use of magnetic nano-chitosan as bio-fertilizer to reduce production period in three cyclamen cultivars. J. Soil Sci. Plant Nutr. 2021. 22: 281–293.

47. Shah, G.M.; Amin, M.; Shahid, M.; Ahmad, I.; Khalid, S.; Abbas, G.; Imran, M.; Naeem, M.A.; Shahid, N. Toxicity of ZnO and Fe2O3 nano-agro-chemicals to soil microbial activities, nitrogen utilization, and associated human health risks. Environ. Sci. Eur. 2022. **34**:106

48. Shahi, M. P., Kumari, P., Mahobiya, D., and Shahi, S. K. (2021). Nano-

bioremediation of environmental contaminants: applications, challenges, and future prospects. *Bioremediation for environmental sustainability*. 83-98.

49. Shahi, M.P., Kumari, P., Mahobiya, D. and Shahi, S.K., (2021). Nano-bioremediation of environmental contaminants: applications, challenges, and future prospects. *Bioremediation for environmental sustainability*, 83-98.

50. Shakoor, N.; Adeel, M.; Nadeem, M.; Abdullah Aziz, M.; Zain, M.; Hussain, M.; Azeem, I.; Xu, M.; Ahmad, M.A.; Rui, Y. Exploring the Effects of Iron Nanoparticles on Plants: Growth, Phytotoxicity, and Defense Mechanisms. In Nanomaterials and Nanocomposites Exposures to Plants, Smart Nanomaterials Technology; Husen, A., Ed.; Springer Nature: Singapore, 2023; pp. 209–226

51. Sharma, A.; Patel, S.; Menghani, E. Synthesis, application and prospects of nano-biofertilizers: A reappraisal. J. Phytol. Res. 2021. 34: 79–85.

52. Sharma, R.; Malaviya, P. Ecosystem Services and Climate Action from a Circular Bioeconomy Perspective. Renew. Sustain. Energy Rev. 2023. 175: 113164.

53. Shcherbakova, E.N.; Shcherbakov, A.V.; Andronov, E.; Gonchar, L.N.; Kalenska, S.; Chebotar, V.K. Combined pre-seed treatment with microbial inoculants and Mo nanoparticles changes composition of root exudates and rhizosphere microbiome structure of chickpea (*Cicer arietinum* L.) plants. Symbiosis 2017. 73: 57–69.

54. Sohail, M. I., Waris, A. A., Ayub, M. A., Usman, M., ur Rehman, M. Z., Sabir, M., and Faiz, T. (2019). Environmental application of nanomaterials: a promise to sustainable future. In *Comprehensive analytical chemistry* (Vol. 87, pp. 1-54). Elsevier.

55. SRUSHTI JOSHI, SUMEET JANI, BHAVESH JANI. (2024). Advancements in Nano Packaging Technologies: Revolutionizing Food Preservation and Safety. BioThink, **1**(2): 119-130.

56. Thirunavukkarasu, A., Nithya, R., and Sivashankar, R. (2020). A review on the role of nanomaterials in the removal of organic pollutants from wastewater. *Reviews in Environmental Science and Bio/Technology*. **19**(4): 751-778.

57. Tripathi, A., and Prakash, S. (2022). Nanobiotechnology: Emerging trends, prospects, and challenges. *Agricultural Nanobiotechnology*. 1-21.

58. Tripathi, A., and Prakash, S. (2022). Nanobiotechnology: Emerging trends, prospects, and challenges. *Agricultural Nanobiotechnology*, 1-21.

59. Vedamurthy, A.B.; Bhattacharya, S.; Das, A.; Shruthi, S.D. Exploring nanomaterials with rhizobacteria in current agricultural scenario. In Advances in Nano-Fertilizers and Nano-Pesticides in Agriculture; Elsevier: Amsterdam, The Netherlands, 2021; pp. 487–503.

60. Yadav, K. K., Singh, J. K., Gupta, N., and Kumar, V. J. J. M. E. S. (2017). A review of nanobioremediation

technologies for environmental cleanup: a novel biological approach. *J Mater Environ Sci*ence. **8(**2): 740-757.

61. Yadav, K. K., Singh, J. K., Gupta, N., and 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**.**

62. Yadav, K. K., Singh, J. K., Gupta, N., and Kumar, V. J. J. M. E. S. (2017). A review of nanobioremediation technologies for environmental cleanup: a novel biological approach. *J Mater Environ Sci*ence. **8**(2): 740-757.