



Bioremediation of Waste Water by Phytoremediation: A Review

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ABSTRACT

Bioremediation is an eco-friendly and cost-effective approach for treating wastewater contaminated with organic pollutants, heavy metals, and other hazardous substances. Phytoremediation of waste water utilizes green plants and associated microbial communities to remove, stabilize, or degrade contaminants from water, soil and sediments. This study also explores integration of nanotechnology and enzymatic approaches with bioremediation, enhancing the efficiency of pollutant degradation. Green-synthesized nanoparticles and microbial enzymes offer promising solutions for the removal of dyes, pharmaceuticals and complex organic pollutants. Bioremediation faces challenges such as variable environmental conditions, limited pollutant tolerance, and slower treatments rates compared to conventional methods. Genetic engineering microbial consortia and constructed wetland systems are improving the effectiveness and scalability of these techniques. Bioremediation is a sustainable and innovative strategy for waste water management that contributes significantly to environmental protection and water resource conservation. This review highlights mechanisms, applications and recent advancements in phytoremediation for waste water treatment processes such as phytoextraction, rhizofiltration, phytostabilization and phytotransformation play a significant role in pollutant removal through plant uptake, adsorption and metabolic transformation. Aquatic macrophytes such as *Eichhornia crassipes*,



Typha latifolia, and *Lemna minor* have demonstrated high efficiency in removing nutrients, heavy metals, and organic compounds from contaminated water systems.

Introduction

Phytoremediation is a biotechnological method that efficiently eliminates metal and metalloid contaminants, with particular environmental applications (Gu, Pengcheng, et al. 2018). Green technology enables the transfer of metalloids and hazardous metals from solutions or adsorption to green plants for detoxification and stabilization (Gu, ShuYing, et al. 2008). Phytoremediation is an environmentally sustainable and cost-effective technique that uses plants to remove or stabilize pollutants in water, sediments, or soil. This approach has several advantages over traditional remediation methods, including lower costs, maintenance, worker exposure, and aesthetic appeal (Sharma and Yeh, 2020). Hyper-accumulators are plants that can efficiently remove metals through accumulation. According to Cho-Ruk et al. (2006) and Smolyakov, Boris S. (2012) plants may remove pollutants from water by absorption or transpiration. Aquatic plant species that can accumulate heavy metals (HM). Plants absorb many hazardous substances and nutrients, but only a tiny percentage are harmful, and when pollution levels increase, plants are injured or die. Water treatment technologies, including physical, chemical, and biological methods, are costly and limited to small amounts of wastewater (Rezania, Shahabaldin, et al. 2015). Phytoremediation is an alternative wastewater treatment method that uses various plants to purify wastewater and remove dangerous chemicals. Plants such as water hyacinth (*Eichhornia crassipes*), cattail (*Typha latifolia*), and duckweed (*Lemna minor*) absorb or sequester contaminants, particularly nutrients and heavy metals. Phytoremediation can reduce nitrogen, phosphorus, and trace metals in wastewater, often as part of a constructed wetland system, and uses microbes found in higher living plants to remove contaminants from water. In situ bioremediation is also known as phytoremediation. Rooted plants and trees can absorb, digest, and detoxify metal and organic chemical contaminants (Ojha, Nishita, et al., 2021). Phytoremediation technology can target heavy metals, aromatic and chlorinated solvents, petroleum hydrocarbons, pesticides, explosives, crude oil, and other contaminants. This strategy utilizes plant interactions in polluted locations, including physical, biochemical, biological, chemical, and microbiological interactions, to mitigate the hazardous effects of pollutants. Disposing of waste goods and residuals into natural water bodies can harm aquatic ecosystems and pose serious dangers to human health. Phytoremediation is a potential approach for removing and recovering surplus nutrients from contaminated waters. The use of aquatic plants in phytoremediation of wastewater is advantageous since



they have enormous potential to absorb and destroy contaminants (Mustafa, Hauwa M., and Gasim Hayder,2021)

Mechanisms of Phytoremediation

Phyto-extraction

Phytoextraction, also known as phytoaccumulation, occurs when metal pollutants concentrate and stabilize in the higher parts of plants. Phytoextraction, alternatively referred to as phytoaccumulation, phytoabsorption, or phytosequestration, involves the extraction of pollutants from soil or water through plant roots, followed by their translocation and accumulation in above-ground biomass, specifically the shoots, which are then harvested (Muthusaravanan et al., 2018).Metals are absorbed by the roots and transferred to the upper parts of the plant, thereby removing heavy metal pollution from the soil by selecting plants that absorb and concentrate toxic metals in different parts of the plant.

Phyto-filtration/Rhizofiltration

Phytofiltration, often referred to as rhizofiltration, involves the adsorption or precipitation of pollutants from a solution onto plant roots or their absorption into roots within the root zone (Khan et al., 2019).This process pertains to the creation of certain compounds in the roots that facilitate the adsorption of pollutants, as particular plants may possess several phytochelatins to enhance the binding ability of contaminants, such as metal ions (Singh, N. P., and Anita Rani Santal, 2015).The primary rhizofiltration processes are precipitation and plant absorption of soil and water, and contaminants are only allowed to enter the root system during this procedure. The root system in rhizofiltration retains several heavy metals (Dietrich, Andrea M., and Gary A. Burlingame,2014).Rhizofiltration promotes rapid root growth and requires less time for cleaning (Sarkar et al. 2011).

Phyto-volatilization

phytoremediation technique is also called phytovolatilization uses plants to absorb contaminants and change them into volatile molecules released into atmosphere through transpiration and metabolic activities in their original or modified forms (Ali, Hazrat, Ezzat Khan, and Ikram Ilahi.,2019). Contaminants are absorbed by the roots, moved to higher plant parts, and released into the atmosphere as volatiles through the leaves. Bioremediation for Sustainable environmental clean-up includes diffusing volatile toxins and leaves' open stomata in a less hazardous form. This entails the removal of contaminants in both gaseous and safer forms. Transpiration is the mechanism by which water vapor



exits leaf surfaces via stomata into the atmosphere. Certain enzymes or genes enable many plant species with extensive root systems to absorb and metabolize pollutants (Muthusaravanan et al. 2018).

Phyto-stabilization

Phytostabilization, also known as phytoimmobilization, employs plants to diminish the mobility and bioavailability of pollutants, thereby preventing their leaching into groundwater or entry into the food chain through processes such as root adsorption or the creation of insoluble compounds in the root zone (Sarwar et al., 2017; Khan et al., 2019). Phytostabilization stabilizes heavy metals, allowing for appropriate absorption and precipitation through soil, sediment, and sludge (Dietrich, Andrea M., and Gary A. Burlingame, 2015). The contaminants are absorbed and accumulated by roots or accumulate inside the rhizosphere.

Phyto-transformation

Pollutants stored by plants are broken down through metabolic processes. The action of compounds generated by plants, such as enzymes, is referred to as phyto-transformation or phytodegradation, which helps eliminate organic pollutants, such as chlorinated solvents and pesticides, and break down complex organic compounds into simpler ones. Plants passively absorb organic contaminants because they lack active transporters. Rhizodegradation involves the breakdown of contaminants in the rhizosphere. Polyaromatic hydrocarbons and polychlorinated biphenyls are examples of organic molecules that rhizospheric bacteria may mineralize. Plants and bacteria produce enzymes such as nitro-reductase, dehalogenase, laccase peroxidase and others that can degrade hazardous xenobiotics (Cherian, Sam, and M. Margarida Oliveira, 2005). Contaminants are absorbed by roots, moved to higher plant parts, and released into the atmosphere as volatiles through the leaves. Bioremediation for Sustainable Environmental Clean-up includes diffusing volatile toxins via open stomata in a less hazardous form. This entails removing contaminants in both gaseous and safer forms.

Table of Bioremediation by phytoplant

S.NO	Plant	Waste water	Treated material	References
1	<i>Eichhornia crassipes</i>	mines wastewater	toxic chromium(Cr),(TDS),	Balamoorthy, Dhivya, et al(2022)



			(COD), (BOD),	
2	<i>Mimosa Pudica</i>	Polluted wastewater	heavy metals like Cd, Pb and Cu	Balamoorthy, Dhivya, et al.(2022)
3	<i>Salvinia molesta and Pistia stratiotes</i>	biologicalwastewater treatment polluted water	nitrates, phosphates, heavy metals	Mustafa,Hauwa M. ,and Gasim Hayder(2021)
4	<i>Oenanthe javanica</i>	livestock wastewater	nitrogen, ammonium nitrogen,nitrite nitrogen,and chemical oxygen demand	Sun, Linhe, et al.(2021)
5	<i>Eichhornia crassipes</i>	industrial wastewater	cellulose, hemicellulose and lignins	Koley, Apurba, et al.(2024)
6	<i>S.molesta,A.f iliculoids and Duckweed</i>	wastewater	phosphates andnitrates concentrations	Matsa, M. M., T. Dube, and O. Mupepi.(2025)
7	<i>Dracaena sanderiana,E ichornia crassipes,col ocaasia esculenta</i>	wastewater	COD),(BOD), nitrogen,ammonium phosphorus	Nguyen, Bich Thi Ngoc, Mitthan Lal Kansal, and Hai-Hoa Nguyen(2024)
8	<i>Vetiveria zizanioides</i>	Tannery industry effluent	suspended solids,Dissolved	Zereen, Ismot, et al.(2024)



			Solids,COD and BOD, Lead	
9	<i>Typha latifolia</i> , <i>E.Cr assipes</i>	Cd and As wastewater	Cd and As wastewater	Khan, Shehryar, et al(2024)
10	<i>Eichhornia crassipes</i> (E AC), <i>Pistia stratiotes</i> (W L), and <i>Arundo donax</i> (GR)	combined wastewater	Organic degradation, metal uptake, and pH stabilization.	Zeb, Bibi Saima, et al(2024)

Bioremediation by green nano-particles

Nanotechnology has considerable promise for the development of next-generation wastewater treatments, with the ability to supplant current wastewater treatment technologies (Rathod, Shreya, et al,2024).Nanotechnology offers financial benefits to the industry through various means, including the employment of microorganisms in nanoparticle synthesis, the advancement of green biotechnology for environmentally friendly manufacturing, and the reduction of pricing(Gupta, Kumar, Sailwal, and Pratyosh Shukla,2022).Nanotechnology holds considerable promise for the development of next-generation wastewater treatments ability to wastewater treatment technologies(Rathod, Shreya, et al,2024).Nanomaterials have strong reactivity, functionalization, a large specific surface area, size-dependent properties, and other features that make them excellent for wastewater treatment(Thangavelu, Lakshmi, et al,2022).Nanoparticles have unique features that can be used to clean polluted water, and their combination with green chemistry offers a way to a cleaner, more sustainable future for our world. This survey addresses the significance of the worldwide wastewater issue and the application of nanoparticles in heavy metal remediation and wastewater treatment(Thangavelu, Lakshmi, and Geetha Royapuram Veeraragavan, 2022).Brown seaweed extracts *Padina pavonica*, *Colpomenia sinuosa* and



Petalonia fascia were used as ferric chloride reductants resulting in the formation of iron oxide nanoparticles. Seaweed extracts can be used as an alternative safe bioremediation method for wastewater, with iron oxide nanoparticles reducing nitrogen and phosphorus and enhancing phytoremediation methods, highlighting the potential of modern biotechnology(El-Sheekh et al., et al,2021).

Table of Bioremediation by green nano-particles

S.NO	Plant	Nano particles	Waste water	Treated material	References
1	<i>Calotropis gigantea</i> (Apple of Sodom) leaf extract	CuO and ZnO nanoparticles.	wastewater treatment	agricultural enhancement and antibacterial activity.Dye activity	Velusamy, Sangeetha, et al(2024)
2	Opuntia peel extract	magnetic iron nanoparticles (O-FeNPs)	wastewater treatment	COD,BOD, total kjelidahl nitrogen (TKN), (TN), ammonia (NH ₃ ⁺), phosphate (PO ₄ ³⁻), total suspended solid (TSS), and nitrate (NO ₃ ⁻),	Ahmed, Hussein Mohamed, et al(2024)
3	<i>Jasminum sambac</i> flower extract	CuO NPs	wastewater treatment	methylene blue	Velmurugan, G., et al.(2024)
4	<i>Azadirachta indica</i>	oxide/reduced graphene oxide(FeNPs/	Waste water	methylene blue dye wastewater	Akhtar, Muhammad Shahbaz, et



		rGO) nanocomposites			al(2024)
5	<i>Pistia stratiotes</i>	CuO NPs	Textile industry wastewater	TDS, Nitrate, Chloride, DO and BOD	Nair, Vaidehi A., et al (2024)
6	<i>Malachra alceifolia</i> (Ma)	Ma-Ag NPs	Waste water treatment	<i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i>	Losetty, Venkatramana, et al.(2024)
7	spinach leaf extracts	ZnO NPs	paper mill effluent	COD in wastewater,	Velmurugan, G., et al(2024)
8	<i>Eucalyptus</i> leaf extract	ZnO NPs	groundwater contamination	calcium ions (Ca ²⁺)removal	Aoun, Abderrazek, Omar Ben Mya, and Djamel Barani.(2024)
9	<i>Eucalyptus globulus</i> leaves	Fe ₃ O ₄ and magnetization coupling	water saline well water treatment	water salinity reduction	Elaoud, Anis, et al.(2024)
10	<i>Ocimum basilicum</i>	ZnO NPs	Pharmaceutical wastes	removal of paracetamol (PCM)	Solmaz, Alper, Talip Turna, and Ayşe



					Baran(2024)
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Bioremediation of waste water by enzyme

Bioremediation employs living organisms to mitigate the hazardous effects of pollutants such as heavy metals, dyes, petroleum waste, and oil spills. Enzymes are biocatalysts that facilitate certain hydrolytic processes in living organisms, playing crucial roles in sectors such as medicine, food, detergents, leather, paper, and textiles. Enzymes are more cost-effective, stable, and reusable. They are environmentally sustainable and represent the most appropriate alternative owing to their agricultural importance (Sarwan, Jyoti, and Nazim Uddin,2024). Bacterial species such as *E. coli*, *Pseudomonas spp.*, *Bacillus pp.*, and *Staphylococcuspp.* can eliminate dyes and heavy metals in soil samples. The plant and microbial degradation can impede processes at particular temperature and pH settings. Microbial strains can also degrade these toxic pigments. Oxygen facilitates aerobic decomposition. Microbial enzymes are crucial for fuel generation, especially in the manufacture of biofuels, such as bioethanol and biodiesel. Cellulases, proteases, and amylases are prevalent in the synthesis of bioethanol. They can also assist in mitigating environmental challenges, such as oil spills in marine ecosystems. Certain microorganisms, such as sulfur-reducing bacteria, function as biofertilizers Further studies are required to develop biosensors, biofuels, and bioremediation employing bacteria.

Table of Bioremediation of waste water by enzyme

S.NO	plant	Polluted water	enzyme	reduction	Reference
1	<i>Musa paradisiaca</i> , <i>Ananas comosus</i> , <i>Citrus sinensis</i> peels	textile waste water	protease, lipase, and amylase activity	BOD,COD,TDS,TSS), pH, and (DO) treatment.	Das, Shohag Chandra, et al.(2024)



2	<i>Saccharum officinarum</i>	agricultural wastes	enzymatic hydrolysis,	wastewater nitrogen removal	Zheng, Qi, et al.(2024)
3	<i>Brassica oleracea var. capitata</i>	industrial dyes and phenols	peroxidase,	industrial dyes and phenols	Mohammed, Weam Abdulwahhab, and Mohanad J. M- Ridha.(2024)
4	<i>Rhus vernicifera</i>	wastewater treatment,	Laccase enzymes	oxidation of phenolic and non-phenolic compounds,	Aghaee, Mehdi, et al.(2024)
5	<i>Euterpe oleracea, Ananas comosus</i>	effluents. Conventional wastewater	laccase enzyme	chemical removal	Golveia, Jhessica Cavalcante de Souza, et al(2024)
6	<i>Armoracia rusticana</i>	microflora found in groundwater	HRP enzyme	reduce phenolic shock	
7	<i>Solanum tuberosum</i> peel	Anthraquinone dye removal	Peroxidase	Free enzyme	Svetozarević, Milica, et al(2021)
8	<i>Trametes hirsuta</i>	pharmaceutical wastewater	laccases	elimination of	El Yagoubi, Younès, et



				pharmaceutical compounds	al.(2023)
9	<i>Aspergillus sclerotiorum</i>	high-fat dairy wastewater	lipases	lipolytic activity	de Moura Dickel, Jaïne Daiane, et al(2023)
10	<i>Musa paradisiaca</i> peel	textile dye removal.	polyphenol oxidase and peroxidase enzyme	textile dye removal.	Muhamad, Nisaporn, Piyasiri Soontornnon Sinchai, and Ubol Tansom,2023

Conclusion

Bioremediation of wastewater is a cost-efficient and environmentally sustainable approach to water contamination, and research and development can enhance bioremediation techniques to address the increasing problems of wastewater treatment in various industrial and environmental settings. Bioremediation of wastewater offers an eco-friendly, economical, and sustainable method for addressing water contamination. Bioremediation successfully eliminates organic contaminants, nutrients, heavy metals, and other hazardous chemicals from wastewater using the natural metabolic processes of microbes, plants, and fungi. Microbial bioremediation, phytoremediation, and enzymatic treatment provide varied treatments for urban and industrial wastewater pollutants. Bioremediation encounters obstacles such as the optimization of settings for peak microbial or plant efficacy, augmentation of contaminant tolerance, and assurance of uniform outcomes across various contaminants. Progress in genetic engineering, microbial consortium design, and engineered wetland systems is facilitating the development of more efficient and durable bioremediation techniques. It is essential to tackle the persistence of developing contaminants, such as pharmaceuticals and microplastics, necessitates innovative bioremediation approaches. Bioremediation coincides with sustainable water management



objectives, decreases chemical inputs, reduces treatment costs, and adds viable elements to integrated wastewater treatment systems globally. These biological solutions can substantially enhance worldwide initiatives to save water supplies and maintain aquatic ecosystems.

Rrferences

- Gu, P., Zhang, S., Li, X., Wang, X., Wen, T., Jehan, R., ... & Wang, X. (2018). Recent advances in layered double hydroxide-based nanomaterials for the removal of radionuclides from aqueous solutions. *Environmental pollution*, 240, 493-505.
- Gu, S., Yang, M., Yu, T., Ren, T., & Ren, J. (2008). Synthesis and characterization of biodegradable lactic acid-based polymers via chain extension. *Polymer International*, 57(8), 982-986.
- Ladislav, S., El-Mufleh, A., Gérente, C., Chazarenc, F., Andrès, Y., & Béchet, B. (2012). Potential of aquatic macrophytes as bioindicators of heavy metal pollution in urban stormwater runoff. *Water, Air, & Soil Pollution*, 223(2), 877-888.
- Cho-Ruk, K., Kurukote, J., Supprung, P., & Vetayasuporn, S. (2006). Perennial plants in the phytoremediation of Pb-contaminated soils.
- Smolyakov, B. S. (2012). Uptake of Zn, Cu, Pb, and Cd by water hyacinth in the initial stage of water-system remediation. *Applied geochemistry*, 27(6), 1214-1219.
- Rezaia, S., Ponraj, M., Talaiekhosani, A., Mohamad, S. E., Din, M. F. M., Taib, S. M., ... & Sairan, F. M. (2015). Perspectives of phytoremediation using water hyacinth for the removal of heavy metals, organic and inorganic pollutants in wastewater. *Journal of environmental management*, 163, 125-133.
- Ojha, N., Karn, R., Abbas, S., & Bhugra, S. (2021, June). Bioremediation of industrial wastewater: A review. In *IOP Conference Series: Earth and Environmental Science* (Vol. 796, No. 1, p. 012012). IOP Publishing.
- Mustafa, H. M., & Hayder, G. (2021). Recent studies on the applications of aquatic weed plants in the phytoremediation of wastewater: A review article. *Ain Shams Engineering Journal*, 12(1), 355-365.



- Ghosh, M., & Singh, S. P. (2005). A review on phytoremediation of heavy metals and utilization of its by-products. *Asian J Energy Environ*, 6(4), 18.
- Muthusaravanan, S., Sivarajasekar, N., & Vivek, J. S., Paramasivan, T., Naushad, M., Prakashmaran, J., ... & Al-Duaij, O. K. (2018). Phytoremediation of heavy metals: mechanisms, methods, and enhancements. *Environmental chemistry letters*, 16(4), 1339-1359.
- Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications, and toxicities. *Arabian journal of chemistry*, 12(7), 908-931.
- Singh, N. P., & Santal, A. R. (2015). Phytoremediation of heavy metals: the use of green approaches to clean the environment. In *Phytoremediation: Management of Environmental Contaminants, Volume 2* (pp. 115-129). Springer International Publishing.
- Dietrich, A. M., & Burlingame, G. A. (2015). Critical review and rethinking of USEPA secondary standards for maintaining organoleptic quality of drinking water. *Environmental science & technology*, 49(2), 708-720.
- Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity and bioaccumulation. *Journal of chemistry*, 2019(1), 6730305.
- Muthusaravanan, S., Sivarajasekar, N., & Vivek, J. S., Paramasivan, T., Naushad, M., Prakashmaran, J., ... & Al-Duaij, O. K. (2018). Phytoremediation of heavy metals: mechanisms, methods, and enhancements. *Environmental chemistry letters*, 16(4), 1339-1359.
- Cherian, S., & Oliveira, M. M. (2005). Transgenic plants in phytoremediation: recent advances and new possibilities. *Environmental science & technology*, 39(24), 9377-9390.
- Balamoorthy, D., Velusamy, P., Rath, B., TR, P., & Kabeto, J. (2022). Removal of heavy metals from wastewater using phytoremediation technology. *Journal of Civil Engineering, Science and Technology*, 13(1), 23-32.
- Mustafa, H. M., & Hayder, G. (2021). Recent studies on the applications of aquatic weed plants in the phytoremediation of wastewater: A review article. *Ain Shams Engineering Journal*, 12(1), 355-365.
- Sun, L., Zhao, H., Liu, J., Li, B., Chang, Y., & Yao, D. (2021). A new green model for bioremediation and resource utilization of livestock wastewater. *International Journal of Environmental Research and Public Health*, 18(16), 8634.



- Koley A, GhoshThakur R., Das K., Gupta N., Banerjee A, Show B-K, ... & Balachandran, S. (2024). Growth dynamics and nutrient removal from biogas slurry using water hyacinth. *Sustainability*, 16(11), 4450.
- Matsa, M. M., Dube, T., & Mupepi, O. (2025). Effectiveness of phytoremediation in waste-water treatment: a case study of Karoi water supply station, Zimbabwe. *International Journal of Environmental Science and Technology*, 22(8), 7013-7024.
- Nguyen, B. T. N., Kansal, M. L., & Nguyen, H. H. (2024). Experimental Study of Phytoremediation. *Innovation in Smart and Sustainable Infrastructure, Volume 2: Select Proceeding of ISSI 2022*, 2, 121.
- Zereen, I., Hossain, M. S., Islam, M. M., & Husna, A. (2024). Bioremediation of industrial wastewater using hydroponically planted vetiver. *J Agr Environ*, 17(1), 32-5.
- Khan, S., Kamal, M., Noor, S., & Afzal, S. M. (2024). Assessment of heavy metals and their treatment through phytoremediation in groundwater along River Kabul in district Charsadda. *Front. Environ. Sci.*, 12, 1392892.
- Zeb, B. S., Mahmood, Q., Irshad, M., Zafar, H., & Wang, R. (2025). Sustainable treatment of combined industrial wastewater: Synergistic phytoremediation with biofilm wetland plants of *Eichhornia crassipes*, *Pistia stratiotes*, and *Arundo donax* *International Journal of Phytoremediation*, 27(1), 128-134.
- Rathod, S., Preetam, S., Pandey, C., & Bera, S. P. (2024). Exploring synthesis and applications of green nanoparticles and the role of nanotechnology in wastewater treatment. *Biotechnology Reports*, 41, e00830.
- Gupta, G. K., Dixit, M., Kapoor, R. K., & Shukla, P. (2022). Xylanolytic enzymes in pulp and paper industry: new technologies and perspectives. *Molecular biotechnology*, 64(2), 130-143.
- Gupta, G. K., Sailwal, M., & Shukla, P. (2024). Sustainable nanotechnology based techniques for mitigating the pollutants from pulp and paper industry. *ACS omega*, 9(49), 47904-47919.
- Rathod, S., Preetam, S., Pandey, C., & Bera, S. P. (2024). Exploring synthesis and applications of green nanoparticles and the role of nanotechnology in wastewater treatment. *Biotechnology Reports*, 41, e00830.
- Thangavelu, L., Veeraragavan, G. R., Mallineni, S. K., Devaraj, E., Parameswari, R. P., Syed, N. H., ... & Bhawal, U. K. (2022). [Retracted] Role of nanoparticles in environmental remediation: an insight into heavy metal pollution from dentistry. *Bioinorganic chemistry and applications*, 2022(1), 1946724.



- Thangavelu, L., & Veeraragavan, G. R. (2022). A survey on nanotechnology-based bioremediation of wastewater. *Bioinorganic chemistry and applications*, 2022(1), 5063177.
- El-Sheekh, M. M., El-Kassas, H. Y., Shams El-Din, N. G., Eissa, D. I., & El-Sherbiny, B. A. (2021). Green synthesis, characterization applications of iron oxide nanoparticles for antialgal and wastewater bioremediation using three brown algae. *International Journal of Phytoremediation*, 23(14), 1538-1552.
- Velusamy, S., Kandasamy, K., Kuppusamy, M. R., Eswaramoorthy, D., Shanmugam, M., & Murugesan, M. (2024). Green-synthesized CuO and ZnO nanoparticles derived from *Calotropis gigantea* (Apple of Sodom): enhancing plant growth, efficient dye removal, and potent antibacterial applications. *Environmental Science and Pollution Research*, 31(32), 44995-45010.
- Ahmed, H. M., El-Khateeb, M. A., Mohamed, N. Y., Sobhy, N. A., & Fawzy, M. E. (2024). Evaluation of different natural waste materials as bio-coagulants for domestic wastewater treatment. *Desalination and Water Treatment*, 317, 100034.
- Velmurugan, G., Chohan, J. S., Paramasivam, P., & Maranan, R. (2024). Green synthesis of silver nanoparticles from southern *Eucalyptus globulus*: Potent antioxidants and photocatalysts for rhodamine B dye degradation. *Desalination and Water Treatment*, 320, 100687.
- Akhtar, M. S., Fiaz, S., Aslam, S., Chung, S., Ditta, A., Irshad, M. A., ... & Nakashima, Y. (2024). Green synthesis of magnetite iron oxide nanoparticles using *Azadirachta indica* leaf extract loaded on reduced graphene oxide and degradation of methylene blue. *Scientific reports*, 14(1), 18172.
- Nair, V. A., Sonali J, M. I., Kumar, P. S., Immaculate, C. A. R., Mythrayee, R., Gayathri, K. V., & Rangasamy, G. (2024). Nano-phytoremediation approach using *Pistia stratiotes*: biosynthesized copper nanoparticles for textile wastewater treatment and toxicity analysis. *Waste and Biomass Valorization*, 15(11), 6465-6477.
- Losetty, V., Dhanalakshmi, M., Devanesan, S., Alsalhi, M. S., Prabu, P., Yadav, C. H., ... & Park, S. H. (2024). Sustainable bioactive copper oxide nanoparticles for enhanced environmental remediation and biomedical solicitations: Experimental and molecular docking investigation. *Inorganic Chemistry Communications*, 170, 113338.
- Aoun, A., Ben Mya, O., & Barani, D. (2025). Green synthesis of zinc oxide nanoparticles using *Eucalyptus* leaf extract for effective calcium removal from groundwater. *Biomass Conversion and Biorefinery*, 15(8), 12581-12590.



- Elaoud, A., Mechi, A., Tlili, H., Ferhi, M., & Hassen, H. B. (2024). Green synthesis and characterization of magnetite nanoparticles using Eucalyptus globulus leaves for water treatment and agronomic valorization. *Environmental Monitoring and Assessment*, 196(9), 786.
- Solmaz, A., Turna, T., & Baran, A. (2024). Removal of paracetamol from aqueous solution with zinc oxide nanoparticles obtained by green synthesis from purple basil (*Ocimum basilicum* L.) waste. *Biomass Conversion and Biorefinery*, 14(9), 10771-10789.
- Sarwan, J., & Uddin, N. (2024). Enhanced production of microbial cellulases as an industrial enzyme-a short review. *Journal of Multidisciplinary Research Advancements*, 2(1), 59-70.
- Das, S. C., Khan, O., Khadem, A. H., Rahman, M. A., Bedoura, S., Uddin, M. A., & Islam, M. S. (2024). Evaluating the biocatalytic potential of fruit peel-derived eco-enzymes for sustainable textile wastewater treatment. *Results in Engineering*, 21, 101898.
- Mohammed, W. A., & M-Ridha, M. J. (2024). Extraction and purification techniques of the biocatalyst cabbage peroxidase enzyme to remove reactive dyes and bisphenol-A pollutants. *Results in Engineering*, 21, 101961.
- Aghae, M., Salehipour, M., Rezaei, S., & Mogharabi-Manzari, M. (2024). Bioremediation of organic pollutants by laccase-metal-organic framework composites: A review of current knowledge and future perspective. *Bioresource Technology*, 406, 131072.
- Golveia, J. C. D. S., Nunes, E. S., Bulhões, T. S., Oliveira, J. R. D., Cunha, L. C. D., Campos, L. C., ... & Schimidt, F. (2024). Amazon acai and pineapple residues induce the enzyme laccase in *pleurotus ostreatus*: Application to bisphenol a bioremediation. *Quimica Nova*, 48(1), e-20250009.
- Mirdamadian, S. H., Asad, S., Dastgheib, S. M. M., & Moghimi, H. (2024). Design of a two functional permeable reactive barrier for synergistic enzymatic and microbial bioremediation of phenol-contaminated waters: laboratory column evaluation: Enzymatic and microbial bioremediation of phenol in a bilayer permeable reactive barrier. *BMC microbiology*, 24(1), 252.
- El Yagoubi, Y., Lemieux, B., Segura, P. A., & Cabana, H. (2023). Characterization of laccases from *Trametes hirsuta* in the context of bioremediation of wastewater treatment plant effluent. *Enzyme and Microbial Technology*, 171, 110308.
- de Moura Dickel, J. D., Carvalho, J. K., Silveira, M. A. D., Menegotto dos Santos, P., Rodrigues, M. L. F., Fagundes-Klen, M. R., ... & da Rosa, M. F. (2023). *Aspergillus sclerotiorum* lipolytic activity and its application in bioremediation of high-fat dairy wastewater environments. *Environmental Science and Pollution Research*, 30(13), 35517-35527.



- Muhamad, N., Sinchai, P. S., & Tansom, U. (2023). Banana peel as bioremediation agent in textile dyes decolorization for wastewater management. *Biochemical Systematics and Ecology*, 106, 104582.
- Narayanan, M., Ali, S. S., & El-Sheekh, M. (2023). A comprehensive review on the potential of microbial enzymes in multipollutant bioremediation: Mechanisms, challenges, and future prospects. *Journal of Environmental Management*, 334, 117532.