INSIGHTS-JOURNAL OF
HEALTH AND REHABILITATION

INSIGHTS-JHR
INSIGHTS-JOURNAL OF HEALTH AND REHABILITATION

BIOTECHNOLOGICAL APPROACHES TO BIOREMEDIATION AND WASTEWATER TREATMENT: UTILIZING MICROBIAL AND ENZYMATIC STRATEGIES TO DEGRADE POLLUTANTS AND TOXIC SUBSTANCES: A REVIEW

Original Research

Sher Ali[1]*, Maliha Munawar[1]
[1]Institute of Molecular Biology and Biotechnology, University of Lahore, Pakistan.
Corresponding Author: Sher Ali, Institute of Molecular Biology and Biotechnology, University of Lahore, Pakistan, drkr1367@gmail.com

Acknowledgement: The authors would like to acknowledge the support of their respective institutions and thank all researchers whose work contributed to the development of this review. Special appreciation is extended to colleagues in environmental biotechnology and microbiology for their valuable insights.

Conflict of Interest: None	Grant Support & Financial Support: None

ABSTRACT

Background: Environmental pollution from industrial, agricultural, and municipal sources presents a significant threat to ecological and human health. As traditional wastewater treatment methods face limitations in cost, efficiency, and pollutant removal, biotechnological approaches have emerged as sustainable alternatives. Microbial and enzymatic bioremediation techniques offer the potential for targeted, eco-friendly degradation of a broad range of contaminants, including heavy metals, hydrocarbons, and synthetic chemicals.

Objective: This narrative review aims to explore recent advances in biotechnological and microbial approaches for bioremediation and wastewater treatment, with a focus on enzymatic catalysis, microbial consortia, and integrated treatment systems.

Main Discussion Points: Key mechanisms such as biosorption, enzymatic degradation, and microbial metabolism are discussed in detail. Special emphasis is placed on the roles of laccases, hydrolases, and oxidoreductases in the breakdown of persistent pollutants. The review also highlights innovations in enzyme engineering, CRISPR-based microbial enhancement, and nanotechnology to improve efficiency and environmental adaptability. Integrated treatment systems, including constructed wetlands and algae-based bioreactors, are reviewed as models for circular economy and resource recovery.

Conclusion: Biotechnological strategies hold transformative potential for pollution control and environmental restoration. However, challenges such as environmental variability, scalability, and regulatory limitations remain. Continued interdisciplinary research and the integration of emerging technologies are essential to optimize these systems for real-world applications.

Keywords: Bioremediation, Enzymatic degradation, Microbial consortia, Wastewater treatment, Synthetic biology, Nanotechnology.

INTRODUCTION

Environmental pollution remains one of the most pressing challenges confronting humanity in the 21st century, exerting profound consequences on ecological systems, public health, and socio-economic stability. Driven largely by industrialization, particularly in sectors such as textiles, cement production, and petroleum refining, pollution has emerged as a complex, multifactorial issue with global ramifications. These industries contribute significantly to the degradation of natural resources, collectively accounting for nearly half of all environmental damage worldwide (1). The adverse effects span multiple domains, including air, water, and soil contamination, each of which carries distinct yet interrelated risks for human populations and ecosystems. According to estimates from the World Health Organization, ambient air pollution alone leads to approximately 4.2 million premature deaths annually, largely attributable to cardiovascular and respiratory conditions (2,3). This alarming burden underscores the critical importance of addressing environmental pollution as a global health priority. Current understanding of industrial pollution reveals a well-documented link between manufacturing processes and the emission of hazardous substances such as carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and heavy metals. These pollutants not only deteriorate environmental quality but also contribute to the formation of secondary pollutants like ground-level ozone and particulate matter (PM2.5), which have been implicated in a range of chronic illnesses including asthma, chronic obstructive pulmonary disease, and certain cancers (4,5). While numerous regulatory interventions have been implemented at national and international levels to mitigate these effects, the persistence of pollution hotspots, particularly in low- and middle-income countries (LMICs), highlights the inadequacy of existing frameworks and the need for more context-specific, enforceable solutions (7).

One of the more disturbing dimensions of industrial pollution is the transboundary movement of hazardous waste. Developed countries often export waste to less economically developed nations, exploiting weaker regulatory environments and insufficient waste management infrastructure. This phenomenon has intensified environmental and public health burdens in receiving countries, where communities frequently lack the resources and political leverage to resist such practices (8). Consequently, the global distribution of pollution-related morbidity and mortality is skewed, with disproportionate impacts borne by vulnerable populations in resource-limited settings. Despite international agreements such as the Basel Convention aiming to regulate the movement of hazardous waste, enforcement remains inconsistent and loopholes persist. Although the scientific literature extensively documents the environmental and health impacts of industrial pollution, critical knowledge gaps remain. For instance, the long-term cumulative effects of low-dose exposure to mixed industrial pollutants are poorly understood. Likewise, the interactions between environmental pollutants and social determinants of health, such as income inequality, urbanization, and access to healthcare, remain underexplored. Furthermore, while many studies focus on individual pollutants or single-sector emissions, fewer investigations adopt a systems-based approach that examines the synergistic effects across multiple pollutants and industrial sources. These gaps hinder the formulation of effective, evidence-based policies capable of addressing the multifaceted nature of industrial pollution (9).

This review aims to critically synthesize recent literature on industrial pollution, with a particular focus on the environmental and health consequences associated with the textile, cement, and petroleum industries. It seeks to evaluate the scope and scale of pollution from these sectors, highlight existing mitigation strategies, and identify areas where further research and regulatory innovation are needed. Emphasis is placed on studies published in the past five years to ensure that the analysis reflects the most current scientific understanding and policy developments. In conducting this review, only peer-reviewed research articles, government reports, and international agency publications published have been included. The review prioritizes data-driven studies that examine pollution pathways, health outcomes, and policy interventions across different geographical settings. This approach enables a comprehensive and comparative analysis of how industrial pollution manifests globally and how different regions respond to it. The rationale for this review lies in the urgent need to consolidate fragmented evidence into a cohesive framework that can inform both policy and practice. While environmental science has made significant strides in measuring pollutant levels and tracking ecological damage, there remains a gap in translating these findings into actionable strategies, especially in LMICs where industrial expansion often outpaces regulatory oversight. Additionally, the review offers novel insights by integrating environmental science with public health perspectives, thereby fostering a more holistic understanding of the issue. It also underscores the ethical implications of pollution-related health disparities and the global responsibility to ensure environmental justice. By synthesizing current evidence, this review endeavors to contribute to a more nuanced and actionable understanding of industrial pollution and its far-reaching implications. In doing so, it aims to guide stakeholders—including policymakers, industry leaders, environmental scientists, and healthcare professionals—toward more effective, equitable, and sustainable solutions.

THEMATIC DISCUSSION

Treatment Methods

Traditional wastewater treatment systems, while widespread, are increasingly viewed as insufficient for modern environmental challenges. Conventional approaches, often based on activated sludge or physical-chemical treatments, suffer from high operational costs and inefficiencies, particularly in removing emerging contaminants like pharmaceuticals and persistent organic pollutants (POPs) (10). In addition to their limited effectiveness, these methods contribute to secondary pollution and generate large volumes of sludge that are difficult to manage. The limitations of traditional techniques have stimulated interest in biotechnological innovations that promise enhanced efficiency and ecological safety.

Applications

Biotechnological applications in wastewater treatment have expanded to include microbial and enzymatic systems capable of transforming pollutants into less harmful compounds. Microbial fuel cells, for example, simultaneously degrade organic pollutants and generate electricity, aligning with the dual goals of waste reduction and energy recovery (11). Similarly, Daphnia-based natural filtration systems and enzyme-assisted treatments are being integrated into wastewater infrastructure to complement conventional systems. These methods offer higher specificity, reduced sludge production, and potential for resource recovery, making them increasingly attractive for sustainable wastewater management.

Bioremediation and Wastewater Treatment

Bioremediation techniques employ biological organisms—especially bacteria, fungi, and plants—to detoxify contaminated environments. They can be divided into in situ and ex situ strategies, with each offering distinct advantages depending on the type and extent of pollution (12). While in situ bioremediation is less invasive and cost-effective, ex situ methods allow for greater control and faster degradation. Genetic modification of microbial species has further improved their pollutant-degrading capabilities, expanding the range of treatable contaminants from hydrocarbons to pharmaceuticals (12,13).

Difference between In Situ and Ex Situ Bioremediation

The practical choice between in situ and ex situ bioremediation depends on site conditions, cost, and pollutant characteristics. In situ approaches, such as bioventing and phytoremediation, maintain soil integrity and are suited for large-scale contamination. Ex situ methods, involving soil excavation and treatment in bioreactors, provide greater efficiency but at higher operational costs (14). Studies comparing the two show that while in situ methods are preferable for long-term ecological restoration, ex situ methods yield quicker results for concentrated pollutants (14,15).

Role of Microbes and Enzymes in Degradation

Microorganisms and their enzymes are fundamental to biodegradation processes. Enzymes such as oxidoreductases, hydrolases, and laccases facilitate the breakdown of complex pollutants like polyethylene and pharmaceuticals (16). Genetically engineered strains have shown improved efficiency in degrading polyethylene terephthalate (PET) and synthetic dyes, especially under varied environmental conditions. These findings underscore the importance of enzymatic versatility and environmental adaptability in bioremediation (16,17).

Factors Affecting Bioremediation Efficiency

Bioremediation success is influenced by microbial species, pollutant bioavailability, and environmental conditions such as pH, temperature, and nutrient levels. Studies indicate that Trichoderma species degrade PAHs optimally at 35°C and neutral pH, whereas sulfate-reducing bacteria function best under slightly acidic conditions (18). Microbial diversity also plays a role; sites with rich microbial communities often require fewer nutrient amendments, enhancing natural attenuation processes (19).

Microbial Approaches to Bioremediation

Recent advances have identified specific microbial consortia capable of degrading complex pollutants. These include mixed bacterial and fungal communities, which perform better than individual strains due to metabolic synergy (20). Algae such as *Chlorella sp.* and cyanobacteria like *Arthrospira platensis* effectively remove heavy metals and pharmaceuticals from wastewater (20,21). Omics-based studies further enable targeted selection of strains for specific bioremediation tasks (21).

Bacterial Bioremediation

Bacteria such as *Pseudomonas*, *Acinetobacter*, and *Bacillus* species dominate bacterial bioremediation due to their metabolic flexibility. These species exhibit high removal efficiencies for hydrocarbons, heavy metals, and pesticides. For example, *Pseudomonas citri* and *Acinetobacter* consortia removed over 91% of hydrocarbons in contaminated soils (22). Metagenomic analysis helps identify key functional genes involved in biodegradation, improving strain selection and process optimization (23).

Fungal Bioremediation

Fungi, particularly white-rot fungi like *Trametes versicolor* and *Phanerochaete chrysosporium*, are effective in degrading xenobiotics and synthetic dyes. These fungi utilize ligninolytic enzymes such as peroxidases and laccases, with some systems achieving 90% decolorization of textile dyes (24). Their ability to form symbiotic relationships with plants enhances heavy metal phytoextraction, further broadening their application in soil and wastewater treatment.

Algal Bioremediation

Microalgae contribute to nutrient and heavy metal removal through biosorption and bioaccumulation. Species such as *Chlorella sorokiniana* and *Tetradesmus reginae* have shown efficacy in wastewater treatment, especially when co-cultivated or immobilized (25). Their biomass can also be converted into biofuels or fertilizers, promoting circular bioeconomy goals. Despite high efficacy, scalability and cost remain significant challenges.

Co-metabolism and Consortia

Microbial consortia enable co-metabolism, enhancing pollutant degradation through shared metabolic pathways. These communities exhibit synergistic interactions that improve breakdown efficiency of complex contaminants like PAHs and phthalates (26). Engineered consortia are being developed to further enhance these effects, though issues like microbial competition and environmental stressors require further investigation.

Enzyme Engineering for Enhanced Activity

Protein engineering has revolutionized enzyme performance in environmental applications. Techniques such as directed evolution and machine learning have yielded stable and specific enzymes for degrading pollutants like dyes and plastics (27). For example, engineered laccases and peroxidases have achieved over 98% degradation efficiency for pollutants such as diclofenac sodium (28).

Enzyme Immobilization Techniques and Bioremediation

Immobilizing enzymes onto supports like covalent organic frameworks enhances their durability and reusability. Immobilized horseradish peroxidase, for instance, achieved over 99% degradation of textile dyes while maintaining catalytic efficiency (29). However, challenges such as leaching and cost of supports still limit broader adoption.

Applications of Biotechnological Approaches in Wastewater Treatment Bioreactors in Wastewater Treatment

Biotechnological systems, including microbial fuel cells and algae-based systems, offer significant advantages in wastewater treatment. These methods enhance resource recovery and reduce environmental impact. Anaerobic Membrane Bioreactors (AnMBRs) stand out by combining high-quality effluent production with energy generation through biogas recovery (30).

Constructed Wetlands and Biofilms

Constructed wetlands utilize biofilms on substrates to degrade pollutants such as microplastics, dyes, and pharmaceuticals. Engineered biofilms, especially those based on genetically modified *E. coli*, have shown promising results in heavy metal removal (31). Parameters like hydraulic retention time and plant selection critically influence system performance (32).

Real-world Case Studies

Case studies demonstrate the successful application of microbial and enzymatic treatments in industrial and municipal wastewater. For instance, constructed wetlands incorporating *Lemna gibba* achieved 90% removal of antibiotics (32). Similarly, microbial consortia reduced petroleum hydrocarbons by over 88% in marine settings (33).

CRITICAL ANALYSIS AND LIMITATIONS

Despite growing evidence supporting the efficacy of biotechnological approaches in wastewater treatment and environmental remediation, critical analysis of the existing literature reveals several methodological and contextual limitations that constrain the reliability and applicability of findings. A common concern is the limited scale and scope of many experimental studies, which are frequently conducted under highly controlled laboratory conditions. Such settings often fail to replicate the complex and variable conditions of real-world environments, resulting in an evidence base that may not adequately predict performance at field or industrial scales. For example, while bench-scale bioreactor systems have demonstrated high removal efficiencies for organic pollutants and heavy metals, the scalability of these results remains questionable due to limited data on operational stability and performance consistency in dynamic environmental conditions (22,23). Another significant limitation lies in the frequent use of small sample sizes and short study durations, particularly in studies assessing microbial degradation pathways or engineered enzymatic systems. These constraints limit the statistical power of findings and hinder the evaluation of long-term environmental impacts and ecological compatibility. Moreover, the absence of randomized controlled trials (RCTs) in bioremediation research makes it difficult to draw definitive causal inferences regarding the superiority of specific microbial or enzymatic strategies over conventional treatment methods. Most studies employ observational or pilot-scale designs, which are prone to selection bias and confounding variables such as uncontrolled nutrient levels or pollutant concentrations, thereby affecting outcome interpretation (24,25).

Bias in methodology also emerges in the form of publication bias, where studies with positive or novel findings are more likely to be published than those reporting negative or inconclusive results. This selective reporting creates an overestimation of effectiveness and underrepresents the challenges encountered in field applications, such as microbial competition, loss of viability, or pollutant resistance. Furthermore, differences in experimental protocols and outcome measures complicate cross-study comparisons. For instance, pollutant removal is quantified using diverse parameters—ranging from concentration reduction and enzymatic activity to ecological toxicity indices—which impedes standardized assessments of treatment success across different biotechnological interventions (26,27). A related concern is the variability in the environmental and microbial parameters assessed. Many studies do not account for real-time fluctuations in pH, temperature, salinity, or microbial interactions, which are essential determinants of bioremediation efficacy. Additionally, engineered solutions such as genetically modified organisms (GMOs) are often studied without full consideration of their ecological risks and adaptability in heterogeneous, open environments. The lack of long-term ecological monitoring further limits the understanding of potential unintended consequences on native microbial communities and ecosystem functions (28).

Generalizability of findings is another critical limitation, as much of the research is context-specific and geographically constrained. Many studies are conducted in specific climatic or geochemical regions, limiting their applicability to different ecosystems or socioeconomic settings. Moreover, there is often inadequate representation of wastewater sources from low-income or resource-constrained settings, where infrastructure and regulatory frameworks differ significantly from those in high-income countries. This restricts the global applicability of proposed biotechnological solutions and undermines their potential for equitable environmental benefit (29). In conclusion, while biotechnological approaches to bioremediation hold significant promise, the existing literature is hampered by methodological weaknesses, inconsistent outcome measures, and a lack of standardization. Greater emphasis on large-scale, well-controlled field studies, standardized performance metrics, and inclusive global research efforts is essential to build a more robust and transferable evidence base.

IMPLICATIONS AND FUTURE DIRECTIONS

The findings presented in this review hold substantial implications for both environmental health management and clinical practice, particularly in contexts where wastewater contamination contributes to public health risks such as waterborne diseases, antimicrobial resistance, and heavy metal toxicity. The implementation of biotechnological strategies, especially microbial and enzymatic bioremediation, can significantly reduce pollutant loads in effluents, thereby diminishing the exposure of vulnerable populations to hazardous contaminants. Integrating bioremediation technologies into municipal and industrial wastewater systems can indirectly benefit patient care by lowering disease transmission vectors, enhancing the safety of water sources, and promoting environmental determinants of health. From a policy-making perspective, the growing body of evidence supports the development of national and international guidelines that integrate biotechnology-based wastewater treatment within public infrastructure plans. As global wastewater volumes increase, there is an urgent need for regulatory bodies to recognize bioremediation as a mainstream treatment option, particularly in low- and middle-income countries where conventional technologies are often financially and logistically unfeasible. Policy frameworks should prioritize investment in nature-based and microbial solutions, and incentivize research into integrated treatment systems that combine physical, chemical, and biological approaches for optimal results (28,29).

Despite the promise shown by current studies, several unanswered questions remain. A major gap lies in the long-term ecological impact of deploying genetically engineered microorganisms in open environments. Although controlled experiments suggest enhanced degradation capacity, the fate of these organisms and their potential interactions with native microbiota require rigorous ecological risk assessment. Similarly, while microbial consortia have demonstrated superior pollutant degradation compared to monocultures, the optimization of their metabolic pathways, resilience under fluctuating environmental conditions, and sustained performance in field applications are areas that remain underexplored (30,31). The application of artificial intelligence (AI) and machine learning (ML) offers an exciting frontier in enhancing the precision, efficiency, and adaptability of bioremediation systems. Future studies should focus on integrating real-time data monitoring with predictive modeling to optimize microbial growth conditions and pollutant degradation pathways in dynamic wastewater systems (32,33). Moreover, the design of low-cost, scalable bioremediation technologies, such as vertical flow constructed wetlands (VFCWs), should be tailored to meet the socioeconomic and climatic realities of resource-limited settings (32). Research must also prioritize technologies that align with circular economy principles, transforming wastewater by-products into valuable resources like bioenergy and agricultural amendments (33).

Methodologically, future research should move beyond laboratory-scale investigations and adopt large-scale, randomized field trials to evaluate the effectiveness and feasibility of biotechnological interventions under real-world conditions. Longitudinal studies with extended follow-up periods are essential to assess the durability of treatment effects, ecosystem recovery, and the potential for pollutant reaccumulation. Furthermore, standardized protocols for measuring bioremediation outcomes—including pollutant degradation rates, microbial viability, and ecological impact—are needed to facilitate cross-study comparisons and meta-analyses. Multidisciplinary collaborations among microbiologists, engineers, clinicians, and policymakers will be pivotal in developing resilient and sustainable wastewater treatment solutions that safeguard both environmental and public health.

CONCLUSION

This review highlights the growing potential of biotechnological innovations—particularly microbial degradation, enzyme catalysis, and genetic engineering—in advancing sustainable wastewater treatment and environmental remediation. Strategies such as genetically engineered microbes, microbial consortia, and enzyme immobilization have demonstrated significant promise in mitigating pollutants including heavy metals, hydrocarbons, and synthetic compounds. The integration of emerging tools like synthetic biology, CRISPR-based genome editing, and nanotechnology further strengthens the efficacy and adaptability of bioremediation systems. While the existing body of evidence supports the effectiveness of these approaches, much of it remains limited to laboratory-scale studies, emphasizing the need for robust, real-world trials to validate long-term performance and ecological safety. Researchers and environmental practitioners are encouraged to prioritize interdisciplinary collaboration and to develop scalable, cost-effective technologies tailored to diverse ecological and socioeconomic contexts. Ultimately, sustained research efforts, guided by standardized methodologies and supported by policy frameworks, are essential to fully realize the potential of biotechnological solutions in achieving global environmental sustainability and circular economy goals.

AUTHOR CONTRIBUTION

Author	Contribution
Sher Ali*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Maliha Munawar	Substantial Contribution to study design, acquisition and interpretation of Data

Author	Contribution
	Critical Review and Manuscript Writing Has given Final Approval of the version to be published

REFERENCES

1. Abdelhamid, M. a. A., Khalifa, H. O., Yoon, H. J., Ki, M., & Pack, S. P. (2024). Microbial Immobilized Enzyme Biocatalysts for Multipollutant Mitigation: Harnessing Nature's Toolkit for Environmental Sustainability. *International Journal of Molecular Sciences*, *25*(16), 8616.
2. Abdullah, K., Wilkins, D., & Ferrari, B. C. (2023). Utilization of—Omic technologies in cold climate hydrocarbon bioremediation: a text-mining approach. *Frontiers in Microbiology*, *14*.
3. Achudhan, A. B., Masilamani, M., Kannan, P., & Saleena, L. M. (2023). In-silico Integration in Environmental Remediation. In *Recent Trends in Constructed Wetlands for Industrial Wastewater Treatment* (pp. 249–263).
4. Adhikary, S., Saha, J., Dutta, P., & Pal, A. (2024). Bacterial Homeostasis and Tolerance to Potentially Toxic Metals and Metalloids through Diverse Transporters: Metal-Specific Insights. *Geomicrobiology Journal*, *41*(5), 496–518.
5. Ahiahonu, E. K., Anku, W. W., Roopnarain, A., Serepa-Dlamini, M. H., & Govender, P. P. (2024). Evaluation of green microalgal strains for simultaneous municipal wastewater treatment and heavy metal bioremediation. *Journal of Chemical Technology & Biotechnology*, *99*(9), 2035–2046.
6. Ahmed, M., Tariq, H., Haroon, F., Ejaz, T., & Tajwar, M. (2023). Optimizing synergistic metabolism in xenobiotic biodegradation: Engineering a pseudomonas putida based microbial consortium. *American Journal of Life Science and Innovation*, *3*(1), 1–7.
7. Akintola, N. a. A. (2024). AI-driven monitoring systems for bioremediation: real-time data analysis and predictive modelling. *World Journal of Advanced Research and Reviews*, *24*(1), 788–803.
8. Akoijam, N., & Joshi, S. R. (2024). Genome editing and genetically engineered bacteria for bioremediation of heavy metals. In *BENTHAM SCIENCE PUBLISHERS eBooks* (pp. 184–221).
9. Alabssawy, A. N., & Hashem, A. H. (2024). Bioremediation of hazardous heavy metals by marine microorganisms: a recent review. *Archives of Microbiology*, *206*(3).
10. Ali, Q., Qasim, A., Sarwar, W., Ahmed, S., & Badshah, M. (2024). Pharmaceuticals as emerging pollutants. In *CRC Press eBooks* (pp. 18–45).
11. Aliko, V., Multisanti, C. R., Turani, B., & Faggio, C. (2022). Get rid of Marine Pollution: Bioremediation an innovative, attractive, and successful cleaning strategy. *Sustainability*, *14*(18), 11784.
12. Al-Madhagi, H. A., & Yazbik, V. (2024). Immobilized peroxidase for bioremediation of environmental pollutants. *Research Journal of Biotechnology*, *19*(7), 138–146.
13. Al-Maqdi, K. A., Elmerhi, N., Athamneh, K., Bilal, M., Alzamly, A., Ashraf, S. S., & Shah, I. (2021). Challenges and Recent Advances in Enzyme-Mediated Wastewater Remediation—A Review. *Nanomaterials*, *11*(11), 3124.
14. Aloud, S. S., Alotaibi, K. D., Almutairi, K. F., Albarakah, F. N., Alotaibi, F., & Ahmed, I. A. (2024). Investigating the Interactive Effect of Arbuscular Mycorrhizal Fungi and Different Chelating Agents (EDTA and DTPA) with Different Plant Species on Phytoremediation of Contaminated Soil. *Sustainability*, *16*(20), 8820.
15. Apriani, I., Yanto, D. H. Y., Hariani, P. L., Widjajanti, H., & Nurhayat, O. D. (2024). Potential of White Rot Fungi from Berbak-Sembilang National Park, Indonesia for Decolorization and Detoxification Commercial Direct Dyes. *Trends in Sciences*, *21*(6), 7610.
16. Arshad, N. I., Iqbal, N. H., Iqbal, N. S. S., Afzaal, N. M., & Rehman, N. Y. (2024). A review on the synergistic Approaches for Heavy metals bioremediation: Harnessing the power of Plant-Microbe interactions. *Lahore Garrison University Journal of Life Sciences*, *8*(2), 268–286.
17. Arya, A. K., Shreya, N., Ponnuchamy, M., Pal, D. B., & Kapoor, A. (2024). Algae biomass valorization for wastewater remediation. In *Clean Energy Production Technologies* (pp. 251–271). https://doi.org/10.1007/978-981-97-0840-6_10
18. Ayilara, M. S., & Babalola, O. O. (2023). Bioremediation of environmental wastes: the role of microorganisms. *Frontiers in Agronomy*, *5*.

19. Baffi, M. A., De Azevedo, L. C. B., Borges, M. F., & Bertini, S. B. (2024). Microbial enzymes in biodegradation of organic pollutants: mechanisms and applications. In *Elsevier eBooks* (pp. 213–242).
20. Bajaj, D., Yadav, V., Dhyani, A., & Wadhwa, N. K. (2024). Exploration of microbial enzymes in bioremediation. In *CRC Press eBooks* (pp. 250–272).
21. Khan, Sher Alam, Ayesha Usman, Zahoor Islam, Rida Fatima, Irum Sajid, Sadiq Sadiq, Ayesha Saleem, and Ishfaq Aziz. 2024. “A Comprehensive Review of Immunomodulatory Drugs in Preventing Secondary Infections in Immunocompromised Patients: A Narrative Review.” Insights-Journal of Health and Rehabilitation 2 (2)
22. Banerjee, S., Gupta, N., Pramanik, K., Gope, M., GhoshThakur, R., Karmakar, A., Gogoi, N., Hoque, R. R., Mandal, N. C., & Balachandran, S. (2023). Microbes and microbial strategies in carcinogenic polycyclic aromatic hydrocarbons remediation: a systematic review. *Environmental Science and Pollution Research*, *31*(2), 1811–1840.
23. Banu, M. M., Reehana, N., & Imran, M. M. (2024). Microbial Degradation of Pesticides in Agricultural Environments: A Comprehensive review of Mechanisms, Factors and Biodiversity. *MOLECULAR SCIENCES AND APPLICATIONS*, *4*, 65–101.
24. Barra, L., & Greco, S. (2023). The potential of microalgae in phycoremediation. In *IntechOpen eBooks*.
25. Bergeson, A. R., & Alper, H. S. (2024). Advancing sustainable biotechnology through protein engineering. *Trends in Biochemical Sciences*, *49*(11), 955–968.
26. Bhoi, R., Shrivastava, A., & Sarkar, A. (2024). Study of microbial communities in degrading toxic pollutants in the wastewater and solid waste treatment industries. In *Elsevier eBooks* (pp. 205–223).
27. Bian, Y., Chen, Y., Zhan, L., Ke, H., Gao, Y., Wang, Q., & Qi, G. (2024). An Enzyme-Induced Carbonate Precipitation Method for ZN2+, NI2+, and CR(VI) remediation: An experimental and simulation study. *Applied Sciences*, *14*(15), 6559.
28. Bindal, N., & Ramesh, S. (2024). Treatment of Wastewater with Phytoremediation Using Water Hyacinth—A Review. In *Lecture notes in civil engineering* (pp. 249–261).
29. Blázquez-Moraleja, A., Cabezuelo, O., Martinez-Haya, R., Schmidt, L. C., Bosca, F., & Marin, M. L. (2023). Organic photoredox catalysts: tuning the operating mechanisms in the degradation of pollutants. *Pure and Applied Chemistry*, *95*(8), 899–912.
30. Bustamante-Torres, M., Romero-Fierro, D., Estrella-Nuñez, J., & Bucio, E. (2021). Microbial degradation of proteins. In *Environmental and microbial biotechnology* (pp. 351–371).
31. Chander, A. M., Singh, N. K., & Venkateswaran, K. (2023). Microbial Technologies in waste management, energy generation and Climate Change: Implications on Earth and space. *Journal of the Indian Institute of Science*, *103*(3), 833–838.
32. Hussain, Zeeshan, Ali Hamza Arshad, Sher Alam Khan, Waqas Mahmood, Hakim Shah, Arooj Sarwar, and Talha Mazhar. 2024. "Microbial Threats to Public Health: Emerging Infectious Diseases and the Role of Pharmacology—Narrative Review." *Insights-Journal of Life and Social Sciences* 2 (1).
33. Banerjee, R., Banerjee, M., & Mondal, S. (2022). Policies and issues in environmental biotechnology research. In *CRC Press eBooks* (pp. 177–201).

