Vol. 17 No. 1 (2026) 175-186

Jurnal Riset
Teknologi Pencegahan Pencemaran Industri

Journal homepage: https://www.jrtppi.id

Integration of Plant Breeding and Environmental Technology in the Prevention of Industrial Pollution

Abdul Jalil, Bejo Suroso, Faridatul Munawaroh, Bagus Tripama

Universitas Muhammadiyah Jember

ARTICLE INFO

Article history:

Received January 04 2026

Received in revised form March 20, 2026

Accepted April 20, 2026

Available online May 20, 2026

Keywords:

Plant Breeding

Phytoremediation

Environmental Technology

Industrial Pollution

ABSTRACT

Increasing industrial activities have intensified environmental pollution caused by heavy metals, persistent organic pollutants, and other hazardous contaminants, posing serious risks to ecosystems and human health. Although numerous studies have investigated phytoremediation and environmental engineering technologies independently, comprehensive reviews examining their integration for industrial pollution prevention remain limited. Therefore, this systematic literature review aims to synthesize current evidence on the integration of plant breeding and environmental technologies to develop more effective and sustainable industrial pollution control strategies. The review followed the PRISMA 2020 guidelines and searched five international scientific databases, namely Scopus, Web of Science, ScienceDirect, SpringerLink, and MDPI, covering publications from 2019 to 2026. Eligible peer-reviewed studies were selected using predefined inclusion and exclusion criteria and synthesized through qualitative content analysis. The findings demonstrate that advances in plant breeding, including genetic engineering, CRISPR-Cas9 genome editing, marker-assisted selection (MAS), and multi-omics approaches, significantly enhance plants' phytoremediation capacity. When integrated with environmental technologies such as adsorption, membrane bioreactors (MBRs), biological reactors, and constructed wetlands, these approaches provide more efficient and sustainable pollution control systems. Evidence synthesized from the reviewed studies indicates that integrated treatment systems can achieve pollutant removal efficiencies exceeding **80–95%** in various industrial wastewater applications, outperforming single-treatment approaches while improving ecosystem sustainability and resource efficiency. Despite these advantages, large-scale implementation remains constrained by high investment costs, system complexity, regulatory challenges, and limited long-term field validation. This review provides a scientific basis for developing integrated industrial wastewater management systems, supports evidence-based environmental policy, and identifies future research priorities involving nanotechnology, artificial intelligence (AI), the Internet of Things (IoT), and advanced genome-editing technologies

Keywords: Plant Breeding; Phytoremediation; Environmental Technology; Industrial Pollution

*Correspondence author.
E-mail: abduljalil@unmuhjember.ac.id (Abdul Jalil)

doi: https://doi.org/10.21771/jrtppi.2026.v17.no1.p175-186

Accreditation number: (Ristekdikti) 158/E/KPT/2021

INTRODUCTION

In recent decades, rapid industrialization and urbanization have intensified environmental pollution, creating complex challenges for ecosystems and human health. Industrial waste contains hazardous contaminants, including heavy metals, persistent organic pollutants, and other toxic substances that are difficult to degrade naturally. These pollutants can spread through soil and water, accumulate in food chains, and threaten environmental stability and public health (Ali et al., 2019; Ding et al., 2022).

Various physicochemical technologies, including adsorption, coagulation-flocculation, precipitation, and membrane filtration, have been widely applied to remove pollutants effectively. However, these methods often involve high operational costs, intensive energy consumption, and the generation of secondary waste requiring further treatment (Crini & Lichtfouse, 2019b; Nidheesh et al., 2021). Consequently, greater attention has been directed toward more sustainable remediation technologies.

Phytoremediation has emerged as a promising alternative by utilizing plants to absorb, stabilize, or degrade environmental pollutants through mechanisms such as phytoextraction, phytostabilization, phytodegradation, and rhizofiltration (Ali et al., 2020). Compared with conventional methods, phytoremediation is more cost-effective, environmentally friendly, and capable of improving soil quality. However, its application remains constrained by relatively slow remediation rates and limited pollutant accumulation capacity (Rezania et al., 2022).

Modern plant breeding and biotechnology offer important opportunities to overcome these limitations. Through genetic selection, marker-assisted selection, genetic engineering, CRISPR-Cas genome editing, and multi-omics technologies, superior genotypes with enhanced tolerance and pollutant accumulation capacity can be developed (Raza et al., 2022; Yan et al., 2020). These advances increase the potential of hyperaccumulator plants, particularly in heavily contaminated environments.

Environmental engineering has also advanced industrial wastewater treatment through technologies such as constructed wetlands, microorganism-based bioreactors, and nanotechnology. Constructed wetlands exploit interactions among plants, microorganisms, and substrates to naturally reduce pollutant loads (Zeng et al., 2020), while nanomaterials significantly improve pollutant adsorption and degradation efficiency (Guerra et al., 2018). Nevertheless, these technologies remain constrained by high investment costs, operational complexity, and long-term sustainability concerns.

Previous review studies have separately examined phytoremediation, plant breeding, and environmental engineering technologies, including hyperaccumulator plants, genome editing, membrane bioreactors, constructed wetlands, and nanotechnology. However, they have rarely explored how advances in plant breeding can be systematically integrated with environmental technologies into a comprehensive industrial pollution control framework. As a result, current knowledge remains fragmented, limiting understanding of the complementary mechanisms, synergistic performance, implementation challenges, and future development of integrated remediation systems.

Several issues also remain unresolved. Plant-based remediation is environmentally friendly and economically attractive but is often limited by slow pollutant uptake, low biomass production, and environmental variability. In contrast, engineering technologies provide rapid and efficient pollutant removal but require substantial investment, high energy consumption, and complex operation. Although recent studies have proposed integrating biological and engineering approaches, evidence regarding long-term effectiveness, scalability, economic feasibility, and industrial implementation remains inconsistent, highlighting the need for a systematic synthesis of current evidence.

Recent developments indicate a shift toward integrated remediation strategies that combine plant breeding with environmental technologies, including genetically improved plants in constructed wetlands, phytoremediation coupled with microbial bioaugmentation, and nanotechnology-assisted plant remediation systems (Cao & Zhang, 2024; Shourie et al., 2024). Such integration has the potential to improve remediation efficiency while enhancing environmental sustainability and resource utilization.

Accordingly, this review addresses four research questions: (1) How does plant breeding improve phytoremediation performance for industrial pollution control? (2) Which environmental technologies are most effective for industrial wastewater treatment? (3) How can plant breeding and environmental technologies be integrated to enhance remediation efficiency and sustainability? (4) What are the major challenges, limitations, and future research priorities for implementing integrated pollution control systems at an industrial scale?

This systematic literature review therefore aims to critically synthesize current evidence on integrating plant breeding and environmental technologies for industrial pollution prevention. Unlike previous reviews focusing on individual remediation methods, this review applies an integrated framework covering: (1) advances in plant breeding for phytoremediation; (2) recent environmental technologies for industrial wastewater treatment; (3) strategies integrating biological and engineering approaches; and (4) evaluation of effectiveness, implementation challenges, and future technological directions. This framework is intended to identify knowledge gaps, assess the current evidence, and provide recommendations for future interdisciplinary research and sustainable industrial wastewater management.

METHODS

This study employed a stematic Literature Review (SLR) as the primary research method to comprehensively examine the integration of plant breeding and environmental technologies for industrial pollution prevention. The SLR approach was selected because it enables the systematic identification, critical evaluation, and synthesis of scientific evidence from previous studies, thereby providing a comprehensive and reliable understanding of current knowledge and future research directions (Page et al., 2021; Snyder, 2019).

The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines, which provide a standardized framework consisting of four sequential stages: identification, screening, eligibility assessment, and inclusion of relevant studies. The PRISMA protocol was adopted to ensure transparency, methodological rigor, and reproducibility throughout the review process. The complete study selection process is illustrated in the PRISMA flow diagram (Figure 1).

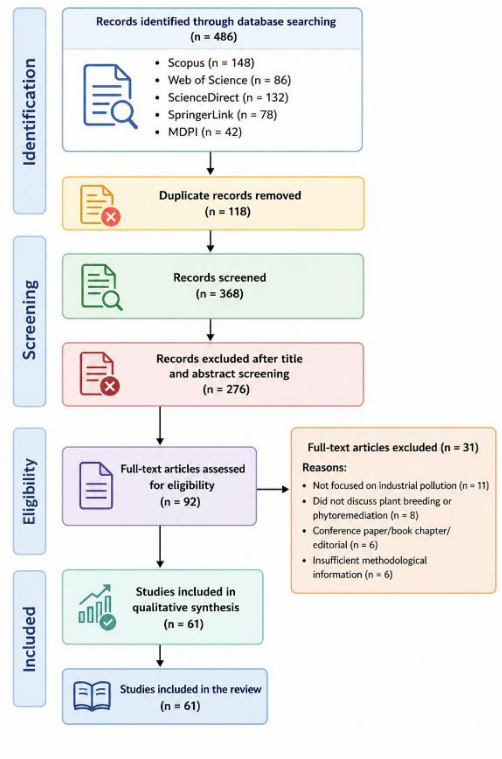

Figure 1 PRISMA flow diagram

A comprehensive literature search was performed using five internationally recognized scientific databases: Scopus, Web of Science, ScienceDirect, SpringerLink, and MDPI. The search covered publications published between 2019 and 2026, representing recent developments in phytoremediation, plant breeding, and environmental technologies. The final database search was conducted in March 2026. Database-specific search syntax was adapted according to the indexing system of each database while maintaining equivalent search concepts. The primary Boolean search strategy included combinations of the following terms:

("plant breeding" OR phytoremediation OR "hyperaccumulator plant" OR "genome editing" OR CRISPR OR "marker-assisted selection") AND ("industrial pollution" OR "industrial wastewater" OR "heavy metal" OR contaminant) AND ("environmental technology" OR "constructed wetland" OR bioreactor OR adsorption OR nanotechnology OR "wastewater treatment").

Studies were selected using predefined inclusion and exclusion criteria. Eligible studies were peer-reviewed journal articles published in English between 2019 and 2026 that investigated industrial pollution, phytoremediation, plant breeding, or environmental technologies and provided sufficient methodological information for evaluation. Experimental studies, field studies, and review articles directly relevant to the research objectives were included. Conference proceedings, editorials, book chapters, duplicate publications, non-English articles, inaccessible full texts, and studies unrelated to industrial pollution or plant-based remediation were excluded from the analysis (Paul & Criado, 2020; Snyder, 2019).

All retrieved records were screened through a multi-stage selection process. Duplicate records were removed prior to title and abstract screening. Subsequently, potentially relevant studies underwent full-text eligibility assessment according to the predefined criteria. To minimize selection bias, article screening and eligibility assessment were independently conducted by two reviewers. Any disagreements regarding study inclusion were resolved through discussion until consensus was achieved.

The selected studies were subsequently synthesized using qualitative thematic content analysis combined with narrative synthesis. Initially, relevant information was extracted from each article, including publication characteristics, pollutant type, plant species, remediation approach, environmental technology, principal findings, and reported limitations. The extracted information was then coded and grouped into four major analytical themes: (1) plant breeding strategies for enhancing phytoremediation capacity; (2) environmental technologies for industrial wastewater treatment; (3) integration strategies between biological and engineering approaches; and (4) effectiveness, implementation challenges, and future research opportunities. This analytical framework enabled the identification of recurring patterns, technological trends, knowledge gaps, and future research priorities (Snyder, 2019).

To enhance the credibility of the review, only literature published in reputable indexed journals was included. Methodological rigor was maintained through the consistent application of the PRISMA 2020 protocol, predefined eligibility criteria, independent article screening, and cross-comparison of findings from multiple studies during the synthesis process. Furthermore, the methodological quality of the included studies was critically considered during data interpretation to reduce potential bias and improve the reliability of the synthesized evidence (Page et al., 2021).

As this study was based exclusively on published literature, ethical approval involving human participants was not required. Nevertheless, the principles of academic integrity were strictly maintained through appropriate citation practices, accurate representation of previous findings, and adherence to established standards of scientific publication ethics. Through this methodological framework, the study aims to provide a transparent, systematic, and evidence-based synthesis that supports the development of more effective and sustainable industrial pollution prevention strategies.

RESULT AND DISCUSSION

The literature synthesis indicates that industrial pollution control has shifted from single-method approaches toward integrated strategies combining plant biotechnology and environmental engineering. Plants developed through breeding and genetic engineering exhibit enhanced capacities to absorb, accumulate, and stabilize pollutants, while environmental technologies provide greater treatment efficiency, faster processing, and improved operational control (Guerra et al., 2018; Raza et al., 2022; Yan et al., 2020).

Technologies such as adsorption, membrane bioreactors (MBR), bioreactors, and constructed wetlands effectively remove both organic and inorganic pollutants. MBR systems produce high-quality effluent but remain limited by membrane fouling and operational costs, whereas constructed wetlands are environmentally friendly but require larger land areas and longer treatment times (Ombadi & Varadharajan, 2022; Zeng et al., 2020).

Evidence further shows that integrated systems consistently outperform single-method approaches. Combining plants, microorganisms, and environmental technologies can increase pollutant removal efficiency to more than 80% in complex wastewater while also improving ecosystem quality and energy efficiency (Shourie et al., 2024).

Despite these advantages, significant challenges remain, including system design complexity, environmental variability, and limited long-term field-scale validation. Further research is therefore required to enhance the stability, scalability, and industrial applicability of integrated pollution control systems.

The Role of Plant Breeding in Controlling Industrial Pollution

Plant breeding plays a strategic role in enhancing phytoremediation as a sustainable approach to industrial pollution control. Phytoremediation utilizes plants to absorb, stabilize, translocate, and degrade pollutants from contaminated soil, water, and sediments. Compared with physical and chemical methods, it is more environmentally friendly, cost-effective, and produces less secondary waste. Through conventional breeding and genetic engineering, plants can be developed with greater tolerance to heavy metals and higher bioaccumulation capacity for contaminants such as Pb, Cd, Cr, As, Hg, and toxic organic compounds (Raza et al., 2022; Yan et al., 2020).

Phytoremediation operates through four principal mechanisms: phytoextraction, phytostabilization, phytodegradation, and rhizofiltration. These processes involve metal transporter proteins such as ZIP and NRAMP, pollutant immobilization in the rhizosphere, enzymatic degradation of toxic compounds, and pollutant uptake by plant roots in aquatic environments (Guerra et al., 2018).

Advances in biotechnology have substantially improved phytoremediation efficiency. Genetic engineering enhances the expression of metal transporter genes, detoxification enzymes, phytochelatins, and metallothioneins, enabling plants to tolerate and accumulate higher levels of heavy metals (Jassal et al., 2023; Yan et al., 2020). CRISPR-Cas9 further enables precise modification of genes associated with metal transport, antioxidant systems, and stress responses, increasing pollutant accumulation and tolerance to adverse environmental conditions (Hyun, 2020). Marker-assisted selection (MAS) accelerates the identification of superior hyperaccumulator genotypes, while genomics, transcriptomics, proteomics, and metabolomics facilitate the discovery of genes and metabolic pathways governing pollutant tolerance and accumulation (Hyun, 2020; Jassal et al., 2023; Raza et al., 2022).

Several hyperaccumulator species, including Cannabis sativa, Linum usitatissimum, Solanum nigrum, Brassica juncea, Vetiveria zizanioides, and Eichhornia crassipes, have demonstrated strong phytoremediation potential. Their effectiveness is influenced not only by species but also by genetic variation, as observed in Ipomoea batatas and Medicago sativa, where different genotypes exhibit distinct heavy metal accumulation and tolerance capacities (Adesina et al., 2020; García-Carrillo et al., 2024; Luo et al., 2021; Saleem et al., 2020; Yan et al., 2020).

Phytoremediation performance is also affected by environmental factors such as soil pH, temperature, organic matter, and nutrient availability, which regulate heavy metal bioavailability and rhizosphere activity. Interactions with plant growth-promoting rhizobacteria (PGPR), endophytic bacteria, and mycorrhizal fungi enhance plant growth, pollutant uptake, and stress tolerance. Likewise, bioaugmentation using heavy-metal-resistant microbial consortia and nanotechnology can significantly improve remediation efficiency by increasing pollutant bioavailability and strengthening plant antioxidant systems (Guerra et al., 2018; Shourie et al., 2024; Yan et al., 2020).

Despite its considerable potential, large-scale implementation remains constrained by limited field validation, slower remediation rates than physicochemical methods, restricted biomass production, potential food-chain contamination, and regulatory issues concerning transgenic plants (Almeida-Naranjo et al., 2021; Yan et al., 2020). Overall, advances in molecular breeding, genome editing, MAS, and omics technologies have greatly expanded opportunities to develop highly efficient hyperaccumulator plants. Nevertheless, optimization of environmental conditions, integration with rhizosphere microorganisms, field-scale validation, and supportive regulatory frameworks remain essential for the sustainable industrial application of plant-breeding-based phytoremediation.

Environmental Technologies in Industrial Waste Treatment

Advances in environmental technology have substantially improved industrial wastewater treatment in response to increasing industrial pollution. Modern treatment systems employ physical, chemical, and biological approaches to remove heavy metals, organic compounds, nutrients, and microbial contaminants while emphasizing energy efficiency, environmental sustainability, and resource recovery (Crini & Lichtfouse, 2019a; Guerra et al., 2018).

Adsorption remains one of the most widely used technologies because of its high effectiveness in removing heavy metals, dyes, and organic pollutants. Common adsorbents include activated carbon, zeolite, biochar, silica, modified clay, and nanomaterials. Activated carbon provides high adsorption capacity through its porous structure, whereas zeolites effectively remove heavy metals by ion exchange (Tan et al., 2020). Nanomaterials such as graphene oxide, carbon nanotubes, and metal oxide nanoparticles further improve adsorption efficiency through their large active surface area (Guerra et al., 2018). However, adsorption is limited by adsorbent regeneration, secondary waste generation, and relatively high operational costs (Crini & Lichtfouse, 2019b).

Membrane bioreactors (MBRs) integrate biological degradation with membrane filtration to produce high-quality effluent by removing BOD, COD, suspended solids, microorganisms, and complex organic compounds, while enabling industrial water reuse (Ombadi & Varadharajan, 2022). Despite these advantages, membrane fouling, high energy demand, and expensive membrane replacement remain major obstacles to large-scale implementation (Ombadi & Varadharajan, 2022).

Biological treatment technologies, including moving bed biofilm reactors (MBBRs) and anaerobic bioreactors, effectively degrade complex organic pollutants. MBBRs enhance degradation efficiency through biofilm-attached moving media (Mohammed et al., 2020), whereas anaerobic bioreactors generate renewable methane with lower energy requirements (Guerra et al., 2018). However, their performance depends on operational conditions such as temperature, pH, retention time, and nutrient availability (Carrasco-correa et al., 2023).

Constructed wetlands provide a sustainable nature-based solution by integrating plants, microorganisms, and substrate media to remove heavy metals, nutrients, organic matter, and suspended solids with low energy demand (Zeng et al., 2020). Plant species such as Typha, Phragmites australis, and Cyperus enhance oxygen transfer and microbial activity, while substrates support pollutant adsorption and filtration (Kumar & Chattopadhyay, 2025). Nevertheless, their application is limited by extensive land requirements, longer treatment times, and sensitivity to climate and wastewater characteristics, making hybrid systems preferable for heavily contaminated wastewater (Dada et al., 2024).

Recent developments increasingly focus on hybrid treatment systems integrating adsorption, membrane bioreactors, biological reactors, and constructed wetlands to maximize pollutant removal while overcoming the limitations of individual technologies (Yang & Malijan, 2026). Emerging applications of nanomaterials, bioelectrochemical systems, and artificial intelligence (AI) further improve operational efficiency and enable real-time monitoring, reflecting the transition toward more adaptive, energy-efficient, and sustainable industrial wastewater treatment systems.

Integration of Plant Breeding and Environmental Technology

The integration of plant breeding and environmental technology has emerged as an innovative strategy for industrial pollution control by combining the sustainability of biological processes with the efficiency of engineering systems. This paradigm shift addresses the limitations of single-method approaches: phytoremediation is environmentally friendly and economical but relatively slow and sensitive to environmental conditions, whereas technologies such as membrane systems, adsorption, and bioreactors provide high removal efficiency but require substantial operational costs and may generate secondary waste (Ijoma et al., 2024; Liu et al., 2024; P. Sharma et al., 2021).

The integrated concept utilizes plants developed through breeding or genetic engineering as biological agents to absorb, accumulate, stabilize, and degrade pollutants, while environmental technologies optimize operational conditions to accelerate and stabilize remediation. This synergy enhances pollutant removal, reduces chemical and energy inputs, and supports circular economy principles by enabling phytoremediation biomass to be reused for bioenergy or industrial applications (Bhat et al., 2021; Guerra et al., 2018; Liu et al., 2024).

Constructed wetlands represent one of the most developed integrated systems, combining plants, microorganisms, substrate media, and hydraulic processes to remove pollutants through physical, chemical, and biological mechanisms. Hyperaccumulator species or improved plant varieties enhance phytoextraction, phytostabilization, and phytodegradation, while vegetation stimulates rhizosphere microbial activity and oxygen transfer, increasing the removal of heavy metals, nutrients, and organic pollutants (Ijoma et al., 2024; Singh et al., 2024; Thakur et al., 2023; Wang et al., 2022). Similarly, floating wetlands integrate aquatic plants with floating structures, promoting microbial colonization and improving the removal of heavy metals, nutrients, and organic contaminants while providing ecological benefits (Li et al., 2021; Pang et al., 2023; Sonu et al., 2000).

The effectiveness of phytoremediation is further enhanced through microbial bioaugmentation, in which microorganisms such as Pseudomonas, Bacillus, mycorrhizal fungi, and plant growth-promoting rhizobacteria (PGPR) accelerate contaminant transformation, improve nutrient availability, and increase plant tolerance and heavy metal uptake (Kumar & Chattopadhyay, 2025; Sahoo et al., 2024). Integration with membrane bioreactors (MBRs) also improves effluent quality by combining biological pollutant reduction with membrane polishing, thereby enhancing treatment efficiency while reducing membrane fouling (Ijoma et al., 2024; Kurniawan et al., 2022).

Recent innovations include bioelectrochemical systems such as constructed wetland–microbial fuel cells (CW-MFCs) and plant microbial fuel cells (PMFCs), which simultaneously treat wastewater and generate renewable electricity through microbial activity (Arliyani et al., 2024; Moqsud, 2024; Singh et al., 2024; Sonu et al., 2000). Advances in CRISPR-Cas9 and omics technologies further strengthen integrated systems by developing hyperaccumulator plants with greater pollutant uptake capacity and providing molecular insights to optimize plant–microbe interactions (Kaur et al., 2021).

Integrated wastewater treatment has also evolved into multi-stage systems that sequentially combine adsorption, constructed wetlands, and biological reactors to treat wastewater containing mixed heavy metals and persistent organic pollutants. These systems have demonstrated pollutant removal efficiencies exceeding 80–95% while improving process stability (Giwa et al., 2021; Islam, 2025). Overall, integrated approaches provide substantial ecological and economic benefits by reducing chemical use and energy demand through natural processes such as photosynthesis, microbial activity, and biogeochemical cycling (Jassal et al., 2023). However, challenges remain regarding system complexity, environmental variability, and investment costs. Future developments should focus on data-driven optimization, integration of IoT and AI technologies, and the development of pollutant-specific genetically improved plants to support sustainable industrial wastewater management.

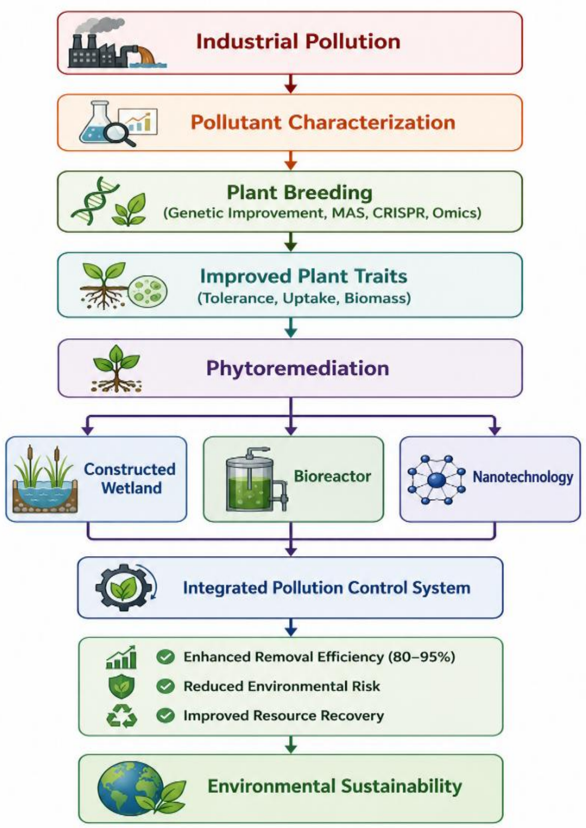

Figure 2. Conceptual Framework for the Integration of Plant Breeding and Environmental Technologies in Industrial Pollution Control

Figure 2 presents a conceptual framework illustrating the integration of plant breeding and environmental technologies for sustainable industrial pollution control. The framework begins with pollutant characterization, which guides the selection of appropriate remediation strategies according to contaminant type and environmental conditions. Plant breeding advances, including genetic improvement, marker-assisted selection (MAS), CRISPR genome editing, and multi-omics technologies, enhance pollutant tolerance, uptake capacity, and biomass production, thereby improving phytoremediation efficiency.

To address the limitations of stand-alone phytoremediation, improved plants are integrated with environmental technologies such as constructed wetlands, bioreactors, and nanotechnology-assisted treatment systems. These complementary technologies operate synergistically to increase pollutant removal efficiency, improve treatment stability, and overcome the limitations of individual remediation methods.

The resulting Integrated Pollution Control System has been reported to achieve pollutant removal efficiencies of approximately 80–95% while reducing environmental risks and promoting resource recovery. Overall, the framework demonstrates that integrating plant breeding with environmental technologies provides a comprehensive strategy for enhancing industrial wastewater treatment, improving resource efficiency, and supporting long-term environmental sustainability.

Effectiveness, Challenges, and Future Perspectives

Although most studies consistently reported improved remediation performance through integrated approaches, substantial differences were observed regarding pollutant removal efficiency. These variations are largely influenced by contaminant characteristics, plant genotype, environmental conditions, reactor configuration, and operational scale. Compared with stand-alone remediation methods, integrated systems combine the biological advantages of phytoremediation with engineered treatment technologies, resulting in more stable and efficient pollutant removal across diverse industrial wastewater conditions (P. Sharma et al., 2021; R. Sharma & Malaviya, 2022). The synergistic interaction among plants, rhizosphere microorganisms, and environmental technologies enhances pollutant uptake, biodegradation, and contaminant transformation, thereby improving overall remediation performance (Ijoma et al., 2024; Zhang et al., 2024).

Table 1. Comparative Analysis of Industrial Pollution Remediation Technologies

Technology	Pollutant Remo	Economic Cost	Environmental	Major Limitations

	val Efficiency		**Sustainability**	
Phytoremediation	Moderate	Low	High	Slow remediation rate and limited pollutant uptake
Adsorption	High	Moderate	Moderate	Adsorbent regeneration and disposal requirements
Membrane Bioreactor (MBR)	Very High	High	Moderate	High energy demand and membrane fouling
Constructed Wetland	High	Low	Very High	Large land requirement and climate dependency
Integrated System (Plant Breeding + Environmental Technology)	Very High	Moderate	Very High	System complexity, higher initial investment, and management requirements

Table 1 demonstrates that no single remediation technology is universally effective under all environmental conditions. Conventional engineering technologies generally provide higher pollutant removal efficiencies but require greater financial investment and operational inputs. In contrast, phytoremediation offers greater environmental sustainability but is limited by slower remediation rates. Integrating plant breeding with environmental technologies combines the strengths of both approaches, improving treatment efficiency while maintaining sustainability. However, successful implementation depends on pollutant characteristics, plant genotype, climatic conditions, and operational scale, requiring site-specific system design. Pollutant removal efficiencies of integrated systems generally range from 80–95%, particularly for industrial wastewater containing heavy metals and persistent organic pollutants, although performance varies with wastewater composition, plant species, microbial communities, and environmental conditions. Laboratory and pilot-scale studies typically report higher efficiencies than field applications because of greater environmental variability and operational complexity (Yan et al., 2020; Singh et al., 2024). Integration with membrane bioreactors (MBRs), constructed wetlands, adsorption, bioelectrochemical systems, and microbial bioaugmentation further enhances treatment stability and enables simultaneous removal of heavy metals, organic pollutants, nutrients, and emerging contaminants (Borgulat et al., 2022; Castellano-Hinojosa et al., 2024).

Despite these promising outcomes, several studies reported only limited improvements over conventional technologies under conditions of high pollutant concentrations, unsuitable plant species, or unstable hydraulic loading, indicating that remediation performance depends on appropriate system design and site-specific environmental conditions rather than integration alone. Integrated systems also provide important ecological and economic benefits by reducing chemical consumption and energy demand while supporting natural processes such as photosynthesis, nutrient cycling, and microbial degradation. In addition, phytoremediation biomass can be utilized for bioenergy, organic fertilizers, or industrial raw materials, supporting resource recovery and circular economy principles (Koul et al., 2022; Kushwaha & Kashyap, 2021). Although initial investment is generally higher, long-term operational costs may decrease because of lower chemical use, reduced sludge production, and biomass utilization. Nevertheless, comprehensive techno-economic evaluations remain essential before large-scale implementation.

Several technical and regulatory constraints continue to limit industrial adoption. System performance is strongly influenced by temperature, pH, nutrient availability, and wastewater characteristics, making field performance less predictable than laboratory results (Fatima et al., 2025). Moreover, membrane bioreactors and bioelectrochemical systems require substantial capital and maintenance costs, while hyperaccumulator plant development demands extensive breeding and field validation (Du et al., 2020; Yan et al., 2020). The deployment of genetically modified or genome-edited plants is further constrained by biosafety regulations, ecological risk assessment, and public acceptance, particularly regarding gene flow, ecological impacts, and long-term environmental safety.

Future research should emphasize interdisciplinary integration of nanotechnology, artificial intelligence (AI), the Internet of Things (IoT), advanced genome editing, and real-time environmental monitoring. Nanomaterials can improve contaminant adsorption and bioavailability, whereas AI- and IoT-based systems enable adaptive process control through continuous environmental monitoring (Badamasi et al., 2025; Dada et al., 2024; Umair et al., 2023). Advances in CRISPR-based genome editing and multi-omics technologies also support the development of plant genotypes with greater pollutant tolerance, uptake capacity, and beneficial interactions with rhizosphere microorganisms (Chen et al., 2024). As illustrated in Figure 2, integrating biological innovations with environmental engineering provides a comprehensive framework for developing adaptive, efficient, and sustainable industrial pollution control systems. Future work should therefore prioritize large-scale validation, techno-economic analysis, biosafety assessment, and interdisciplinary collaboration to accelerate practical implementation.

CONCLUSION

Based on this systematic literature review, the integration of plant breeding and environmental technologies offers a promising strategy for sustainable industrial pollution control. Advances in plant breeding, including conventional breeding, marker-assisted selection (MAS), CRISPR-based genome editing, and multi-omics approaches, enhance phytoremediation by improving plant tolerance, pollutant uptake, and biomass production. When integrated with environmental technologies such as adsorption, membrane bioreactors (MBRs), constructed wetlands, biological reactors, and nanotechnology-assisted systems, these approaches improve pollutant removal efficiency, reduce environmental risks, and support resource recovery. The reviewed studies indicate that integrated systems can achieve pollutant removal efficiencies of approximately 80–95%, although performance depends on pollutant characteristics, plant species, environmental conditions, and operational scale. Despite their potential, large-scale implementation remains limited by system complexity, economic considerations, field validation, and biosafety regulations related to genetically modified plants. This review provides a conceptual framework for integrating biological and engineering approaches and highlights the need for future research focusing on large-scale implementation, techno-economic evaluation, biosafety assessment, and the integration of emerging technologies such as artificial intelligence (AI), the Internet of Things (IoT), nanotechnology, and advanced genome-editing techniques.

References

Adesina, I., Bhowmik, A., Sharma, H., & Shahbazi, A. (2020). A Review on the Current State of Knowledge of Growing Conditions , Agronomic Soil Health Practices and Utilities of Hemp in the United States. Agriculture, 10(129), 1–15.

Ali, H., Khan, E., & Ilahi, I. (2019). Environmental Chemistry and Ecotoxicology of Hazardous Heavy Metals : Environmental Persistence , Toxicity , and Bioaccumulation. Journal of Chemistry, 1–14. https://doi.org/10.1155/2019/6730305

Ali, H., Khan, E., & Sajad, M. A. (2020). Phytoremediation of heavy metals—Concepts and applications. Chemosphere, 91(7), 869–881. https://doi.org/https://doi.org/10.1016/j.chemosphere.2013.01.075

Almeida-naranjo, C. E., Belén, M., Cabrera, G., & Guerrero, V. H. (2021). Caffeine Removal From Synthetic Wastewater Using Magnetic Fruit Peel Composites : Material Characterization , Isotherm And Kinetic Studies. Environmental Challenges, 5(100343), 1–11. https://doi.org/10.1016/j.envc.2021.100343

Alves, A. R. A., Yin, Q., Oliveira, R. S., Silva, E. F., & Novo, L. A. B. (2022). Plant Growth-Promoting Bacteria In Phytoremediation Of Metal-Polluted Soils: Current Knowledge And Future Directions. Science of the Total Environment, 838, 1–11. https://doi.org/10.1016/j.scitotenv.2022.156435

Arliyani, I., Noori, T., & Ammarullah, I. (2024). RSC Advances Constructed Wetlands Combined With Microbial Fuel Cells (CW-Mfcs) As A Sustainable Technology For Leachate Treatment And Power Generation. RSC Advances, 14, 32073–32100. https://doi.org/10.1039/D4RA04658G

Badamasi, H., Abdullahi, U. A., Kumar, A. P., Iya, I. D., Varra, V., & Olaleye, A. A. (2025). Nanotechnology-Assisted Phytoremediation of Heavy Metal Contaminated Soils: A State-of-the-Art Review on Recent Progress, Challenges, and Future Directions. Soil and Sediment Contamination: An International Journal, 00(00), 1–44. https://doi.org/10.1080/15320383.2025.2536035

Bhat, J. A., Yu, D., Bohra, A., Ganie, S. A., & Varshney, R. K. (2021). Features And Applications Of Haplotypes In Crop Breeding. Communications Biology, 1–12. https://doi.org/10.1038/s42003-021-02782-y

Borgulat, J., Ponikiewska, K., Jałowiecki, Ł., Strugała-Wilczek, A., & Płaza, G. (2022). Are Wetlands as an Integrated Bioremediation System Applicable for the Treatment of Wastewater from Underground. Energies, 15(4419), 1–19. https://doi.org/https://doi.org/10.3390/

Cao, M., & Zhang, Y. (2024). Reductive sequestration of Cr (VI) by phosphorylated nanoscale zerovalent iron. Journal of Environmental Management, 352, 119987. https://doi.org/https://doi.org/10.1016/j.jenvman.2023.119987

Carrasco-correa, E. J., Mompó-roselló, Ò., & Simó-alfonso, E. F. (2023). Environmental Technology & Innovation Calcium Oxide Nanofertilizer As Alternative To Common Calcium Products For The Improvement Of The Amount Of Peel Fruit Calcium. Environmental Technology & Innovation, 31, 103180. https://doi.org/10.1016/j.eti.2023.103180

Castellano-Hinojosa, A., Gallardo-Altamirano, M. J., Pozo, C., Gonz´alez-Martínez, A., & Gonz´alez-L´opez, J. (2024). Hydraulic Retention Time Drives Changes In Energy Production And The Anodic Microbiome Of A Microbial Fuel Cell (MFC). Journal Of Water Process Engineering, 59(February), 1–11. https://doi.org/10.1016/j.jwpe.2024.104966

Chen, F., Chen, L., Yan, Z., Xu, J., Feng, L., He, N., Guo, M., Zhao, J., Chen, Z., Chen, H., Yao, G., & Liu, C. (2024). Recent Advances Of CRISPR- Based Genome Editing For Enhancing Staple Crops. Frontiers in Plant Science, September, 1–21. https://doi.org/10.3389/fpls.2024.1478398

Crini, G., & Lichtfouse, E. (2019a). Advantages and disadvantages of techniques used for wastewater treatment. Environmental Chemistry Letters, 17, 145–155. https://doi.org/https://doi.org/10.1007/s10311-018-0785-9

Crini, G., & Lichtfouse, E. (2019b). Advantages And Disadvantages Of Techniques Used For Wastewater Treatment. Environmental Chemistry Letters, 17(1), 145–155. https://doi.org/10.1007/s10311-018-0785-9

Dada, M. A., Majemite, M. T., Obaigbena, A., & Daraojimba, O. H. (2024). Review Of Smart Water Management : Iot And AI In Water And Wastewater Treatment. World Jurnal of Advanced Research and Reviews, 21(01), 1373–1382. https://doi.org/https://doi.org/10.30574/wjarr.2024.21.1.0171

Ding, C., Chen, J., Zhu, F., Chai, L., Lin, Z., & Zhang, K. (2022). Biological Toxicity of Heavy Metal (loid) s in Natural Environments : From Microbes to Humans. Frontiers in Environmental Science, 10(May), 1–23. https://doi.org/10.3389/fenvs.2022.920957

Du, X., Shi, Y., & Jegatheesan, V. (2020). A Review on the Mechanism , Impacts and Control Methods of Membrane Fouling in MBR System. Membranes, 10(24), 1–33. https://doi.org/10.3390/membranes10020024

Fatima, M., Shukla, N., Afzal, S., Mishra, M., Pandey, A., Chaudhary, N., Patel, A., & Singh, N. K. (2025). Phycoremediation of industrial wastewater: Mechanisms, efficiency, and future prospects. Bioresource Technology Reports, 32, 102385. https://doi.org/https://doi.org/10.1016/j.biteb.2025.102385

García-Carrillo, M., Flores-Hernández, E. A., Leos-Escobedo, L., Ramírez-Gottfried, R. I., Ruiz-Machuca1, L. M., Luna-Ortega, J. G., Preciado-Rangel, P., & Concilco-Alberto, E. (2024). Heavy Metals Phytoextraction Potential Of Medicago Sativa L. Irrigated With Waste And Groundwater. Rev. Int. Contam. Ambie, 40, 669–676. https://doi.org/https://doi.org/10.20937/RICA.55089

Giwa, A., Yusuf, A., Balogun, H. A., Sambudi, N. S., Bilad, M. R., Adeyemi, I., Chakraborty, S., Curcio, S., & Drioli, E. (2021). Recent advances in advanced oxidation processes for removal of contaminants from water: A comprehensive review. Process Safety and Environmental Protection, 146, 220–256.

https://doi.org/https://doi.org/10.1016/j.psep.2020.08.015

Guerra, F. D., Attia, M. F., Whitehead, D. C., & Alexis, F. (2018). Nanotechnology for Environmental Remediation : Materials and Applications. Molecules, 23(1760), 1–23. https://doi.org/10.3390/molecules23071760

Hyun, T. K. (2020). CRISPR / Cas-based genome editing to improve abiotic stress tolerance in plants. Botanica Serbica, 44(2), 121–127. https://doi.org/https://doi.org/10.2298/BOTSERB2002121H

Ijoma, G. N., Lopes, T., Mannie, T., & Mhlongo, T. N. (2024). Exploring Macrophytes ' Microbial Populations Dynamics To Enhance Bioremediation In Constructed Wetlands For Industrial Pollutants Removal In Sustainable Wastewater Treatment. In Symbiosis (Vol. 92, Issue 3). Springer Netherlands. https://doi.org/10.1007/s13199-024-00981-9

Islam, F. A. S. (2025). Advanced Wastewater Treatment Technologies in Addressing Future Water Scarcity through Resource Recovery and Reuse. Journal of Engineering Research and Reports, 27(5), 370–398. https://doi.org/https://orcid.org/0000-0003-1589-7685

Jassal, S., Mittal, I., Warmoota, R., Sharma, A., Goyal, D., & Gupta, N. (2023). Sustainable Waste Water Treatment : Opportunities and Challenges. Brazilian Archives Of Biology and Technology, 66, 1–15. https://doi.org/https://doi.org/10.1590/1678-4324-2023220546

Kaur, H., Pandey, D. K., Goutam, U., & Kumar, V. (2021). CRISPR/Cas9-Mediated Genome Editing Is Revolutionizing The Improvement Of Horticultural Crops: Recent Advances And Future Prospects. Scientia Horticulturae, 289(17), 110476. https://doi.org/https://doi.org/10.1016/j.scienta.2021.110476

Koul, B., Yakoob, M., & Shah, M. P. (2022). Agricultural waste management strategies for environmental sustainability. Environmental Research, 206, 112285. https://doi.org/https://doi.org/10.1016/j.envres.2021.112285

Kumar, A., & Chattopadhyay, S. (2025). Performance Evaluation of a Constructed Wetland System for Wastewater Treatment in the Yamuna Expressway Industrial Development Authority (YEIDA) Area , India. International Journal of Environmental Impacts, 8(4), 645–654. https://doi.org/https://doi.org/10.18280/ijei.080402 Received:

Kurniawan, S. B., Ramli, N. N., Said, N. S. M., Alias, J., Imron, M. F., Abdullah, S. R. S., Othman, A. R., Purwanti, I. F., & Hasan, H. A. (2022). Heliyon Practical Limitations Of Bioaugmentation In Treating Heavy Metal Contaminated Soil And Role Of Plant Growth Promoting Bacteria In Phytoremediation As A Promising Alternative Approach. Heliyon, 8(4), 1–14. https://doi.org/10.1016/j.heliyon.2022.e08995

Kushwaha, P., & Kashyap, P. L. (2021). A Review of Advances in Bioremediation of Heavy Metals by Microbes and Plants. Journal of Natural Resource Conservation and Management, 2(1), 65–80. https://doi.org/10.51396/ANRCM.2.1.2021.65-80

Li, K., Qi, J., Zhang, F., Miwornunyuie, N., Amaniampong, P. S., Koomson, D. A., Chen, L., Yan, Y., Dong, Y., Setordjie, V. E., & Samwini, A. M. (2021). The Role of Wetland Plants on Wastewater Treatment and Electricity Generation in Constructed Wetland Coupled with Microbial Fuel Cell. Applied Sciences, 11(7454), 1–14. https://doi.org/https://doi.org/10.3390/app11167454

Liu, N., Zhao, J., Du, J., Hou, C., Zhou, X., Chen, J., & Zhang, Y. (2024). Non-phytoremediation and phytoremediation technologies of integrated remediation for water and soil heavy metal pollution: A comprehensive review. Science of The Total Environment, 948, 174237. https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.174237

Luo, J., Li, H., Liu, T., Polle, A., Peng, C., & Luo, Z. B. (2021). Variation in cadmium accumulation and tolerance among sweet potato genotypes. Environmental and Experimental Botany, 182, 104307. https://doi.org/https://doi.org/10.1016/j.envexpbot.2020.104307

Mohammed, Z. B., Abdulkareem, F. A., & Resheq, A. S. (2020). The Performance of Moving Bed Biofilm Reactor in Wastewater Treatment. Journal of Green Engineering (JGE), 10(10), 9160–9175.

Moqsud, M. A. (2024). Plant Microbial Fuel Cell. Licensee IntechOpen, 1–11. https://doi.org/http://dx.doi.org/10.5772/intechopen.1004327

Nidheesh, P. V., Zhou, M., & Oturan, M. A. (2021). An overview on the removal of synthetic dyes from water by electrochemical advanced oxidation processes. Chemosphere, 157, 210–227. https://doi.org/https://doi.org/10.1016/j.chemosphere.2017.12.195

Ombadi, M., & Varadharajan, C. (2022). Urbanization And Aridity Mediate Distinct Salinity Response To Floods In Rivers And Streams Across The Contiguous United States. Water Research, 220(118664), 1–9. https://doi.org/10.1016/j.watres.2022.118664

Ozyigit, I. I., & Dogan, I. (2015). Plant-Microbe Interactions in Phytoremediation. In Chapter. https://doi.org/httpsz;//dx.doi.org/10.1016/B978-0-12-799937-1.00009-7

Page, M. J., Mckenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-wilson, E., Mcdonald, S., … Moher, D. (2021). The PRISMA 2020 Statement: An Updated Guideline For Reporting Systematic Reviews. Research Methods And Reporting, 1–9. https://doi.org/10.1136/bmj.n71

Pang, Y. L., Quek, Y. Y., Lim, S., & Shuit, S. H. (2023). Review On Phytoremediation Potential Of Floating Aquatic Plants For Heavy Metals : A Promising Approach. Sustainability, 15(1290), 1–23. https://doi.org/https://doi.org/10.3390/su15021290

Paul, J., & Criado, A. R. (2020). The art of writing literature review: What do we know and what do we need to know? International Business Review, 29(4), 101717. https://doi.org/https://doi.org/10.1016/j.ibusrev.2020.101717

Raza, A., Tabassum, J., Zahid, Z., Charagh, S., Bashir, S., Barmukh, R., Khan, R. S. A., Jr., F. B., Zhang, C., Chen, H., Varshney, W. Z., & K., A. (2022). Advances In " Omics " Approaches For Improving Toxic Metals / Metalloids Tolerance In Plants. Frontiers in Plant Science, 12(January), 1–28. https://doi.org/10.3389/fpls.2021.794373

Rezania, S., Ponraj, M., Talaiekhozani, A., Mohamad, S. E., Md Din, M. F., Taib, S. M., Sabbagh, F., & Sairan, F. M. (2022). Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater. Journal of Environmental Management, 295, 113318. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113318

Sahoo, R., Sow, S., Ranjan, S., Rajan, D., Dhirendra, K., Roy, K., & Kumar, S. (2024). Unveiling The Potential Of Plant Growth Promoting Rhizobacteria (PGPR) In Phytoremediation Of Heavy Metal. Discover Applied Sciences, 6(324), 1–20. https://doi.org/10.1007/s42452-024-06024-8

Saleem, M. H., Ali, S., Rehman, M., Hasanuzzaman, M., Rizwan, M., Irshad, S., Shafiq, F., Iqbal, M., Alharbi, B. M., Alnusaire, T. S., & Qari, S. H. (2020). Jute : A Potential Candidate for Phytoremediation of Metals — A Review. Plants, 9(258), 1–14. https://doi.org/10.3390/plants9020258

Sharma, P., Tripathi, S., Purchase, D., & Chandra, R. (2021). Integrating phytoremediation into treatment of pulp and paper industry wastewater: Field observations of native plants for the detoxification of metals and their potential as part of a multidisciplinary strategy. Journal of Environmental Chemical Engineering, 9(4), 105547. https://doi.org/https://doi.org/10.1016/j.jece.2021.105547

Sharma, R., & Malaviya, P. (2022). Constructed wetlands for textile wastewater remediation: A review on concept, pollutant removal mechanisms, and integrated technologies for efficiency enhancement. Chemosphere, 290, 133358. https://doi.org/https://doi.org/10.1016/j.chemosphere.2021.133358

Shourie, A., Mazahar, S., & Singh, A. (2024). Biotechnological Approaches For Enhancement Of Heavy Metal Phytoremediation Capacity Of Plants. Environmental Monitoring and Assessment, 196(789), 1–18. https://doi.org/10.1007/s10661-024-12940-4

Singh, P., Singh, G., Singh, A., Kumar, V., & Reetika, M. (2024). Macrophytes for Utilization in Constructed Wetland as Efficient Species for Phytoremediation of Emerging Contaminants from Wastewater. Wetlands, 44(22), 1–24. https://doi.org/10.1007/s13157-024-01770-2

Snyder, H. (2019). Literature Review As A Research Methodology : An Overview And Guidelines. Journal of Business Research, 104(July), 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Sonu, K., Sogani, M., & Syed, Z. (2000). Integrated Constructed Wetland-Microbial Fuel Cell using

Biochar as Wetland Matrix : Influence on Power Generation and Textile Wastewater Treatment. ChemistrySelect, 6, 1–7. https://doi.org/doi.org/10.1002/slct.202102033

Tan, K. B., Vakili, M., Horri, B. A., Poh, P. E., Abdullah, A. Z., & Salamatinia, B. (2020). Adsorption of dyes by nanomaterials: Recent developments and adsorption mechanisms. Separation and Purification Technology, 150, 229–242. https://doi.org/https://doi.org/10.1016/j.seppur.2015.07.009

Thakur, T. K., Barya, M. P., Dutta, J., Mukherjee, P., Thakur, A., Swamy, S. L., & Anderson, J. T. (2023). Integrated Phytobial Remediation of Dissolved Pollutants from Domestic Wastewater through Constructed Wetlands : Resource Recovery. Water, 15(3877), 1–50. https://doi.org/https://doi.org/10.3390/w15223877

Umair, M., Zia-ur-Rehman, M., Qazi, M. A., Rizwan, A., Qamar, M. J., & Razzaq, S. (2023). Nanoparticles-Assisted Phytoremediation of Polluted Soils: Potential Application and Challenges. In Management of Environmental Contaminants (Vol. 7). https://doi.org/https://doi.org/10.1007/978-3-031-17988-4_23

Wang, Y., Narayanan, M., Chen, X., Li, Z., Natarajan, D., & Ma, Y. (2022). Plant Growth-Promoting Bacteria In Metal- Contaminated Soil : Current Perspectives On Remediation Mechanisms. Frontiers in Microbiology, August, 1–17. https://doi.org/10.3389/fmicb.2022.966226

Wang, Z., Ma, J., Tang, C. Y., Kimura, K., Wang, Q., & Han, X. (2022). The optimization and regulation of energy consumption for MBR process: A critical review. Journal of Environmental Chemical Engineering, 10(5), 108406. https://doi.org/https://doi.org/10.1016/j.jece.2022.108406

Xiao, Y., & Watson, M. (2019). Guidance on conducting a systematic literature review. Journal of Planning Education and Research, 39(1), 93–112. https://doi.org/https://doi.org/10.1177/0739456X17723971

Yan, A., Wang, Y., Tan, S. N., Yusof, M. L. M., Ghosh, S., & Chen, and Z. (2020). Phytoremediation: A Promising Approach for Revegetation of Heavy Metal-Polluted Land. Frontiers in Plant Science, 11(April), 1–15. https://doi.org/10.3389/fpls.2020.00359

Yang, K. M., & Malijan, I. (2026). Hybrid Fungal Wetland Systems For Advanced Textile Wastewater Treatment : A Comprehensive Review. International Journal of Environmental Science and Technology, 23(330), 1–12. https://doi.org/10.1007/s13762-026-07113-4

Zeng, D., Wu, J., Mu, Y., Li, H., Deng, M., Wei, Y., & Sun, W. (2020). An Assessment of Tourism Climate Comfort in the China – Pakistan Economic Corridor. Sustainability, 12(6981), 1–12. https://doi.org/10.3390/su12176981

Zhang, Y., Han, Y., Xie, E., Wang, X., Yang, Y., & Jia, F. (2024). Phytoremediation performance of mixed planting patterns and the associated rhizosphere microbial community in pilot-scale constructed wetlands. Chemosphere, 361, 142482. https://doi.org/https://doi.org/10.1016/j.chemosphere.2024.142482