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BIOTECHNOLOGICAL BIOREMEDIATION SOLUTIONS FOR ENVIRONMENTS CONTAMINATED WITH PHARMACEUTICAL WASTE - A REVIEW

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Abstract

In recent years, increasing attention has been directed toward the issue of waste generation and the development of strategies for its mitigation. The environmental impact of pharmaceutical waste—originating from medical facilities, the pharmaceutical industry, pharmacies, and households—containing persistent and biologically active compounds capable of contaminating soils and aquatic systems, promoting ecological imbalances and the emergence of antimicrobial resistance, can be reduced through the application of biotechnological approaches as sustainable remediation solutions. The study highlights the effectiveness of organisms such as Pseudomonas spp., Trametes versicolor, and Chlorella vulgaris in decreasing the concentrations of persistent pharmaceutical compounds. The conclusions emphasize the necessity of adopting integrated management strategies and strengthening the regulatory framework, thereby positioning bioremediation as a priority direction for the protection of ecosystems and public health.

Key words*: pharmaceutical waste, bioremediation, Pseudomonas spp., Trametes versicolor, Chlorella vulgaris.*

INTRODUCTION

The ongoing rise in worldwide consumption of pharmaceutical products has resulted in a novel form of pollution: pharmaceutical waste, also referred to as medical waste. This includes expired or unused medicines, as well as residues from manufacturing processes and use in medical institutions or households. The persistent and toxic nature of these compounds, in conjunction with their capacity for bioaccumulation, poses a significant threat to the environment and public health. This contributes to phenomena such as antimicrobial resistance, ecological imbalances, and the contamination of natural resources. Inadequate management of pharmaceutical waste enables contaminants to migrate into soils, groundwater, and surface waters, thereby disturbing ecosystem stability and posing risks to public health (Sahota & Sharma, 2022). Environmental exposure to pharmaceutical compounds has been correlated with antimicrobial resistance, endocrine and behavioural effects in every kind of organism, and potential risks to human health (United Nations Environment Programme, n.d.-a). Consequently, the issue represents both an ecological and a global health challenge. Conventional disposal practices, particularly landfilling and incineration, present notable limitations related to infrastructure and economic cost, operational efficiency, and the risk of secondary emissions or leachate-related contamination (Srinivasan at al., 2025; World Health Organization, 2014a). Within this framework, emerging biotechnological approaches offer promising strategies for environmentally compatible remediation of pharmaceutical residues (Sahota et al., 2021). These methods commonly use microorganisms, microbial enzymes, and plants to facilitate degradation and detoxification processes and they are often presented as lower-impact alternatives with potential for scale-up in engineered treatment systems (Ayilara & Babalola, 2023).

The environmental implications of pharmaceutical waste constitute a complex and increasingly prominent concern in the context of globalization and expanding pharmaceutical consumption. Contamination by these

substances produces direct and indirect effects on biodiversity, natural resource quality, and ultimately human health. Furthermore, pollution generated by residual pharmaceuticals is often insufficiently addressed in conventional environmental protection policies, contributing to ongoing and difficult-to-manage environmental exposure.

A salient characteristic of pharmaceutical waste is its categorisation as a waste stream despite its inherent biologically active constituents. These constituents possess the potential to exert deleterious effects on the environment and human health if not managed in an appropriate manner. Unlike most other waste streams, pharmaceutical residues require heightened control due to associated hazards, including the development of antimicrobial resistance, endocrine disruption within ecosystems, and accumulation along trophic chains. In many situations, the absence of an efficient separate collection system results in improper disposal, such as discarding with household waste or releasing into sewage networks, leading to direct adverse environmental impacts.

Pharmaceutical waste originates from multiple sources, and its volume and composition may vary substantially depending on the sector of generation, the applied waste management policies, and the level of awareness among the personnel involved (United Nations Environment Programme, n.d.-b; World Health Organization, 2024b). These sources include medical facilities, hospital and community pharmacies, households and individual users, care centres and nursing homes, the pharmaceutical industry, veterinary practices, livestock production units, and research programs and laboratories.

The management of pharmaceutical waste is shaped by national and international legal and policy framework intended to protect public health and the environment. These frameworks allocate responsibilities for the collection, transport, treatment, and disposal of medicinal waste to manufacturers, pharmacies, healthcare facilities, waste operators, and local authorities. The legal provisions exist both at the European Union level and at the national level. The most relevant include: Directive 2008/98/EC on waste, Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures (CLP), Directive 2010/75/EU on industrial emissions, Regulation (EU) 2019/6 on veterinary medicinal products, Law No. 211/2011 on waste management, Ministry of Health Order No. 1226/2012, Law No. 95/2006 on healthcare reform, and Law No. 104/2011 on ambient air quality.

This study aims to evaluate the environmental impact of pharmaceutical waste, and identify associate risks, and examine current as well as emerging biotechnological remediation strategies. Through a multidisciplinary perspective, it seeks to provide a coherent understanding of the issue and to outline future research and implementation directions for environmental and public health protection.

BIOREMEDIATION: PRINCIPLES AND APPLICABILITY

Bioremediation is widely regarded as one of the most promising environmentally compatible approaches for reducing the impact of pharmaceutical residues in contaminated matrices. The process relies on the metabolic activity of living organisms, mainly bacteria, fungi, and microalgae, which can transform or mineralize pharmaceutical compounds into less harmful intermediates or end products. Its conceptual basis lies in the natural ability of these organisms to use complex organic molecules as carbon or energy sources, or to transform them co-metabolically through oxidative, reductive, and hydrolytic enzymatic pathways. Recent reviews emphasize that microbial remediation is particularly attractive for pharmaceutical contaminants because it can be integrated into wastewater treatment systems and may reduce the reliance on more energy-intensive physico-chemical methods (Shah et al., 2024; Bhaskaralingam et al., 2025; Srinivasan et al., 2025).

A critical factor in the practical application of bioremediation is the selection of appropriate biological agents and the optimization of environmental conditions governing their metabolic performance. Parameters such as pH, temperature, dissolved oxygen, redox state, nutrient availability, hydraulic conditions, and contaminant concentration strongly influence biodegradation kinetics and transformation

pathways. In applied systems, two main strategies are commonly discussed: biostimulation, which enhances the activity of indigenous microbial communities through nutrient or electron acceptor amendment, and bioaugmentation, which introduces specialized strains or consortia with higher degradative capacity. Current literature also stresses that the success of these strategies depends on pollutant bioavailability, competition within microbial communities, and the compatibility of inoculated strains with local environmental conditions (Shah et al., 2024; Srinivasan et al., 2025).

The applicability of bioremediation to pharmaceutical pollution spans a broad range of environmental compartments, including wastewater, surface waters, sediments, soils, and certain solid waste streams. In biological wastewater treatment plants, pharmaceuticals are often only partially removed, and removal efficiencies vary considerably according to the chemical structure of each compound, hydraulic retention time, sludge age, and operational conditions. For contaminated soils, both *in situ* and *ex situ* approaches have been investigated, including nutrient amendment, aeration, engineered biopiles, and bioreactor-based treatment. Although these systems can substantially reduce the concentration of some pharmaceuticals, the literature consistently notes that highly persistent compounds such as carbamazepine and some antibiotics remain difficult to eliminate completely through biological treatment alone (Singh et al., 2024; Mansour et al., 2025; Srinivasan et al., 2025).

Figure 1 presents specific techniques of removal efficiency (in average) for some compounds.

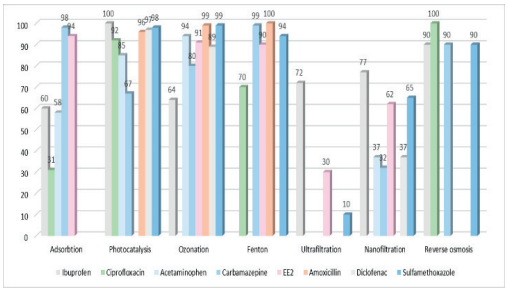

Figure 1. Removal efficiency (%) of selected compounds (Source: Mansour et al., 2025)

The major advantages of bioremediation include relatively low energy demand, lower chemical input, operational flexibility, and the possibility of targeting complex mixtures of organic contaminants under environmentally mild conditions. However, the method also presents important limitations, including long treatment times, incomplete mineralization, formation of transformation products, and limited predictability under variable field conditions. For this reason, the recent literature increasingly frames bioremediation not as a universal stand-alone solution, but as a core component of integrated treatment systems coupled with enzymatic, photocatalytic, electrochemical, or adsorption-based technologies (Bhaskaralingam et al., 2025; Mansour et al., 2025; Singh et al., 2024).

MICROORGANISMS USED IN PHARMACEUTICAL DEGRADATION

Microorganisms constitute the central biological drivers of pharmaceutical bioremediation because of their metabolic diversity and their ability to transform structurally complex xenobiotics. In the context of pharmaceutical removal, bacteria, filamentous fungi, and microalgae have received the greatest attention. Their contribution may involve direct biodegradation, co-metabolic transformation, biosorption, intracellular accumulation, or the secretion of extracellular enzymes capable of attacking recalcitrant molecular structures. Recent reviews indicate that no single microbial group is universally effective against all classes of pharmaceuticals, which explains the growing interest in mixed cultures and engineered consortia (Shah et al., 2024; Srinivasan et al., 2025; Pantha et al., 2025).

Among bacteria, genera such as *Pseudomonas*, *Bacillus*, *Sphingomonas*, and *Rhodococcus* are frequently highlighted because of their broad catabolic versatility and tolerance to contaminated environments. These taxa have been associated with the degradation or transformation of pharmaceuticals including analgesics, antibiotics, beta-blockers, and antiepileptic compounds. Their performance is generally linked to oxygenase-mediated oxidation, hydrolysis, and co-metabolic

pathways, as well as to their capacity to participate in biofilm-based treatment systems. Nevertheless, the literature also emphasizes that observed removal efficiencies are strongly compound-specific and often depend on the presence of auxiliary substrates and acclimatized microbial communities (Shah et al., 2024; Srinivasan et al., 2025).

Fungi, particularly white-rot fungi, are increasingly recognized as effective agents for the transformation of pharmaceutically active compounds because they produce extracellular oxidative enzymes with relatively broad substrate specificity. Species such as *Trametes versicolor*, *Phanerochaete chrysosporium*, and *Pleurotus ostreatus* have been widely investigated for the removal of anti-inflammatory drugs, antibiotics, endocrine-active compounds, and other persistent micropollutants. Their remediation potential is typically attributed to laccases, manganese peroxidases, lignin peroxidases, and cytochrome P450-related systems, which allow the oxidation of aromatic and otherwise recalcitrant molecules. The fungal approach is especially promising for compounds that are poorly removed in conventional activated sludge systems (Chmelová et al., 2024).

Microalgae have also emerged as relevant biological tools for the treatment of pharmaceutical contaminants, especially in aquatic systems and polishing stages of wastewater treatment. Species such as *Chlorella vulgaris* and *Scenedesmus obliquus* are frequently cited for their capacity to remove pharmaceuticals through a combination of bioadsorption, bioaccumulation, photobio-transformation, and metabolism-linked degradation. Although their removal efficiencies can vary widely with light, nutrient balance, biomass productivity, and contaminant concentration, recent reviews identify algal systems as promising low-impact platforms for integrated remediation strategies (OECD, 2022).

At the mechanistic level, pharmaceutical biodegradation is usually discussed in terms of oxidation-reduction reactions, hydrolysis, dealkylation, dehalogenation, ring cleavage, sorption-mediated uptake, and co-metabolic conversion. Oxygenases and peroxidases are especially relevant for aromatic and hydrophobic compounds, whereas hydrolases, esterases, and amidases contribute to the cleavage of ester and amide bonds present in several drug classes. In many cases, partial transformation rather than complete mineralization is observed, which makes the identification of intermediates and toxicity assessment of degradation products an important research priority (Chmelová et al., 2024; Shah et al., 2024; Srinivasan et al., 2025).

PHYTOREMEDIATION

Phytoremediation is increasingly described in the literature as a sustainable, low-input technology for the remediation of soils, sediments, and waters contaminated with pharmaceutical residues and other emerging pollutants. The approach exploits the capacity of plants and their associated rhizosphere microbiota to absorb, accumulate, transform, immobilize, or stimulate the degradation of contaminants. In contrast with more aggressive treatment methods, phytoremediation is generally valued for its lower energy requirements, landscape compatibility, and potential integration into nature-based systems such as constructed wetlands and buffer zones (Singh et al., 2024; Di Stasio et al., 2025; Pantha et al., 2025).

The principal phytoremediation mechanisms discussed in the literature include phytoextraction, phytodegradation, phytostabilization, and rhizodegradation. In the context of pharmaceutical pollution, rhizosphere-driven processes are often particularly important because plant roots release exudates that stimulate microbial communities capable of transforming micropollutants. Direct plant uptake may also occur, followed by translocation, sequestration, or enzymatic transformation inside plant tissues. However, the relative contribution of plant metabolism versus microbially mediated rhizosphere degradation remains system-dependent and is still being actively investigated, especially for complex mixtures of pharmaceuticals (Singh et al., 2024; Pantha et al., 2025).

Several plant taxa have been examined for their remediation potential, including woody species

such as *Populus* spp. and *Salix* spp., as well as wetland and crop species used in engineered treatment systems. Woody plants are often considered advantageous because of their rapid growth, deep root systems, and strong interaction with rhizosphere microbes, while aquatic and semi-aquatic species are frequently incorporated into constructed wetlands for continuous treatment of contaminated water. By contrast, the use of model plants such as *Arabidopsis thaliana* is mainly relevant for mechanistic research rather than for direct large-scale remediation. The literature therefore supports the use of plant-based systems, but usually in the context of carefully selected species, site-specific design, and combined plant-microbe interactions (Pantha et al., 2025).

Phytoremediation also benefits from integration with other biological approaches, especially rhizosphere bioaugmentation, plant growth-promoting microorganisms, and enzyme-assisted treatment concepts. More exploratory research has extended this framework toward engineered plants, synthetic biology, and hybrid phytoremediation platforms, although these approaches remain largely at the experimental or pilot stage. Current reviews consistently point out that phytoremediation is constrained by slow kinetics, seasonal variability, contaminant bioavailability, and limited effectiveness under very high contamination loads. As a result, it is best interpreted as a sustainable complementary technology rather than a universally sufficient stand-alone remediation option (Singh et al., 2024; Wang et al., 2024; Pantha et al., 2025).

INNOVATIVE BIOLOGICAL TECHNOLOGIES

Beyond classical bioremediation and phytoremediation, recent research has increasingly focused on innovative biological technologies that attempt to improve selectivity, stability, and process efficiency in the removal of pharmaceutical contaminants. These technologies include free and immobilized enzymes, microbe-material interfaces, nanobiotechnology-based systems, engineered microbial consortia, and hybrid bio-physico-chemical platforms. Although many of these solutions remain under development, they reflect a broader shift in remediation research toward modular and multifunctional treatment systems designed for complex contaminant mixtures (Mansour et al., 2025; Srinivasan et al., 2025; Salehpour et al., 2026).

Enzyme-based remediation has attracted substantial attention because enzymes can catalyze highly specific transformation reactions under mild operating conditions. Among the most studied biocatalysts are laccases, peroxidases, monooxygenases, dioxygenases, esterases, and lipases. Laccases derived from fungal systems, particularly *Trametes versicolor*, are widely reported to oxidize a broad spectrum of pharmaceuticals, including anti-inflammatory compounds, antibiotics, hormones, and other aromatic pollutants. Immobilization on solid supports can improve enzyme stability, facilitate reuse, and support integration into membranes, packed-bed reactors, and advanced filtration units, although cost, enzyme deactivation, and mediator requirements remain important practical challenges (Chmelová et al., 2024; Thathola et al., 2024; Singh et al., 2024).

Nanobiotechnology has introduced new possibilities for pharmaceutical remediation by combining biological catalysts or cells with functional nanomaterials that enhance adsorption, catalysis, immobilization, sensing, or electron transfer. Reported approaches include enzyme-coated nanoparticles, nanostructured supports for immobilized biocatalysts, reactive metal oxides, graphene-based composites, and hybrid biopolymer nanocomposites. These systems may improve catalytic efficiency and contaminant capture, but the current literature also highlights concerns regarding material recovery, life-cycle sustainability, ecotoxicological assessment, and large-scale deployment. Consequently, nanobiotechnology is best described at present as a rapidly developing research direction with significant potential, rather than a mature universal solution (Salehpour et al., 2026).

Another emerging direction involves the use of synthetic biology and engineered microbial consortia to enhance the transformation of difficult pharmaceutical compounds. In principle, genetically tailored microorganisms may be designed to express specific catabolic

enzymes or optimized pathways, while synthetic communities may distribute degradation functions across multiple compatible strains. This concept is scientifically compelling because it addresses metabolic bottlenecks and broadens substrate coverage; however, in environmental remediation it is still constrained by biosafety, regulatory acceptance, ecological stability, and deployment challenges outside controlled reactors. For that reason, most current discussions remain prospective rather than implementation-driven (European Commission, 2024).

A significant trend within this field is the development of hybrid systems that combine biological processes with photocatalytic, electrochemical, adsorption-based, or membrane-assisted treatment. Examples discussed in recent reviews include photo-biocatalytic systems, bioelectrochemical reactors such as microbial fuel cells, microalgae-electrocatalytic configurations, and bioactive porous filters. These integrated platforms are attractive because they can improve removal of recalcitrant pharmaceuticals while reducing some of the limitations of individual technologies. At the same time, the literature repeatedly notes that scale-up, economics, by-product control, and treatment of real wastewater matrices remain major barriers to routine application (Corona-Martínez et al., 2025; Mansour et al., 2025).

CLASSICAL AND MODERN BIOREMEDIATION METHODS IN THE LITERATURE

Over the past two decades, pharmaceutical residues have been increasingly recognized as a distinct class of emerging contaminants because they occur in surface waters, groundwater, drinking-water sources, soils, and sediments, while many conventional wastewater treatment systems were not designed to remove them efficiently (OECD, 2019; Srinivasan et al., 2025). This growing concern is also linked to evidence that some pharmaceutical compounds can affect aquatic organisms at very low concentrations and may contribute to broader ecological risks, including endocrine disruption, behavioural changes, and the selection of antimicrobial resistance (OECD, 2019).

Conventional remediation and disposal methods, including standard biological wastewater treatment, incineration, and controlled landfilling, remain important components of pharmaceutical waste management, but the literature consistently highlights their limitations. Wastewater treatment plants frequently achieve only partial removal of pharmaceutical residues, particularly for structurally persistent compounds, while disposal-based strategies may generate secondary environmental burdens if emissions, ash, or leachate are not properly controlled (OECD, 2019; Mahmud et al., 2025). Consequently, conventional systems are increasingly regarded as necessary but insufficient for addressing diffuse and chronic pharmaceutical contamination.

Among modern approaches, microbial bioremediation is one of the most extensively investigated strategies because it relies on the metabolic and co-metabolic capacity of bacteria, fungi, and mixed microbial consortia to transform pharmaceutical contaminants under aerobic or anaerobic conditions (Srinivasan et al., 2025). Recent reviews identify bacterial genera such as *Pseudomonas*, *Bacillus*, and *Rhodococcus* as particularly relevant due to their catabolic versatility, whereas fungal systems are valued for extracellular oxidative enzyme production and their capacity to attack more recalcitrant molecules (Flórez-Restrepo et al., 2025; Srinivasan et al., 2025). However, degradation efficiency remains highly dependent on environmental conditions, contaminant bioavailability, and compound-specific physicochemical properties (Srinivasan et al., 2025).

Phytoremediation occupies an important place in the recent literature as a low-input and environmentally compatible option for soils, wetlands, and polishing systems exposed to pharmaceutical contamination. Its effectiveness is generally associated with plant uptake, rhizosphere-assisted degradation, sequestration, and plant-microbe interactions rather than with rapid contaminant destruction alone. At the same time, recent meta-analytical work emphasizes that phytoremediation is limited by

slow kinetics, seasonal variability, and reduced effectiveness against highly persistent compounds, which is why it is usually presented as a complementary technology rather than a stand-alone solution (Pantha et al., 2025).

More advanced developments in the field include enzyme-based and hybrid remediation systems. In particular, laccases and other oxidative enzymes, especially those derived from ligninolytic fungi, have been widely studied for their ability to degrade a broad range of pharmaceutically active compounds under relatively mild conditions (Chmelová et al., 2024; Singh et al., 2024). Immobilization strategies have further increased interest in enzymatic systems by improving catalyst stability and reusability, although practical implementation is still constrained by enzyme cost, deactivation, and process optimization challenges (Chmelová et al., 2024; Ezra et al., 2025).

In parallel, nanobiotechnology and other hybrid platforms have expanded the scope of modern bioremediation by combining biological catalysts with functional materials for adsorption, photocatalysis, and enhanced transformation. These systems show substantial promise in controlled studies, but the literature also stresses unresolved concerns related to scale-up, catalyst recovery, ecotoxicological safety, and long-term environmental performance (Srinivasan et al., 2025; Salehpour et al., 2026). Consequently, the dominant conclusion in recent reviews is that the future of pharmaceutical remediation lies in integrated treatment trains that combine classical biodegradation principles with enzymatic engineering, materials-based enhancement, and system-level process design (Pantha et al., 2025; Salehpour et al., 2026).

COMPLEMENTARY PLANT-BASED, ENZYMATIC, AND HYBRID STRATEGIES FOR PHARMACEUTICAL WASTE REMEDIATION

Phytoremediation is increasingly described as a complementary remediation strategy for pharmaceutical pollution because it combines plant uptake, rhizosphere-assisted transformation, and microbially mediated detoxification under relatively low-input conditions. In this framework, the rhizosphere is particularly important, since root-associated microbial communities can enhance the degradation of pharmaceutical residues through co-metabolic and enzyme-driven processes. Recent reviews therefore present plant-microbe systems not as isolated biological tools, but as interactive remediation platforms in which plants improve contaminant access and microbial communities accelerate transformation and detoxification (OECD, 2019; Pantha et al., 2025).

A consistent theme in the recent literature is that rhizosphere engineering can improve phytoremediation performance. Reviews on microbe-assisted phytoremediation show that inoculation with plant growth-promoting and pollutant-degrading rhizobacteria can stimulate root development, increase biomass, and enhance contaminant removal, especially in wetland and wastewater-treatment settings. At the same time, authors emphasize that the outcome remains species- and site-dependent, because plant physiology, microbial compatibility, pollutant class, and environmental conditions jointly determine remediation efficiency. For this reason, plant–microbe consortia are increasingly presented as promising but still optimization-dependent systems rather than universally transferable solutions (Oubohssaine & Dahmani, 2024).

Another expanding branch of the literature concerns enzyme-based remediation, particularly the use of purified oxidoreductases such as laccases and peroxidases for the transformation of structurally complex pharmaceutical molecules. These enzymes are attractive because they offer relatively high substrate specificity, operate under mild reaction conditions, and avoid the process-control challenges associated with maintaining viable microbial cultures in industrial applications. However, reviews consistently note that commercial deployment is still constrained by enzyme instability, mediator requirements, production cost, and limited operational lifetime. As a result, enzyme immobilization on solid supports has become a major research direction, since it can improve catalyst stability, facilitate recovery, and increase reuse potential in continuous treatment

systems (Chmelová et al., 2024; Thathola et al., 2024; Wang et al., 2024; Singh et al., 2024).

Nanotechnology is also increasingly discussed as an enabling platform for pharmaceutical remediation, especially in hybrid systems that combine photocatalysis, adsorption, and biologically assisted degradation. Functional nanomaterials can accelerate contaminant transformation, improve catalyst immobilization, and support compact treatment configurations, but the literature remains cautious about large-scale implementation. Reviews repeatedly identify unresolved concerns related to nanoparticle recovery, long-term environmental fate, ecotoxicological safety, and the possibility that the remediation material itself could introduce secondary risks. Consequently, recent scholarship tends to frame nanotechnology not as a stand-alone answer, but as part of a broader class of hybrid remediation systems that require life-cycle and risk assessment before full-scale adoption (OECD, 2019; Salehpour et al., 2026).

From a management perspective, the literature increasingly argues that effective control of pharmaceutical waste requires more than end-of-pipe treatment. OECD and European policy documents stress that source reduction, separate collection of unused medicines, public awareness, and integration with existing waste and wastewater systems are essential complements to biotechnological remediation. In practice, this means that the environmental value of phytoremediation, enzymatic treatment, and hybrid technologies depends not only on technical performance but also on regulatory design, collection infrastructure, and stakeholder coordination. The dominant conclusion in current reviews is therefore that sustainable pharmaceutical-waste management must combine biological innovation with prevention, governance, and public participation (European Commission, 2019; OECD, 2019; OECD, 2022).

CONCLUSIONS

The issue of pharmaceutical waste has gained significant prominence as a major environmental and public health concern, primarily due to its persistence, biological activity, and pervasive presence in both aquatic and terrestrial ecosystems. As shown throughout this review, the inadequate management of expired, unused, and residual pharmaceuticals facilitates their release into soils, surface waters, groundwater, and wastewater systems, where they may contribute to antimicrobial resistance, ecotoxicological effects, endocrine disruption, and long-term ecosystem imbalance. The problem is further intensified by the diversity of waste sources, the incomplete effectiveness of conventional treatment systems, and the persistent gap between existing regulatory frameworks and practical implementation.

The literature reviewed indicates that conventional disposal and treatment practices, although still necessary, are not sufficient to address the complexity of pharmaceutical contamination. Wastewater treatment plants frequently achieve only partial removal, while disposal options such as landfilling and incineration may create secondary environmental burdens when not adequately controlled. For this reason, biotechnological remediation has gained increasing attention as a lower-impact and potentially more sustainable alternative.

Among the available strategies, microbial bioremediation remains one of the most extensively investigated approaches because of the metabolic versatility of bacteria, fungi, and microalgae in transforming pharmaceutical compounds. At the same time, the evidence clearly shows that no single organism or process is universally effective, and that removal performance depends strongly on environmental conditions, contaminant properties, and system design. Phytoremediation also represents a valuable complementary option, especially in low-input and nature-based treatment systems, although its application is constrained by relatively slow kinetics and strong site dependence. Likewise, enzyme-based technologies, nanobiotechnology, and hybrid treatment platforms offer promising advances in selectivity and efficiency, yet they still face important barriers related to cost, stability, scale-up, ecological safety, and operational feasibility.

A central conclusion of this study is that the remediation of pharmaceutical waste cannot

rely on a single technology or on end-of-pipe treatment alone. The most promising direction is the development of integrated management systems that combine source reduction, separate collection, public awareness, regulatory enforcement, and advanced biological or hybrid remediation technologies. In this context, bioremediation should be viewed as a key component of broader, multi-barrier treatment strategies.

Finally, future progress in this field will depend on closer integration between environmental science, biotechnology, public policy, and waste-management practice. Further research is needed on transformation products, long-term ecotoxicological effects, full-scale process optimization, and the adaptation of remediation systems to local environmental and institutional conditions. Sustainable pharmaceutical-waste management will therefore require both technological innovation and coordinated governance in order to reduce environmental exposure and better protect ecosystem integrity and human health.

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