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Microbial Bioremediation of Pharmaceutical Residues in Wastewater: Current Advances and Future Prospects - Review Article

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ABSTRACT

Pharmaceutical residues are increasingly detected in wastewater and receiving waters because pharmaceutical use, excretion, manufacturing, disposal and agricultural activities continually introduce biologically active compounds into aquatic systems. Conventional wastewater treatment can reduce some residues, but removal is compound- and process-dependent and does not always demonstrate complete degradation. This review examines microbial bioremediation of pharmaceutical residues in wastewater, with emphasis on bacterial and fungal systems, microbial consortia, removal mechanisms, operating factors, current applications, challenges and the African context. The evidence assembled in the supplied literature shows that individual bacteria and fungi can transform or degrade selected pharmaceuticals, while mixed microbial communities can provide complementary metabolic activities for complex contaminant mixtures. Reported studies include substantial degradation of ibuprofen by Achromobacter strains, ciprofloxacin transformation by specialized bacteria, removal of pharmaceuticals by white-rot fungi, and improved performance from bacterial–fungal or microalgae–bacteria consortia. The review also distinguishes removal from degradation because adsorption or transformation can lower aqueous concentrations without complete destruction of the parent compound. pH, temperature, pharmaceutical concentration, microbial community characteristics, nutrients, oxygen availability and contact time can influence performance. Evidence from real hospital, municipal and pharmaceutical-industry wastewaters indicates that translation from controlled experiments to practical treatment remains a major challenge. African evidence demonstrates occurrence and ecological concerns in several settings and includes microbial-remediation studies in Nigeria and South Africa, but also reveals important gaps in monitoring, treatment evaluation and scale-up. Future progress will depend on tailored microbial consortia, immobilized enzymes, molecular and multi-omics approaches, and integration of microbial processes with existing wastewater treatment systems.

KEYWORDS: Pharmaceutical residues; wastewater; microbial bioremediation; biodegradation; biotransformation; biosorption; fungi; bacteria; microbial consortia; emerging contaminants

1. INTRODUCTION AND PHARMACEUTICAL CONTAMINATION

A.1.1 Pharmaceutical Residues in Wastewater

Pharmaceutical residues are biologically active chemical compounds or their metabolites that enter environmental compartments following the use, manufacture, disposal, or handling of medicines. They include substances used in human and veterinary medicine and occur across diverse therapeutic groups, including antibiotics, analgesics and non-steroidal anti-inflammatory drugs (NSAIDs), β-blockers, psychiatric medicines, lipid regulators, antiretroviral drugs, hormones, and other therapeutic agents. Unlike many conventional pollutants, pharmaceuticals are intentionally designed to produce biological effects at relatively low doses. Their environmental occurrence is therefore of concern even when they are present at trace concentrations [1,2].

Pharmaceuticals are widely discussed as contaminants of emerging concern (CECs). The term does not necessarily mean that these substances are newly invented or newly released; rather, it reflects increasing recognition of their environmental occurrence, persistence, biological activity, and potential ecological or human-health significance. Emerging contaminants comprise a broad group of substances that may not be adequately addressed by conventional wastewater treatment or routine environmental monitoring. Pharmaceutical residues form an important component of this group because conventional wastewater treatment

systems were generally designed around conventional pollution parameters and are not optimized for the complete removal of many trace organic micropollutants [3].

The environmental occurrence of pharmaceutical residues is closely connected with the way medicines are used and eliminated. Following administration, a proportion of many pharmaceutical compounds may be excreted unchanged or as biologically active metabolites through urine and feces. These residues can enter domestic sewage and subsequently wastewater treatment plants (WWTPs). Additional residues may enter wastewater directly from pharmaceutical manufacturing, hospitals and healthcare facilities, household disposal of unused medicines, and other point and diffuse sources. Veterinary medicines and agricultural activities provide further pathways through animal manure, contaminated runoff, and land application. Landfills and leachates may also contribute to the movement of pharmaceutical residues into water and soil [4,5,6,7].

Pharmaceutical residues have been detected in wastewater effluents, surface water, groundwater, drinking-water sources, sewage sludge, sediments, and soils. Concentrations are commonly reported from the nanogram-per-litre (ng/L) to microgram-per-litre (µg/L) range, although substantially higher concentrations may occur in particular waste streams, especially near pharmaceutical production facilities. A review of South African evidence reported more than 100 pharmaceutical compounds across wastewater and receiving waters, with concentrations ranging from ng/L to µg/L [8]. [9] similarly reported widespread occurrence of pharmaceuticals in groundwater and surface water and identified antibiotics, including sulfamethoxazole, among frequently detected groups.

For the purpose of this review, eight representative pharmaceuticals are used to illustrate the diversity of residues reported in wastewater and aquatic environments: diclofenac, ibuprofen, naproxen, paracetamol (acetaminophen), sulfamethoxazole, ciprofloxacin, carbamazepine, and atenolol. These compounds represent several commonly reported therapeutic groups and provide practical examples for discussing occurrence, sources, environmental concerns, and microbial remediation. They are not intended to represent the entire pharmaceutical contaminant spectrum.

The persistence of pharmaceutical residues in wastewater is particularly important because conventional biological treatment may reduce some compounds without completely eliminating them. [1] reported that conventional activated-sludge treatment is not uniformly efficient for pharmaceutical pollutants, while biological treatment processes such as membrane bioreactors have attracted interest for improved removal. [3] likewise emphasized that conventional wastewater treatment systems are not specifically designed to remove emerging contaminants occurring at trace concentrations in complex wastewater matrices. Continued detection of pharmaceuticals in treated effluents therefore provides an important rationale for investigating more effective and sustainable treatment approaches, including microbial bioremediation.

B.1.2 Sources and Environmental Concerns

The environmental entry of pharmaceutical residues can be understood as a connected pathway beginning with production and use and extending through discharge, redistribution, and environmental exposure. Hospitals and healthcare facilities are important point sources because pharmaceuticals administered to patients and used in clinical activities can be released through hospital wastewater. Household wastewater contributes residues following medicine consumption and excretion, while inappropriate disposal of unused or expired medicines can introduce active pharmaceutical ingredients into sewage or solid-waste streams. Pharmaceutical manufacturing facilities may release concentrated or complex mixtures of residues when production wastewater is inadequately treated. Agriculture adds another pathway through the use of veterinary medicines and the application of contaminated manure or wastewater to land [4,5,6].

Wastewater treatment plants are a critical control point in this pathway. Pharmaceutical residues entering a WWTP may undergo biological transformation, adsorption onto sludge, chemical transformation, partial degradation, or passage through the treatment process followed by discharge in treated effluent. The fate of a particular compound depends on its chemical properties, concentration, microbial degradability, sorption behaviour, treatment configuration, and operating conditions. Importantly, apparent removal from the water phase does not necessarily mean complete destruction of the pharmaceutical molecule. A compound may be transferred to sludge or transformed into one or more products that require separate assessment [1,3]. This distinction is central to bioremediation because the objective is not simply to lower the measured concentration in water, but to achieve safe and effective transformation or removal.

Hospital and municipal wastewater provide complementary examples of this problem. [10] examined β-blockers, lipid regulators, psychiatric medicines, and cancer-related drugs in hospital effluents and municipal wastewater and assessed their removal in a conventional activated-sludge WWTP. Their findings illustrate why wastewater sources need to be considered separately: hospital discharges can introduce pharmaceutical mixtures that are subsequently combined with broader municipal loads. The resulting wastewater entering a treatment plant is chemically complex, and microorganisms responsible for treatment may be exposed to multiple pharmaceutical compounds simultaneously.

Pharmaceutical manufacturing represents another important source because production wastewater may contain high pollutant loads and residual active ingredients. [11] investigated wastewater generated during pharmaceutical production and reported residual antibiotics together with substantial organic pollution and biological toxicity. Such waste streams can differ considerably from ordinary municipal wastewater and may require source-specific treatment before discharge.

Agriculture can extend pharmaceutical contamination from water into soils and food-related pathways. Pharmaceutical residues may reach agricultural land through animal manure, irrigation with contaminated or inadequately treated wastewater, and deposition of contaminated materials. Once present in soil, pharmaceuticals may be retained by soil particles, transformed, leached into groundwater, transported by runoff, or taken up by plants. [12] highlighted wastewater effluent, sewage sludge, animal manure, runoff, and leaching as important pathways for the occurrence and movement of pharmaceuticals in soils.

The environmental concerns associated with pharmaceutical residues arise from their biological activity and continuous environmental input. Even when concentrations are low, repeated discharge can produce chronic exposure for aquatic organisms. Pharmaceutical residues may affect aquatic microorganisms, algae, plants, invertebrates, fish, and other non-target organisms. Reported concerns include physiological and behavioural changes, endocrine-related effects, reproductive effects, toxicity, and disruption of ecological processes. Environmental significance depends not only on measured concentration but also on persistence, biological potency, mixture effects, and repeated exposure [13,2,5].

Antibiotics require particular attention because environmental exposure may contribute to antimicrobial resistance (AMR). Antibiotic residues released through healthcare, household, industrial, and agricultural pathways can create selective pressure in environmental microbial communities. [7] identified wastewater as an important route through which antibiotics enter aquatic environments and noted concerns about antibiotic-resistant bacteria and resistance genes. [14] further described pharmaceutical wastes, healthcare effluents, manufacturing processes, agricultural runoff, and inappropriate disposal as pathways contributing to environmental antibiotic pollution and the spread of antibiotic resistance. [4] also emphasized the relationship between environmental antibiotic residues, resistance, persistence, and potential human exposure through contaminated water and food-chain pathways.

Human-health concerns are therefore both direct and indirect. Direct concerns may arise when contaminated water or food results in exposure to biologically active pharmaceutical compounds. Indirect concerns may result from ecological disruption, antimicrobial resistance, and the persistence or transformation of pharmaceutical residues into products whose environmental behaviour differs from that of the parent compound. [15] emphasized the importance of proper disposal, effective treatment, monitoring, public education, and regulation in protecting water resources and public health.

The evidence also shows that pharmaceutical contamination is geographically widespread but unevenly monitored. [8] found that more than 100 pharmaceutical compounds had been reported in South African wastewater and receiving waters, while monitoring evidence was concentrated in certain provinces and was absent or limited in others. [9] similarly highlighted the need for stronger surveillance of pharmaceuticals in groundwater and surface water, particularly in low- and middle-income settings. The absence of reported contamination should therefore not automatically be interpreted as evidence of absence; it may also reflect limited monitoring, analytical capacity, or available data.

Overall, pharmaceutical residues enter wastewater through multiple interconnected pathways and can subsequently move into surface water, groundwater, soils, sediments, and biological systems. Their environmental significance is strengthened by continuous input, biological activity, incomplete removal during conventional treatment, and the possibility of transformation or accumulation in environmental compartments. These characteristics make pharmaceutical residues an important target for improved treatment technologies. For this review, the central issue is therefore not simply whether pharmaceutical residues can be removed from wastewater, but whether microbial systems can transform or degrade them effectively, under what conditions, and with what limitations.

Pharmaceutical group	Representative compounds	Typical environmental entry	Main concern
Analgesics/NSAIDs	Diclofenac, ibuprofen, naproxen, paracetamol	Household and hospital wastewater; excretion	Ecotoxicity and chronic exposure
Antibiotics	Sulfamethoxazole, ciprofloxacin	Household, hospital, pharmaceutical and agricultural sources	Antimicrobial resistance and ecological effects
Anticonvulsant/psychiatric drugs	Carbamazepine	Municipal and hospital wastewater	Persistence and incomplete removal
β-blockers	Atenolol	Hospital and municipal wastewater	Aquatic exposure and biological activity

Figure 1. Conceptual pathway of pharmaceutical residues from sources through wastewater to microbial treatment and reduced contamination.

2. MICROBIAL BIOREMEDIATION APPROACHES

C.2.1 Bacterial Bioremediation

Bacteria are central to biological wastewater treatment because of their metabolic diversity and ability to use a wide range of organic compounds as carbon or energy sources. The supplied literature shows that pharmaceutical degradation by bacteria is

compound-specific and can involve specialized isolates, acclimated sludge communities, activated sludge, or engineered biological reactors. Reviews describe bacterial participation in the degradation of antibiotics, analgesics and other pharmaceutical compounds, while experimental studies demonstrate that selected strains can transform individual residues under defined conditions [16,17,18].

Ibuprofen provides a clear example of strain-dependent bacterial biodegradation. [19] evaluated Achromobacter spanius S11 and Achromobacter piechaudii S18 isolated from contaminated water. Both strains were able to use ibuprofen as a carbon source, but their performance differed markedly. A. spanius S11 achieved 91.18% degradation after 72 h and 95.7% after 144 h, whereas A. piechaudii S18 achieved 72.39% and 73.01% after three and seven days, respectively. Metabolite analysis indicated an initial hydroxylation followed by oxidation involving monooxygenases and dehydrogenases, while measured enzyme activities included catechol 1,2-dioxygenase and laccase. This study demonstrates that bacterial remediation can involve measurable chemical transformation rather than simple transfer of a contaminant out of the water phase.

Ciprofloxacin has likewise been investigated using specialized bacterial isolates. [20] isolated Stutzerimonas stutzeri R2 and Exiguobacterium indicum R4 from pharmaceutical wastewater. Under co-metabolic conditions, UHPLC measurements showed 51–77% degradation by R2 and 60–68% by R4 after five and ten days, while degradation was lower when ciprofloxacin was supplied as the sole carbon source. The degraded residues showed reduced antimicrobial activity against Escherichia coli and Staphylococcus aureus. [21] similarly isolated Paraclostridium sp. strain S2 from sulfate-reducing sludge. Its ciprofloxacin removal involved rapid sorption followed by biotransformation, with proposed reactions including piperazine-ring cleavage, hydroxylation, decarboxylation and OH/F substitution. The study therefore illustrates why measured disappearance must be separated from the underlying mechanism.

Bacterial communities can also contribute to treatment without being selected as a single pharmaceutical-degrading strain. [22] screened bacteria from sewage sludge and identified Bacillus subtilis AQ03 as a strain capable of degrading selected sulfonamide antibiotics. In a moving-bed reactor, complete removal of the studied antibiotics was reported after several days, alongside reductions in BOD, COD, nitrate and phosphate. Such studies suggest that bacterial systems may simultaneously address pharmaceutical residues and conventional wastewater parameters, although the specific pharmaceutical fate still needs to be distinguished from general organic-load removal.

The bacterial literature also highlights an important limitation. Antibiotic-degrading traits occur in microbial communities that are themselves exposed to antimicrobial selection pressure. [17] noted that the application of microbial antibiotic-degradation traits requires consideration of the genetic basis of degradation because transferable genetic clusters could have implications for antimicrobial resistance. [23] provides a related caution: activated sludge removed more than 80% of diclofenac at 1 mg/L and more than 99% at a higher concentration, but the study identified adsorption onto sludge as the principal removal mechanism and also detected multidrug-resistant bacteria in the sludge. The result should therefore not be presented as bacterial biodegradation of diclofenac. It is better interpreted as evidence that microbial treatment systems can remove pharmaceuticals through mechanisms other than biodegradation while simultaneously requiring attention to resistance risks.

Overall, bacterial bioremediation is promising because bacteria can provide specialized metabolic pathways, adapt to pharmaceutical exposure and operate within established biological treatment systems. However, the evidence does not support treating all bacterial removal percentages as equivalent. The strength of the evidence is greatest where analytical methods demonstrate transformation or degradation products and where the microbial mechanism is identified.

D.2.2 Fungal Bioremediation

Fungi provide a complementary route for pharmaceutical remediation because many species produce extracellular and intracellular enzymes capable of transforming chemically diverse compounds. White-rot fungi are particularly important because their ligninolytic enzyme systems include laccases and peroxidases, while intracellular oxidative systems can also participate in pharmaceutical transformation. Reviews of fungal remediation emphasize that whole fungal cells and isolated enzymes can both contribute to pharmaceutical removal, but the relative contribution of biosorption, biodegradation and enzymatic transformation depends on the organism, compound and wastewater matrix ([24];; [25]).

Experimental studies provide strong examples of fungal activity against several pharmaceutical groups. [26] screened four white-rot fungi against ibuprofen, clofibric acid and carbamazepine. Ibuprofen was extensively degraded by all four fungi tested. Trametes versicolor was additionally able to degrade approximately 91% of clofibric acid and approximately 58% of carbamazepine, while Ganoderma lucidum also degraded part of carbamazepine. The study further showed that extracellular manganese peroxidase and a laccase-mediator system did not appear to initiate the first step of all degradation reactions, whereas cytochrome P450 inhibition suggested a role for intracellular oxidation in some pathways.

[27] provide a particularly useful example for diclofenac because the study followed degradation intermediates rather than reporting disappearance alone. T. versicolor pellets achieved at least 94% diclofenac removal within the first hour at both a relatively high concentration and an environmentally relevant lower concentration. Two hydroxylated intermediates, 4′-hydroxydiclofenac and 5-hydroxydiclofenac, were identified, and both the parent compound and intermediates disappeared after

24 h. The authors also observed a reduction in measured ecotoxicity. This evidence supports a mechanistic interpretation in which fungal transformation proceeds through intermediate products before further disappearance.

[28] reported complete degradation of most of the tested PPCPs by selected white-rot fungi, although fluoxetine and diazepam were only partially removed. This variability is important because it demonstrates that fungal performance cannot be generalized across pharmaceutical classes. The physicochemical properties of the compound, fungal species, enzyme system and wastewater conditions all influence the outcome.

More recent reviews emphasize the potential of fungal enzymes for treatment but also identify limitations. [29] describes laccases, peroxidases and cytochrome P450 systems as important components of fungal pharmaceutical transformation and notes that substrate specificity, enzyme stability and environmental conditions influence performance. [30] similarly identifies oxidoreductases as promising biocatalysts but emphasizes the need to improve enzyme stability, operation in real aqueous matrices, immobilization and integration with other treatment processes.

Fungal remediation is therefore valuable not because fungi uniformly remove pharmaceuticals, but because their enzymatic diversity can provide transformation routes that differ from conventional bacterial treatment. The most convincing studies are those that identify degradation products or enzyme involvement and distinguish true transformation from physical removal.

E.2.3 Microbial Consortia

Microbial consortia combine microorganisms with complementary metabolic capabilities and can be advantageous when a pharmaceutical mixture is too complex for a single organism. The rationale is that one organism may transform a compound into an intermediate that another organism can further metabolize. Cross-feeding, co-metabolism and sequential enzyme activities are therefore central concepts in consortium-based remediation [31].

[32] demonstrated the practical potential of an immobilized bacterial consortium in real pharmaceutical wastewater. A four-strain consortium was immobilized on Luffa and operated in batch and continuous modes. The consortium produced several enzymes, including alcohol dehydrogenase, aldehyde dehydrogenase, monooxygenase, catechol 2,3-dioxygenase and hydroquinol 1,2-dioxygenase. During 61 days of continuous operation in an aerobic fixed-film bioreactor, average reductions of 96.8% COD, 92.6% phenolic compounds and 95.2% suspended solids were reported. GC–MS analysis indicated that most organic contaminants were transformed into less problematic metabolites. Although these results concern the overall wastewater matrix rather than a single pharmaceutical residue, they illustrate how immobilized microbial communities can maintain treatment activity in a real industrial stream.

Mixed fungal–bacterial communities have also been tested in real hospital wastewater. [33] developed fungal biofilms on rotating biological contactors initially inoculated with T. versicolor. Over time, the system developed a diversified fungal and bacterial community and operated for 75 days. Pharmaceutical micropollutant removal was particularly high for azithromycin (98.4 ± 0.7%), metronidazole (83 ± 8%) and sulfamethoxazole (76 ± 10%). Importantly, the study was conducted under non-sterile conditions and without strict temperature control, providing evidence that mixed communities can remain functional in complex wastewater.

Other studies show that microbial consortia can improve treatment of specific pharmaceutical mixtures. [34] used mixed-culture microbes with photocatalysis for ciprofloxacin removal and reported 94% removal, with a higher total organic carbon removal rate than photocatalysis alone. [35] used a microalgae–bacteria consortium with wastewater treatment plant secondary effluent and achieved 96.54% removal of cephalexin and 92.38% removal of erythromycin, while the resistance genes blaTEM and ermB decreased by 0.56 and 1.75 logs, respectively. [36] found that a mixed Trichoderma harzianum–Pseudomonas fluorescens biofilm removed acetaminophen and its by-product 4-aminophenol rapidly and biodegraded acetaminophen approximately five times faster than the fungal culture alone.

[37] illustrate another direction: assembling co-cultures from microorganisms already isolated from sewage sludge. Among 127 artificial co-cultures, minimal consortia containing selected Penicillium species, Cladosporium cladosporioides and co-existing bacteria achieved more than 80% degradation of tested pharmaceutical active compounds. The study linked the observed transformation to hydroxylation and reported low ecotoxicity effects for the resulting derivatives.

Despite these advantages, consortia introduce new management problems. Community composition can change with wastewater conditions, individual members may compete rather than cooperate, and engineered consortia may raise regulatory concerns. The evidence therefore supports consortia as a promising strategy, but not as an automatic replacement for single-strain systems. Their value is greatest when complementary metabolism, community stability and treatment conditions can be controlled.

Pharmaceutical	Microorganism/system	Mechanism	Reported outcome
Ibuprofen	Achromobacter spanius S11	Biodegradation; hydroxylation/oxidation	91.18% degradation at 72 h; 95.7% at 144 h
Ciprofloxacin	Stutzerimonas stutzeri R2; Exiguobacterium indicum R4	Biodegradation/biotransformation	Under co-metabolism, UHPLC showed 51–77% and 60–68% degradation after 5–10 days
Ciprofloxacin	Paraclostridium sp. S2	Sorption followed by	Specific biotransformation

Pharmaceutical	Microorganism/system	Mechanism	Reported outcome
		biotransformation	rate 1975.7 ± 109.1 μg g−1 cell dry weight h−1 at 20 mg/L
Diclofenac	Trametes versicolor pellets	Fungal transformation; laccase/P450-associated pathways	≥94% removal within 1 h; hydroxylated intermediates identified
Clofibric acid / carbamazepine	Trametes versicolor	Fungal degradation	Approximately 91% and 58% degradation, respectively
Acetaminophen	T. harzianum + Pseudomonas fluorescens biofilm	Mixed-culture biodegradation	Complete removal of acetaminophen and 4-aminophenol at about 7 h; faster than pure fungal culture
Cephalexin / erythromycin	Microalgae–bacteria consortium	Biological removal	96.54% and 92.38% removal; blaTEM and ermB decreased
Azithromycin / metronidazole / sulfamethoxazole	Fungal–bacterial biofilm in real hospital wastewater	Biological treatment/advanced bio-oxidation	98.4 ± 0.7%, 83 ± 8% and 76 ± 10% removal
Diclofenac / carbamazepine / ketoprofen	Mixed fungal–bacterial co-cultures	Biodegradation/biotransformation	Selected minimal consortia achieved >80% degradation

3. MECHANISMS AND FACTORS AFFECTING REMEDIATION

F.3.1 Mechanisms of Pharmaceutical Removal

Microbial removal of pharmaceuticals occurs through several overlapping processes, but the present review follows the guideline by focusing on four mechanisms: biodegradation, biotransformation, biosorption and enzyme-mediated degradation. Distinguishing these mechanisms is essential because a reduction in dissolved concentration is not sufficient evidence of destruction of the pharmaceutical molecule.

Biodegradation. Biodegradation refers to microbial conversion of pharmaceutical compounds through metabolic processes that can ultimately produce smaller or more mineralized products. Bacteria and fungi can use pharmaceutical compounds as carbon sources in some cases or transform them through co-metabolic reactions in others. [19] provides a direct example in which Achromobacter strains degraded ibuprofen as a carbon source and generated identifiable metabolites. Similarly, [16] reviews biological treatment systems in which bacteria, fungi and algae contribute to pharmaceutical degradation. The degree of degradation, however, depends on the compound and microbial system.

Biotransformation. Biotransformation is broader than complete biodegradation because the parent pharmaceutical can be converted into one or more transformation products without complete mineralization. [38] identified transformation products from sulfamethoxazole and ciprofloxacin in an anaerobic fixed-bed reactor treating municipal sewage. [21] reported ciprofloxacin sorption followed by biotransformation and proposed piperazine-ring cleavage, hydroxylation, decarboxylation and OH/F substitution as major reactions. These studies demonstrate why removal percentages should not automatically be described as biodegradation. The identity and toxicity of transformation products are part of the treatment outcome.

Biosorption. Biosorption is the passive or active binding of pharmaceutical molecules to biological materials rather than their destruction. Microbial biomass, fungal biomass and algae can provide functional groups and surfaces that interact with pharmaceutical compounds. [39] identifies pH, contact time, biosorbent dosage and initial concentration as important parameters for biosorption. [40] similarly reviews microbial biomass and microbial-derived biomaterials as biosorbents or biodegradation supports. [23] provides an applied example in which activated sludge adsorbed diclofenac rapidly. Because the pharmaceutical may remain associated with sludge, biosorption should not be equated with detoxification or mineralization.

Enzyme-mediated degradation. Enzymes can catalyze oxidation or other transformation reactions that alter pharmaceutical structures. Fungal laccases, peroxidases and cytochrome P450 systems are repeatedly identified in the supplied literature. [29] describes extracellular laccases and peroxidases together with intracellular cytochrome P450 monooxygenases as important fungal systems. [30] emphasizes oxidoreductase enzymes and the potential value of immobilization, while [41] demonstrated an immobilized laccase system capable of removing diclofenac, amoxicillin, carbamazepine and ciprofloxacin from water and wastewater. Enzyme-based treatment is attractive because the catalytic component can potentially be separated from whole-cell growth requirements, although stability, matrix effects and regeneration remain important considerations.

The four mechanisms can occur simultaneously. A pharmaceutical may first adsorb onto microbial biomass, undergo enzymatic transformation, and then be further metabolized by the same organism or another member of a microbial community. Consequently, mechanistic studies using analytical identification of intermediates provide stronger evidence than concentration measurements alone [42,43].

G.3.2 Factors Affecting Remediation

pH. pH can alter microbial activity, enzyme performance, pharmaceutical ionization and the surface charge of microbial biomass. [29] reports that fungal pharmaceutical transformation is influenced by environmental conditions, while [39] identifies pH as a

major process parameter for biosorption. [23] found that diclofenac adsorption onto activated sludge was higher under acidic conditions. The effect is therefore not a universal optimum; it depends on the pharmaceutical, microorganism and mechanism involved.

Temperature. Temperature affects microbial growth, enzyme activity, mass transfer and community composition. [44] compared aerobic granular sludge systems at 7 and 26 °C and found that pharmaceutical removal was more progressive at the higher temperature, while the microbial community was strongly dependent on operating temperature. [45] likewise reported reduced biodegradation efficiency in a hospital-wastewater membrane bioreactor when operated at 10–15 °C. Temperature control can therefore become particularly important in real systems where seasonal variation occurs.

Pharmaceutical concentration. Concentration can determine whether microorganisms tolerate, transform or are inhibited by a pharmaceutical. [46] studied a mixture of five pharmaceuticals at a total influent concentration of 500 µg/L in membrane bioreactors and observed changes in floc size, membrane fouling and microbial community characteristics under high pharmaceutical exposure. Concentration also affects biosorption capacity and kinetics [39]. Laboratory studies conducted at elevated concentrations should therefore be interpreted cautiously when translating results to trace environmental concentrations.

Microbial population. The identity, abundance and functional diversity of microorganisms influence treatment performance. [47] examined activated sludge from 15 pharmaceutical wastewater treatment plants and found that bacterial community structure varied between aerobic and anaerobic systems and was associated with environmental conditions and treatment functions. Specialized degraders can provide high activity against individual compounds, whereas diverse communities may provide complementary pathways for mixtures.

Nutrients. Nutrient availability can affect microbial growth and co-metabolic degradation. [22] reported that nutrient amendments improved degradation of selected sulfonamide antibiotics by B. subtilis AQ03. Nutrient conditions therefore need to support microbial activity without creating an unnecessarily nutrient-rich effluent.

Oxygen. Oxygen availability determines whether aerobic oxidation, anaerobic metabolism or alternative electron-accepting processes dominate. The supplied studies include aerobic fixed-film, activated-sludge and anaerobic sulfate-reducing systems, demonstrating that different microbial pathways can be associated with pharmaceutical transformation. [21] provides an example of ciprofloxacin transformation by a strain isolated from sulfate-reducing sludge, while [38] identified transformation products in an anaerobic fixed-bed reactor. Oxygen conditions should therefore be matched to the metabolic capabilities of the selected microbial community.

Contact time. Pharmaceutical transformation requires sufficient contact between the contaminant and active microbial or enzymatic systems. [23] observed rapid diclofenac adsorption within minutes, whereas true biodegradation studies commonly require hours or days. [19] observed major ibuprofen degradation over 72–144 h, and Aguilar-Romero et al. (2024) reported substantial ibuprofen degradation and mineralization over days. Contact time must therefore be interpreted together with mechanism: rapid adsorption is not equivalent to slow biological mineralization.

Taken together, these factors explain why microbial remediation results vary between studies. A microbial system optimized for one pharmaceutical, concentration and wastewater matrix cannot automatically be expected to perform identically under different conditions [18].

4. CURRENT APPLICATIONS, CHALLENGES AND AFRICAN PERSPECTIVE

H.4.1 Laboratory versus Real Wastewater

A major distinction in the literature is whether microbial treatment has been evaluated in synthetic or laboratory wastewater or in actual wastewater. Controlled laboratory systems are valuable because they allow researchers to isolate variables such as pharmaceutical concentration, temperature, pH and contact time. However, real wastewater contains mixtures of pharmaceuticals, organic matter, nutrients, suspended solids, competing microorganisms and other contaminants that can alter microbial activity and pharmaceutical fate.

Evidence from synthetic systems illustrates the value and limitation of controlled conditions. [44] evaluated aerobic granular sludge using synthetic hospital wastewater and showed that temperature affected pharmaceutical removal and microbial community structure. [48] investigated emerging pharmaceuticals in membrane bioreactors under controlled solid retention times and found the 40-day SRT gave the best overall pharmaceutical elimination among the tested conditions. [46] used synthetic wastewater containing five pharmaceuticals and showed that high pharmaceutical exposure altered floc size, membrane fouling and microbial community characteristics.

Real wastewater studies provide a different level of evidence. [45] examined twelve pharmaceuticals in hospital wastewater treated by a submerged membrane bioreactor. More than 70% removal by biodegradation was reported for several compounds, including sulfamethoxazole, clarithromycin, acebutolol, estrone and caffeine, while lower performance occurred for compounds such as diclofenac and venlafaxine. The study also found that lower temperatures reduced biodegradation efficiency. These findings demonstrate both the promise of biological treatment and the compound-specific nature of performance in a complex matrix.

[32] used an immobilized four-bacterial-strain consortium to treat real pharmaceutical-industry wastewater in batch and continuous operation. The 61-day continuous study achieved substantial reductions in COD, phenolic compounds and suspended solids, showing that microbial systems can remain functional beyond short laboratory experiments. [33] likewise operated a fungal–bacterial biofilm system on real hospital wastewater for 75 days and achieved high removal of several antibiotic micropollutants under non-sterile conditions.

Pilot-scale evidence is also available. [49] evaluated an integrated pilot-scale process for real pharmaceutical factory wastewater using a combination of biological and electrochemical reactors. Although the study addressed toxic organic pollutants rather than a defined set of pharmaceutical residues, it illustrates the type of system-level approach required for industrial wastewater, where high pollutant loads and complex matrices challenge standalone biological treatment.

The comparison therefore does not support a simple conclusion that laboratory systems are ineffective. Rather, laboratory studies are useful for identifying mechanisms and optimal conditions, whereas real-wastewater studies are necessary to determine whether those mechanisms remain effective when multiple contaminants and variable operating conditions are present. The gap between these two levels of evidence remains one of the central issues for microbial pharmaceutical remediation.

I.4.2 Major Challenges

Slow degradation. Some pharmaceutical compounds are recalcitrant or are transformed more slowly than conventional organic pollutants. [17] noted that some antibiotics, including sulfonamides, can be resistant to natural biodegradation. Slow kinetics reduce reactor productivity and may require longer hydraulic or solid retention times. Laboratory studies can also report high removal over periods that are difficult to reproduce economically at full scale.

Mixed contaminants. Wastewater rarely contains a single pharmaceutical. Hospital, municipal and industrial streams can contain mixtures of pharmaceuticals together with conventional organic matter and other contaminants. Mixtures can produce competition for microbial enzymes or create synergistic toxicity. [31] emphasizes the value of consortia for complex contaminant mixtures, while [46] demonstrated that high pharmaceutical exposure can alter microbial communities and membrane behaviour. Treatment therefore needs to be evaluated under realistic mixtures rather than only single-compound conditions.

Transformation products. A decrease in parent pharmaceutical concentration does not prove detoxification. [38] identified transformation products from sulfamethoxazole and ciprofloxacin in anaerobic treatment, while [27] identified hydroxylated diclofenac intermediates. Some studies report reduced toxicity of products, but transformation products cannot be assumed to be harmless without analytical and toxicity assessment. This is particularly important when treatment is evaluated only by parent-compound disappearance.

Variable microbial performance. Microbial activity depends on pH, temperature, pharmaceutical concentration, nutrients, oxygen, community composition and contact time. [44], [45] and [18] all illustrate the importance of environmental and biological conditions. Performance can therefore vary between wastewater plants and seasons even when nominal treatment configurations are similar.

Scale-up difficulties. Many promising studies remain at laboratory or pilot scale. Fungal remediation reviews emphasize challenges associated with maintaining fungal activity, enzyme stability and treatment performance in real matrices [24,30,29]. [50] similarly identifies the need for further work on the actual efficiency and technoeconomic feasibility of microbial fuel-cell-based pharmaceutical wastewater treatment. Scale-up must therefore consider reactor design, biomass retention, fouling, operating costs, process control, regulatory requirements and long-term stability rather than removal efficiency alone.

These challenges are interdependent. For example, increasing contact time may compensate for slow degradation but reduce treatment capacity; increasing microbial biomass may improve removal but alter sludge properties; and combining microbial treatment with another process may improve transformation while increasing cost. The most realistic future pathway is therefore likely to involve optimized biological systems integrated with complementary treatment technologies rather than reliance on a single universal microbial process.

J.4.3 African Perspective

The African perspective needs to be interpreted in light of the uneven availability of monitoring and treatment evidence. A review of African wastewater effluents by Necibi et al. (2021) notes that socioeconomic constraints, limited wastewater infrastructure and analytical limitations make contaminants of emerging concern particularly challenging to manage. The supplied evidence therefore supports identifying specific country-level examples rather than making continent-wide claims.

Nigeria. [51] investigated diclofenac and ibuprofen in wastewater from three wastewater treatment plants in south-western Nigeria. Maximum concentrations reached 166.1 µg/L for diclofenac in an influent sample and 62.0 µg/L for ibuprofen in an effluent sample. Ibuprofen posed high ecological risk to fish across the assessed effluent and receiving-water samples. The study provides direct evidence of pharmaceutical occurrence and ecological concern but was not a microbial-remediation experiment. In contrast, [52] evaluated bacterial treatment of pharmaceutical-industry wastewater in Ede, Osun State, using Bacillus subtilis. The study reported reductions in several physicochemical parameters after biological treatment, including COD, TDS, nitrate, phosphate, magnesium, calcium and zinc. This provides a local example of bacterial treatment of pharmaceutical-industry wastewater, although the study focused on overall wastewater quality rather than detailed pharmaceutical compound degradation.

South Africa. South African evidence demonstrates both occurrence and remediation research. [8] reviewed more than 100 pharmaceutical compounds reported in South African wastewater and receiving waters and highlighted uneven geographic monitoring. More recently, [53] detected ciprofloxacin, sulfamethoxazole and erythromycin in the Sand River in Polokwane and identified ecological and antimicrobial-resistance concerns associated with some compounds. For remediation, [54] evaluated Chlorella spp. for removal of sulfamethoxazole, efavirenz and nevirapine under controlled conditions. Removal efficiencies ranged from 10–60% for efavirenz, 5–51% for nevirapine and 10–50% for sulfamethoxazole. The study attributes removal partly to interactions between pharmaceuticals and functional groups on the algal cell surface, indicating that biosorption contributed to the observed treatment effect. Because the experiments were controlled rather than full-scale municipal treatment, they provide evidence of potential rather than proof of large-scale applicability.

Kenya and East Africa. The supplied Kenyan literature is more focused on pharmaceutical wastewater management and occurrence than on direct microbial remediation. [55] examined pharmaceutical wastewater generation and treatment practices in Kenyan factories and identified the management of pharmaceutical effluent as an important environmental issue. [56] reviewed antiretroviral contamination in African water systems and identified Kenya and South Africa as important locations for reported detections, while also noting that remediation work remains limited. [57] found that improper pharmaceutical disposal is a continuing concern across East African countries and linked poor handling to environmental contamination and antimicrobial-resistance concerns.

Overall, the African evidence points to three linked gaps: incomplete monitoring, limited direct testing of microbial pharmaceutical degradation under real African wastewater conditions, and limited translation of promising laboratory systems into long-term treatment. The available Nigerian and South African studies demonstrate that both contamination and microbial-remediation research exist, but the evidence base remains too uneven to support broad claims about performance across the continent. This makes region-specific pilot studies and stronger analytical monitoring important priorities.

Major challenge	Evidence from supplied literature	Future research need
Slow degradation	Some pharmaceuticals and antibiotic groups are recalcitrant; biological kinetics can require hours to days.	Improve strain selection, community design, enzyme systems and reactor retention strategies.
Mixed contaminants	Real wastewater contains pharmaceutical mixtures and other organic/inorganic constituents that can alter microbial performance.	Test microbial systems with realistic mixtures and real wastewater matrices.
Transformation products	Ciprofloxacin, sulfamethoxazole, diclofenac and other compounds can form measurable transformation products.	Combine chemical identification with toxicity assessment and mineralization measurements.
Variable microbial performance	pH, temperature, concentration, nutrients, oxygen and community composition alter treatment outcomes.	Develop robust operating windows and monitor microbial community function during treatment.
Scale-up difficulties	Many studies remain laboratory-scale; real wastewater and long-term operation are less common.	Use pilot and long-duration studies with technoeconomic, stability and regulatory assessment.

5. FUTURE PROSPECTS AND CONCLUSION

K.5.1 Future Research Directions

The first priority is the development of tailored microbial consortia. Single strains can show strong activity against individual pharmaceuticals, but real wastewater contains mixtures and fluctuating conditions. Consortia can combine complementary pathways through cross-feeding, co-metabolism and sequential transformation. [31] identifies these interactions as a major advantage of consortium-based treatment, while [37] demonstrates that systematic assembly of compatible microorganisms can produce high degradation of several pharmaceutical active compounds. Future work should therefore move from simply collecting high-performing isolates toward designing stable communities whose composition and function can be maintained in real wastewater.

The second priority is enzyme-based treatment and immobilization. Fungal laccases, peroxidases and related oxidoreductases can transform pharmaceutical molecules without requiring continuous growth of whole microorganisms. [30] identifies immobilization as a route to improved enzyme stability, reuse and industrial applicability. [41] provides a practical example in which laccase was immobilized on activated carbon derived from pomegranate peels and used for pharmaceutical removal in water and wastewater. The future challenge is to demonstrate stable activity over repeated cycles in complex matrices while assessing transformation products and treatment costs.

The third priority is the use of metagenomics and other molecular approaches. Pharmaceutical wastewater treatment depends on microbial communities rather than isolated organisms alone. [47] showed that bacterial community structure in pharmaceutical

wastewater treatment plants varied with treatment conditions and that environmental parameters were associated with community functions. Multi-omics approaches can extend this understanding by linking community composition to metabolic pathways and resistance-related responses. [58] proposes the integration of metagenomics, transcriptomics and metabolomics for higher-resolution pathway reconstruction and process optimization. Such tools could help identify organisms and pathways that remain active under realistic wastewater conditions.

The fourth priority is integration with existing wastewater treatment systems. Microbial remediation should not be treated as a technology that must replace every conventional process. Instead, biological systems can be incorporated into membrane bioreactors, fixed-film reactors, microbial fuel cells, constructed treatment systems or hybrid biological–oxidative processes. [50] highlights the potential of microbial fuel cells, while [30] discusses hybrid enzyme-based systems. Integration can allow each process to address a different limitation, such as recalcitrant compounds, transformation products or conventional organic load.

Artificial intelligence can be considered briefly as an emerging supporting tool rather than a separate treatment technology. [58] describes applications of machine learning and AI for process diagnostics, predictive modelling and bioreactor control. The immediate value of such tools is likely to be in optimizing existing biological systems rather than replacing microbiological understanding.

Across all four directions, the central research need is movement from laboratory proof-of-concept to realistic, long-duration and economically defensible treatment. Future studies should report not only percentage removal but also degradation pathways, transformation-product toxicity, microbial-community stability, operating requirements, energy and material demands, and performance in real wastewater. This would make comparisons between studies more meaningful and improve the prospects of practical implementation.

5.2 CONCLUSION

Pharmaceutical residues are persistent and biologically active contaminants that enter wastewater through human and veterinary use, hospitals, households, manufacturing, agriculture and disposal pathways. Their continuous introduction, incomplete removal and potential ecological and public-health consequences justify the development of treatment approaches that can function effectively in complex wastewater systems.

The literature reviewed here shows that microorganisms can transform or remove selected pharmaceutical residues. Bacteria can provide specialized degradation pathways for compounds such as ibuprofen and ciprofloxacin; fungi can use diverse oxidative systems to transform pharmaceuticals; and mixed microbial communities can combine complementary metabolic activities. However, removal is not synonymous with biodegradation. Adsorption, biotransformation and enzyme-mediated reactions can all contribute to apparent removal, and transformation products must be considered when evaluating treatment safety.

Performance varies with the pharmaceutical, microorganism, community structure and environmental conditions. pH, temperature, concentration, nutrients, oxygen, microbial population and contact time can alter treatment outcomes. Laboratory studies are valuable for mechanistic understanding, but evidence from real hospital, municipal and pharmaceutical-industry wastewater shows that complex matrices and long-term operation remain important challenges. Slow degradation, mixed contaminants, transformation products, variable microbial performance and scale-up difficulties continue to limit routine application.

The African evidence reinforces the need for stronger monitoring and locally relevant treatment studies. Nigeria and South Africa provide examples of both pharmaceutical contamination and microbial-remediation research, while evidence from Kenya and wider East Africa highlights wastewater-management and disposal gaps. More realistic regional studies are required before performance can be generalized across African wastewater systems.

Future progress should therefore focus on stable microbial consortia, immobilized enzymes, molecular and multi-omics approaches, and integration of microbial processes with existing wastewater treatment infrastructure. The most useful research will connect laboratory mechanisms with long-term performance in real wastewater and will evaluate not only removal efficiency but also transformation, toxicity, microbial stability, cost and scale-up feasibility.

REFERENCES

1) Tiwari, B.; Sellamuthu, B.; Ouarda, Y.; Drogui, P.; Tyagi, R. D.; Buelna, G. (2017). Review on fate and mechanism of removal of pharmaceutical pollutants from wastewater using biological approach. Bioresource Technology, 224, 1–12. https://doi.org/10.1016/j.biortech.2016.11.042
2) Wydro, U.; Wolejko, E.; Luarasi, L.; Puto, K.; Taraseviciene, Z.; Jablonska-Trypuc, A. (2024). A review on pharmaceuticals and personal care products residues in the aquatic environment and possibilities for their remediation. Sustainability, 16(1), 169. https://doi.org/10.3390/su16010169
3) Morin-Crini, N.; Lichtfouse, E.; Fourmentin, M.; et al. (2022). Removal of emerging contaminants from wastewater using advanced treatments. A review. Environmental Chemistry Letters, 20, 1333–1375. https://doi.org/10.1007/s10311-021-01379-5

4) Akhter, S.; Bhat, M. A.; Ahmed, S.; Siddiqui, W. A. (2024). Antibiotic residue contamination in the aquatic environment, sources and associated potential health risks. Environmental Geochemistry and Health, 46(10), 387. https://doi.org/10.1007/s10653-024-02146-5
5) Aziz, K. H. H.; Mustafa, F. S.; Karim, M. A. H.; Hama, S. (2025). Pharmaceutical pollution in the aquatic environment: advanced oxidation processes as efficient treatment approaches: a review. Materials Advances, 6, 3433–3454. https://doi.org/10.1039/D4MA01122H
6) Lunghi, C.; Valetto, M. R.; Caracciolo, A. B.; et al. (2025). Call to action: Pharmaceutical residues in the environment: threats to ecosystems and human health. Drug Safety, 48(4), 315–320. https://doi.org/10.1007/s40264-024-01497-3
7) Samrot, A. V.; Wilson, S.; Sanjay Preeth, R. S.; et al. (2023). Sources of antibiotic contamination in wastewater and approaches to their removal—An overview. Sustainability, 15(16), 12639. https://doi.org/10.3390/su151612639
8) Munzhelele, E. P.; Mudzielwana, R.; Ayinde, W. B.; Gitari, W. M. (2024). Pharmaceutical contaminants in wastewater and receiving water bodies of South Africa: A review of sources, pathways, occurrence, effects, and geographical distribution. Water, 16(6), 796. https://doi.org/10.3390/w16060796
9) Sanusi, I. O.; Olutona, G. O.; Wawata, I. G.; Onohuean, H. (2023). Occurrence, environmental impact and fate of pharmaceuticals in groundwater and surface water: a critical review. Environmental Science and Pollution Research, 30, 90595–90614. https://doi.org/10.1007/s11356-023-28802-4
10) Ulvi, A.; Aydin, S.; Aydin, M. E. (2022). Fate of selected pharmaceuticals in hospital and municipal wastewater effluent: occurrence, removal, and environmental risk assessment. Environmental Science and Pollution Research, 29, 75609–75625. https://doi.org/10.1007/s11356-022-21131-y
11) Xue, J.; Lei, D.; Zhao, X.; et al. (2022). Antibiotic residue and toxicity assessment of wastewater during the pharmaceutical production processes. Chemosphere
12) Pérez-Lucas, G.; Navarro, S. (2024). How pharmaceutical residues occur, behave, and affect the soil environment. Journal of Xenobiotics, 14(4), 1343–1377. https://doi.org/10.3390/jox14040076
13) Khan, A. H.; Aziz, H. A.; Khan, N. A.; et al. (2022). Impact, disease outbreak and the eco-hazards associated with pharmaceutical residues: a critical review. International Journal of Environmental Science and Technology. https://doi.org/10.1007/s13762-021-03158-9
14) Ajekiigbe, V. O.; Agbo, C. E.; Ogieuhi, I. J.; et al. (2025). The increasing burden of global environmental threats: role of antibiotic pollution from pharmaceutical wastes in the rise of antibiotic resistance. Discover Public Health, 22, 120. https://doi.org/10.1186/s12982-025-00506-9
15) Fakhri B., M. S.; Ghassemi Barghi, N.; Moradnia Mehdikhanmahaleh, M.; et al. (2024). Pharmaceutical wastewater toxicity: An ignored threat to the public health. Sustainable Environment, 10(1), 2322821. https://doi.org/10.1080/27658511.2024.2322821
16) A. Moghaddam; D. Khayatan; P. Esmaeili Fard Barzegar; R. Ranjbar; M. Yazdanian; E. Tahmasebi; M. Alam; K. Abbasi; H. Esmaeili Gouvarchin Ghaleh; H. Tebyaniyan (2023). Biodegradation of pharmaceutical compounds in industrial wastewater using biological treatment: a comprehensive overview. International Journal of Environmental Science and Technology. https://doi.org/10.1007/s13762-023-04880-2
17) Aindrila Kayal; Sukhendu Mandal (2022). Microbial degradation of antibiotic: future possibility of mitigating antibiotic pollution. Environmental Monitoring and Assessment. https://doi.org/10.1007/s10661-022-10314-2
18) Upeksha Gayangani Jayasekara; Tony Hadibarata; Dwi Hindarti; Budi Kurniawan; Mohammad Noor Hazwan Jusoh; Paran Gani; Inn Shi Tan; Adhi Yuniarto; Rubiyatno; Mohd Hairul Bin Khamidun (2025). Environmental bioremediation of pharmaceutical residues: microbial processes and technological innovations: a review. Bioprocess and Biosystems Engineering. https://doi.org/10.1007/s00449-024-03125-x
19) Nashwa A. H. Fetyan; Ayan A. Asair; Ismail M. Ismail; Tamer A. Elsakhawy; Sherif M. Elnagdy; Mahmoud S. M. Mohamed (2024). Bacterial Degradation of Ibuprofen: Insights into Metabolites, Enzymes, and Environmental Fate Biodegradation of Ibuprofen by Achromobacter Species. Microbiology Research. https://doi.org/10.3390/microbiolres15040154
20) Qurban Ali; Rida Zainab; Malik Badshah; Warda Sarwar; Samiullah Khan; Ghulam Mustafa; Tanveer Ibrahim; Safia Ahmed (2024). Prospecting the biodegradation of ciprofloxacin by Stutzerimonas stutzeri R2 and Exiguobacterium indicum strain R4 isolated from pharmaceutical wastewater. H2Open Journal. https://doi.org/10.2166/h2oj.2024.103
21) Heting Fang; Akashdeep Singh Oberoi; Zhiqing He; Samir Kumar Khanal; Hui Lu (2021). Ciprofloxacin-degrading Paraclostridium sp. isolated from sulfate-reducing bacteria-enriched sludge: Optimization and mechanism. Water Research. https://doi.org/10.1016/j.watres.2021.116808
22) Ponnuswamy Vijayaraghavan; A. Amala Lourthuraj; Mariadhas Valan Arasu; Naif AbdullahAl-Dhabi; Balasubramani Ravindran; Soon WoongChang (2021). Effective removal of pharmaceutical impurities and nutrients using biocatalyst from the municipal wastewater with moving bed packed reactor. Environmental Research. https://doi.org/10.1016/j.envres.2021.111777

23) Mohamed S. Elshikh; Dina S. Hussein; Fatimah S. Al-khattaf; Rabab Ahmed Rasheed El-Naggar; Khalid S. Almaary (2022). Diclofenac removal from the wastewater using activated sludge and analysis of multidrug resistant bacteria from the sludge. Environmental Research. https://doi.org/10.1016/j.envres.2022.112723
24) Muhammad B. Asif; Faisal I. Hai; Lakhveer Singh; William E. Price; Long D. Nghiem (2017). Degradation of Pharmaceuticals and Personal Care Products by White-Rot Fungi—a Critical Review. Current Pollution Reports. https://doi.org/10.1007/s40726-017-0049-5
25) Andreia Silva; Cristina Delerue-Matos; Sónia A. Figueiredo; Olga M. Freitas (2019). The Use of Algae and Fungi for Removal of Pharmaceuticals by Bioremediation and Biosorption Processes: A Review. Water
26) Ernest Marco-Urrea; Miriam Pérez-Trujillo; Teresa Vicent; Gloria Caminal (2009). Ability of white-rot fungi to remove selected pharmaceuticals and identification of degradation products of ibuprofen by Trametes versicolor. Chemosphere. https://doi.org/10.1016/j.chemosphere.2008.10.040
27) Ernest Marco-Urrea; Miriam Pérez-Trujillo; Carles Cruz-Morató; Gloria Caminal; Teresa Vicent (2010). Degradation of the drug sodium diclofenac by Trametes versicolor pellets and identification of some intermediates by NMR. Journal of Hazardous Materials. https://doi.org/10.1016/j.jhazmat.2009.11.112
28) A. I. Rodarte-Morales; G. Feijoo; M. T. Moreira; J. M. Lema (2011). Degradation of selected pharmaceutical and personal care products (PPCPs) by white-rot fungi. World Journal of Microbiology and Biotechnology. https://doi.org/10.1007/s11274-010-0642-x
29) Mohd Faheem Khan (2025). Fungi for Sustainable Pharmaceutical Remediation: Enzymatic Innovations, Challenges, and Applications—A Review. Processes. https://doi.org/10.3390/pr13041034
30) Helena Sá; Michele Michelin; Teresa Tavares; Bruna Silva (2022). Current Challenges for Biological Treatment of Pharmaceutical-Based Contaminants with Oxidoreductase Enzymes: Immobilization Processes, Real Aqueous Matrices and Hybrid Techniques. Biomolecules. https://doi.org/10.3390/biom12101489
31) Fatmata Sesay; Richard Edmond Victor Sesay; Musa Kamara; Xuesong Li; Chengxin Niu (2025). Biodegradation of pharmaceutical contaminants in wastewater using microbial consortia: Mechanisms, applications, and challenges. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2025.125564
32) Shabnam Murshid; Gnana Prakash Dhakshinamoorthy (2021). Application of an immobilized microbial consortium for the treatment of pharmaceutical wastewater: Batch-wise and continuous studies. Chinese Journal of Chemical Engineering. https://doi.org/10.1016/j.cjche.2020.04.008
33) A. Cruz del Álamo; M. I. Pariente; R. Molina; F. Martínez (2022). Advanced bio-oxidation of fungal mixed cultures immobilized on rotating biological contactors for the removal of pharmaceutical micropollutants in a real hospital wastewater. Journal of Hazardous Materials. https://doi.org/10.1016/j.jhazmat.2021.128002
34) Yidi Li; Lixiang Chen; Xiaochun Tian; Lifeng Lin; Rui Ding; Weifu Yan; Feng Zhao (2021). Functional role of mixed-culture microbe in photocatalysis coupled with biodegradation: Total organic carbon removal of ciprofloxacin. Science of The Total Environment. https://doi.org/10.1016/j.scitotenv.2021.147049
35) Daniel Aparecido da Silva Rodrigues; Camila Cristina Rodrigues Ferreira da Cunha; Daiana Rocha do Espirito Santo; André Luis Corrêa de Barros; Andressa Rezende Pereira; Silvana de Queiroz Silva; Aníbal da Fonseca Santiago; Robson José de Cássia Franco Afonso (2021). Removal of cephalexin and erythromycin antibiotics, and their resistance genes, by microalgae-bacteria consortium from wastewater treatment plant secondary effluents. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-021-15351-x
36) Mehri Shabani; Maxime Pontié; Habibollah Younesi; Mouna Nacef; Ahmad Rahimpour; Mostafa Rahimnejad; Racha Medjda Bouchenak Khelladi (2021). Biodegradation of acetaminophen and its main by-product 4-aminophenol by Trichoderma harzianum versus mixed biofilm of Trichoderma harzianum/Pseudomonas fluorescens in a fungal microbial fuel cell. Journal of Applied Electrochemistry. https://doi.org/10.1007/s10800-020-01518-w
37) Gabriela Angeles-de Paz; Alejandro Ledezma-Villanueva; Tatiana Robledo-Mahón; Clementina Pozo; Concepción Calvo; Elisabet Aranda; Jessica Purswani (2023). Assembled mixed co-cultures for emerging pollutant removal using native microorganisms from sewage sludge. Chemosphere. https://doi.org/10.1016/j.chemosphere.2022.137472
38) Rodrigo B. Carneiro; Carolina A. Sabatini; Guilherme M. Titato; Tanare C. R. Ferreira; Marcelo Zaiat; Álvaro J. Santos-Neto (2022). New biotransformation pathways from sulfamethoxazole and ciprofloxacin removal in sewage treatment along the spatial profile of an anaerobic fixed bed bioreactor. Bioresource Technology Reports. https://doi.org/10.1016/j.biteb.2022.100944
39) Zdravka Velkova; Kristiana Lazarova; Gergana Kirova; Velizar Gochev (2025). Recent Advances in Pharmaceuticals Biosorption on Microbial and Algal-Derived Biosorbents. Processes. https://doi.org/10.3390/pr13020561
40) Lăcrămioara Rusu; Elena-Mirela Suceveanu; Alexandra-Cristina Blaga; Florin Marian Nedeff; Daniela Șuteu (2023). Insights into Recent Advances of Biomaterials Based on Microbial Biomass and Natural Polymers for Sustainable Removal of Pharmaceuticals Residues. Polymers. https://doi.org/10.3390/polym15132923

41) Osamah J. Al-sareji; Mónika Meiczinger; Raed A. Al-Juboori; Ruqayah Ali Grmasha; Manolia Andredaki; Viola Somogyi; Ibijoke A. Idowu; Csilla Stenger-Kovács; Miklós Jakab; Edina Lengyel; Khalid S. Hashim (2023). Efficient removal of pharmaceutical contaminants from water and wastewater using immobilized laccase on activated carbon derived from pomegranate peels. Scientific Reports. https://doi.org/10.1038/s41598-023-38821-3
42) Mathiyazhagan Narayanan; Sabariswaran Kandasamy; Jintae Lee; Selvaraj Barathi (2023). Microbial degradation and transformation of PPCPs in aquatic environment: A review. Heliyon. https://doi.org/10.1016/j.heliyon.2023.e18426
43) S. Karishma; P. R. Yaashikaa; P. Senthil Kumar; R. Kamalesh; A. Saravanan; Gayathri Rangasamy (2023). Promising approaches and kinetic prospects of the microbial degradation of pharmaceutical contaminants. Environmental Science: Advances. https://doi.org/10.1039/d3va00194f
44) Barbara Muñoz-Palazon; Aurora Rosa-Masegosa; Ramiro Vilchez-Vargas; Alexander Link; Susanna Gorrasi; Jesus Gonzalez-Lopez; Alejandro Gonzalez-Martinez (2022). Biological removal processes in aerobic granular sludge for treating synthetic hospital wastewater: Effect of temperature. Journal of Water Process Engineering. https://doi.org/10.1016/j.jwpe.2022.102691
45) Bhagyashree Tiwari; Yassine Ouarda; Patrick Drogui; Rajeshwar D. Tyagi; Marc Antoine Vaudreuil; Sébastien Sauvé; Gerardo Buelna; Rino Dubé (2021). Fate of Pharmaceuticals in a Submerged Membrane Bioreactor Treating Hospital Wastewater. Frontiers in Water. https://doi.org/10.3389/frwa.2021.730479
46) Chengyue Li; Xin Du; Chuyi Huang; Zhenghua Zhang (2023). Effects of High Pharmaceutical Concentrations in Domestic Wastewater on Membrane Bioreactor Treatment Systems: Performance and Microbial Community. Membranes. https://doi.org/10.3390/membranes13070650
47) Jinli Zheng; Xin Huang; Linjun Gao; Xu Xu; Lijun Hou; Tianming Cai; Shuyu Jia (2024). Deciphering the core bacterial community structure and function and their response to environmental factors in activated sludge from pharmaceutical wastewater treatment plants. Environmental Pollution. https://doi.org/10.1016/j.envpol.2024.123635
48) Raghad Asad Kadhim Alobaidi; Kubra Ulucan-Altuntas; Rasha Khalid Sabri Mhemid; Neslihan Manav-Demir; Ozer Cinar (2021). Biodegradation of Emerging Pharmaceuticals from Domestic Wastewater by Membrane Bioreactor: The Effect of Solid Retention Time. International Journal of Environmental Research and Public Health. https://doi.org/10.3390/ijerph18073395
49) Wei Dai; Ji-Wei Pang; Jie Ding; Yu-Qian Wang; Lu-Yan Zhang; Nan-Qi Ren; Shan-Shan Yang (2023). Study on the removal characteristics and degradation pathways of highly toxic and refractory organic pollutants in real pharmaceutical factory wastewater treated by a pilot-scale integrated process. Frontiers in Microbiology. https://doi.org/10.3389/fmicb.2023.1128233
50) L. Bhim Sen Thapa; Soumya Pandit; Sanchita Bipin Patwardhan; Sakshi Tripathi; Abhilasha Singh Mathuriya; Piyush Kumar Gupta; Ram Bharosay Lal; Tanmoy Roy Tusher (2022). Application of Microbial Fuel Cell (MFC) for Pharmaceutical Wastewater Treatment: An Overview and Future Perspectives. Sustainability. https://doi.org/10.3390/su14148379
51) A. S. Ajibola; A. O. Adebiyi; D. O. Nwaeke; F. O. Ajibola; G. O. Adewuyi (2021). Analysis, Occurrence and Ecological Risk Assessment of Diclofenac and Ibuprofen Residues in Wastewater from Three Wastewater Treatment Plants in South-Western Nigeria.. Journal of Applied Sciences & Environmental Management. https://doi.org/10.4314/jasem.v25i3.5
52) Lawal Ibraheem Kehinde; Abideen A. Adekanmi; Lawal Kola Ahmad; Owolabi Oluwafemi Akinkunmi; Olasunkanmi Busayo Tomi; Oluwagbemiga Micheal Ajewole (2022). Bioremediation of Waste Water from Pharmaceutical Industry by Bacteria (Bacillus subtilis). Journal of Environmental Issues and Climate Change. https://doi.org/10.59110/jeicc.v1i1.64
53) Jean Sagwati Mdumela; Tsolanku Sidney Maliehe; Yannick Nuapia; Marks Matee Sebaiwa; Tlou Nelson Selepe (2026). Environmental and Human Health Risk Assessment of Pharmaceutical Pollutants Detected in the Sand River in Polokwane, South Africa. Safety. https://doi.org/10.3390/safety12030078
54) Ntombiphumile Perceverence Tenza; Precious Nokwethemba Mahlambi (2025). An Innovative Bioremediation Approach for the Removal of Antibiotic and Antiretroviral Drug Contaminants From Wastewater Using Chlorella spp.. Water and Environment Journal. https://doi.org/10.1111/wej.70004
55) Anne W. Njuguna; Wangai Eng. Ndirangu; Alfred O. Prof. Mayabi (2024). An Investigation into the Management of Pharmaceutical Wastewater in Kenya.
56) Andile Bheki Zitha; Somandla Ncube; Nomvano Mketo; Hlengilizwe Nyoni; Lawrence Mzukisi Madikizela (2022). Antiretroviral Drugs in Water: An African Challenge with Kenya and South Africa as Hotspots and Plausible Remediation Strategies. Chemistry Africa. https://doi.org/10.1007/s42250-022-00417-1
57) Petro Karungamye; Anita Rugaika; Kelvin Mtei; Revocatus Machunda (2022). The pharmaceutical disposal practices and environmental contamination: A review in East African countries. HydroResearch. https://doi.org/10.1016/j.hydres.2022.11.001
58) Prabhaharan Renganathan; Lira A. Gaysina; Cipriano García Gutiérrez; Edgar Omar Rueda Puente; Juan Carlos Sainz-Hernández (2025). Harnessing Engineered Microbial Consortia for Xenobiotic Bioremediation: Integrating Multi-Omics and AI for Next-Generation Wastewater Treatment. Journal of Xenobiotics. https://doi.org/10.3390/jox15040133

59) Tarun Mishra; Pankaj Bharat Tiwari; Swarna Kanchan; Minu Kesheri (2025). Advances in Microbial Bioremediation for Effective Wastewater Treatment. Water. https://doi.org/10.3390/w17223196
60) Mohamed Chaker Necibi; Driss Dhiba; Souad El Hajjaji (2021). Contaminants of Emerging Concern in African Wastewater Effluents: Occurrence, Impact and Removal Technologies. Sustainability. https://doi.org/10.3390/su13031125
61) Sumira Malik; Jutishna Bora; Sagnik Nag; Sweta Sinha; Sagar Mondal; Sarvesh Rustagi; Richismita Hazra; Harshavardhan Kumar; Vishnu D. Rajput; Tatiana Minkina; Najwane Said Sadier; Abdulmajeed G. Almutary (2023). Fungal-Based Remediation in the Treatment of Anthropogenic Activities and Pharmaceutical-Pollutant-Contaminated Wastewater. Water. https://doi.org/10.3390/w15122262
62) Inés Aguilar-Romero; Fernando Madrid; Jaime Villaverde; Esmeralda Morillo (2024). Ibuprofen-enhanced biodegradation in solution and sewage sludge by a mineralizing microbial consortium. Shift in associated bacterial communities. Journal of Hazardous Materials. https://doi.org/10.1016/j.jhazmat.2023.132970
63) Humaira Saeed; Sudhakar Padmesh; Aditi Singh; Abhishek Nandy; Sujit Pratap Singh; Ravi K. Deshwal (2024). Impact of veterinary pharmaceuticals on environment and their mitigation through microbial bioremediation. Frontiers in Microbiology. https://doi.org/10.3389/fmicb.2024.1396116
64) Ayodeji Amobonye; Christiana E. Aruwa; Sesan Aransiola; John Omame; Toyin D. Alabi; Japareng Lalung (2023). The potential of fungi in the bioremediation of pharmaceutically active compounds: a comprehensive review. Frontiers in Microbiology. https://doi.org/10.3389/fmicb.2023.1207792
65) Ahmad Hussaini Jagaba; Shamsul Rahman Mohamed Kutty; Mohamed Hasnain Isa; Aiban Abdulhakim Saeed Ghaleb; Ibrahim Mohammed Lawal; Abdullahi Kilaco Usman; Abdullahi Haruna Birniwa; Azmatullah Noor; Sule Abubakar; Ibrahim Umaru; Anwar Ameen Hezam Saeed; Haruna Kolawole Afolabi; Usman Bala Soja (2022). Toxic Effects of Xenobiotic Compounds on the Microbial Community of Activated Sludge. ChemBioEng Reviews. https://doi.org/10.1002/cben.202100055