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BIOREMEDIATION AS A STRATEGY FOR RECOVERING WATER CONTAMINATED BY FLOODS ASSOCIATED WITH CLIMATE CHANGE:

EMPHASIS ON REMOVING EMERGING POLLUTANTS

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Final Course Work presented to the Environmental and Sanitary Engineering Course at the Federal University of Fronteira Sul (UFFS), as a requirement to obtain the degree of Bachelor's in Environmental and Sanitary Engineering.

ADVISOR: PROF. DR. HELEN TREICHEL

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Dissertation presented to the Postgraduate Program in Environmental and Sanitary Engineering at the Federal University of Fronteira Sul (UFFS) as a partial requirement for obtaining the degree of Environmental and Sanitary Engineer.

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I dedicate this work to my parents,
who always made my education a
priority, and today, the completion of
my studies is a victory not only for
me, but for us!

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I sincerely thank my family, who have always been by my side with love, support, and words of encouragement, especially in the most challenging moments. Every achievement throughout this journey was also yours.

I want to express my sincere gratitude to all the professors who were part of my academic journey during my undergraduate studies, especially my advisor, Professor Helen Treichel, for her guidance and support throughout this work.

I also express my most profound solidarity with all those affected by the floods that hit the state of Rio Grande do Sul in 2024, especially the victims, the grieving families, and all those who faced irreparable losses.

This work is inspired by the courage and resilience of the families from Rio Grande do Sul who lost so much in this catastrophic event that devastated the state. It is a sincere attempt to contribute, through science and knowledge, to mitigating the secondary impacts caused by events as devastating as floods.

ABSTRACT

Climate change has increased the frequency of floods, dispersing emerging contaminants into water bodies and posing a growing challenge to environmental quality. This study presents a literature review on bioremediation as a sustainable strategy for treating and recovering waters contaminated by extreme hydrological events. Studies published between 2020 and 2025 were analyzed, focusing on microorganisms and technologies applied to the degradation of pollutants, including pharmaceuticals, pesticides, plastics, and heavy metals. Bacterial, fungal, and algal species, as well as mixed microbial consortia, showed high removal rates, often exceeding 90%. Innovative technologies, including enzymatic immobilization, membrane bioreactors, and other integrated systems, further enhanced process efficiency. The results emphasize that bioremediation, combined with advances in environmental biotechnology, represents an effective, economical, and ecologically safe alternative for mitigating water pollution in scenarios intensified by climate change.

Keywords: Emerging contaminants; Microorganisms; Environmental risk of flooding; Biotechnological treatment.

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LIST OF ABBREVIATIONS AND ACRONYMS

Acronyms	Description
UFFS	Federal University of the Southern Frontier
ABFT	Autotrophic bioflocs
ABGS	Algal-bacterial granular sludge
BMFCs	Bacterial microbial fuel cells
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
diCB	Dichlorobiphenyl
EPS	Extracellular polymeric substances
FPs	Point sources
FMFCs	Fungal microbial fuel cells
FNPs	Non-point sources
FTW	Constructed wetlands
Hg	Mercury
LAS	Linear alkylbenzene sulfonates
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MABC	Microalgae–bacteria consortia
MBT	2-mercaptobenzothiazole
MerA	Mercuric reductase
MerB	Organomercurial lyase
MFCs	Microbial fuel cells
Ni	Nickel
PAHs	Polycyclic aromatic hydrocarbons
PCP	Pentachlorophenol
PCB	Polychlorinated biphenyl
PCR	Polymerase chain reaction
PE	Polyethylene
PEs	Emerging pollutants
PFCPs	Pharmaceutical and personal care products
PLA	Polylactic acid
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene
PVA	Polyvinyl alcohol
Pb	Lead
PET	Polyethylene terephthalate
triCB	Trichlorobiphenyl
tetraCB	Tetrachlorobiphenyl
OFF	Organophosphates

SUMMARY

1 INTRODUCTION

Climate change has increased the frequency and magnitude of extreme events, such as floods, causing significant impacts on aquatic ecosystems, public sanitation systems, and water security (Apostolaki, 2025).

Among the main factors associated with the worsening of this process is atmospheric warming, which increases the air's capacity to retain water vapor, intensifying humidity levels and, consequently, precipitation volumes (Bolan et al., 2025).

Additionally, climate phenomena such as La Niña directly influence regional precipitation patterns, resulting in more intense and frequent rainfall in many areas. The combination of global warming and the intensification of these natural phenomena creates a scenario of growing hydrological risk, with increased unpredictability and severity of extreme events. This scenario affects not only historically vulnerable regions but also territories previously considered to be low in flood susceptibility (Bolan et al., 2025).

In addition to the direct impacts of flooding, floodwaters can carry pollutants and contaminants, potentially contaminating waterways and harming animals and human health (Bolan et al., 2025).

During floods, water percolates and leaches into various environments, including streets, homes, hospitals, construction sites, transportation systems, urban solid waste disposal areas, sewage systems, and industrial and agricultural areas (Bolan et al., 2025). Consequently, a wide variety of contaminants of emerging concern are released, such as pharmaceuticals, personal hygiene products, antibiotics, pesticides, herbicides, surfactants, endocrine-disrupting compounds, disinfection byproducts, detergents, plastics, and heavy metals, which have been detected in aquatic environments after intense precipitation events (Lim, Kah Yee et al., 2021).

In this context, bioremediation emerges as a promising alternative, defined by Erickson et al. (1992) as the degradation of organic compounds by microorganisms into non-toxic forms to improve the environmental quality of contaminated sites.

It is important to note that, unlike the biodegradation of organic compounds, in which the molecules are destroyed, metals and metalloids are not directly eliminated by microbial processes. However, after being transformed, immobilized, or detoxified, these compounds can be further treated through bioremediation (Alexander, Martin, 1999).

One of the fundamental principles of bioremediation is that, for a waste to be decomposed by microbial activity, it must serve as a food source for microorganisms that possess the specific enzymes necessary for its degradation (Borzani, 2001).

One of the main benefits of adding microorganisms, whether native to the contaminated area or isolated from other environments, is the enhancement of the degradation process, known as bioaugmentation. Furthermore, although most bioremediation systems operate under aerobic conditions, performing them under anaerobic conditions allows microorganisms to degrade molecules that would otherwise be recalcitrant (Vidali, M., 2001). Both bacteria and fungi have been extensively studied for their ability to degrade a variety of environmental pollutants, including recalcitrant polycyclic aromatic hydrocarbons, halogenated hydrocarbons, and nitroaromatic compounds (Singh, A. et al., 2004).

Besides its theoretical importance and practical applicability, bioremediation can be performed directly at the contaminated site (in situ). This is generally a more cost-effective remediation measure with minimal environmental disruption, thereby enabling permanent waste disposal, reducing long-term civil liabilities, and achieving greater public acceptance. The method can also be integrated with other physical or chemical treatment techniques to optimize processes (Boopathy, R., 2001).

Given that bioremediation can be an effective strategy for treating water contaminated by floods, especially regarding emerging pollutants, this review article aims to evaluate its feasibility, with an emphasis on pollutant removal, and to explore the most recent innovations for this application.

2 OBJECTIVES

2.1 General Objective

The objective of this work is to conduct a literature review that compiles current studies on different methods and microorganisms used in bioremediation technology, with the aim of analyzing their potential applications in the recovery of water contaminated by emerging pollutants, especially those resulting from extreme hydrological events.

2.2 Specific Objectives

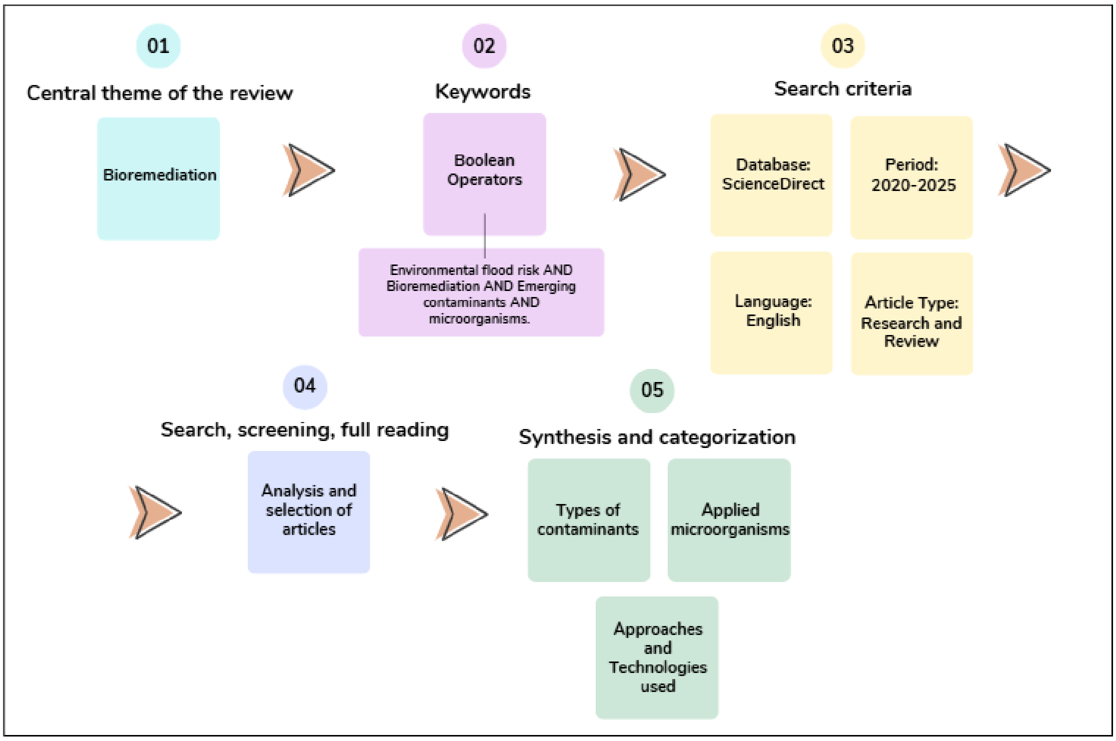
- Classify the types of contaminants addressed in recent studies related to water contamination due to extreme events;
- Determine the microorganisms most commonly applied in bioremediation strategies, considering their effectiveness and applicability;
- Identify the main technologies used in bioremediation processes applied to the recovery of contaminated water;
- Analyze the mitigation strategies proposed in the reviewed studies, with a focus on managing environmental risks associated with floods and emerging pollutants.

3 METHODOLOGY

The research was conducted through a literature review, aiming to gather, analyze, and discuss the current state of scientific knowledge on the topic. This was achieved through the collection and critical analysis of relevant publications in the literature, enabling the identification of advances, gaps, and trends in previous research.

Figure 1 illustrates the methodological steps employed in this study. The approaches and procedures adopted in each phase of the process are described in detail below.

Figure 1-Sequence of processes carried out in the development of the study.



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3.1 Defining the Topic and Scope of the Review

The scope of this review encompasses the central theme of "bioremediation and its associated technologies", to analyze and synthesize recent scientific advances and applications in this field.

3.1 Formulating Keywords

3.1.1 Boolean Operators

To ensure that the search results aligned with the objectives of this review, Boolean operators were used as a logical tool for combining keywords in the selected search engine. The use of these operators enabled the refinement of results, thereby increasing search accuracy. In particular, the "AND" operator was used, which restricts the search to publications that contain all the specified terms.

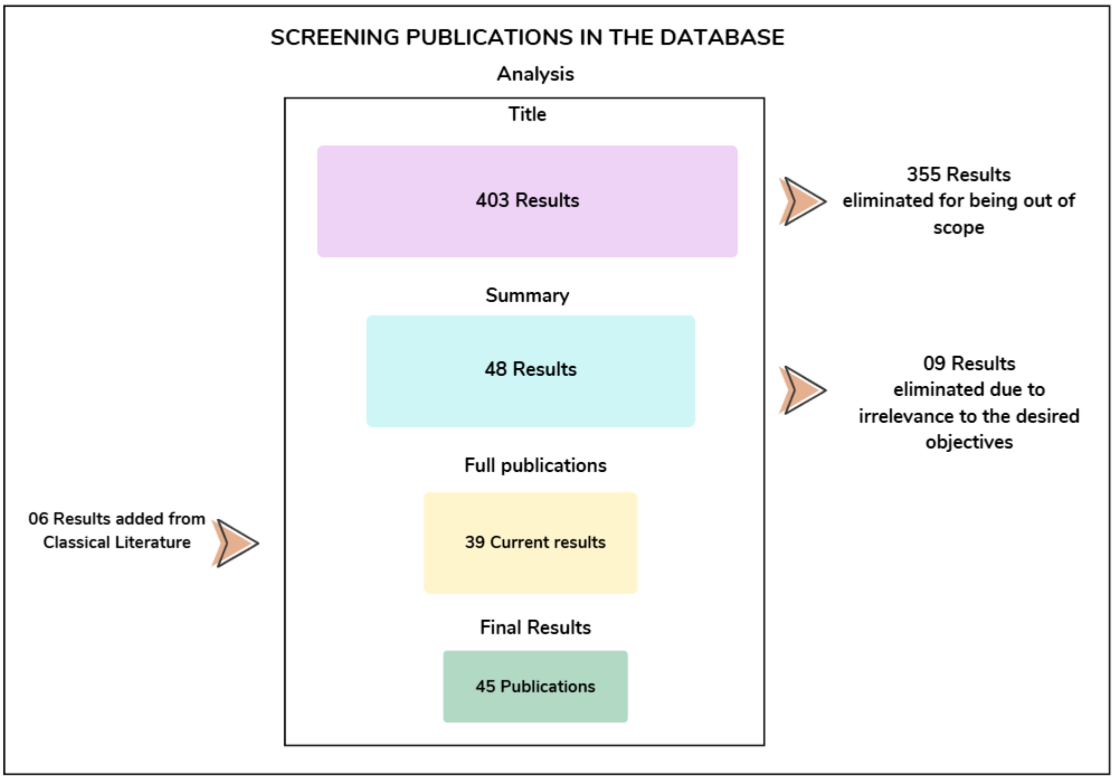
Keywords: Environmental flood risk AND Bioremediation AND Emerging contaminants AND microorganisms. 3.2.2 Defining Search Criteria

The database used for this study was the ScienceDirect online platform, where filters were applied to select publications classified as review and research articles. To ensure the timeliness and relevance of the results, the time frame was established as 2020 to 2025. Additionally, only articles written in English were included, providing greater comprehensiveness and standardization of the sources consulted.

3.2 Search and Screening of Articles

On May 14, 2025, a search was conducted in the ScienceDirect database using Boolean operators with the following keywords: Environmental flood risk AND Bioremediation AND Emerging contaminants AND Microorganisms. The search yielded 403 publications. After reading the titles, 48 articles were considered relevant to the objectives of this review. These articles were analyzed in full, resulting in the selection of 39 articles most relevant to this review. It is worth noting that, during the preparation of this review, concepts from classical literature were also incorporated. Although not covered by the previously defined search criteria and keywords, these were considered relevant and included in the final results. The screening system used to select the publications is presented below, as illustrated in Figure 2:

Figure 2-System used for screening publications.



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The process began with a review of titles and abstracts to identify relevant articles, followed by the exclusion of duplicate information and out-of-scope material. Subsequently, the selected articles were analyzed for their abstracts and full texts, enabling the final selection of studies for this review.

3.3 Summary and categorization of results

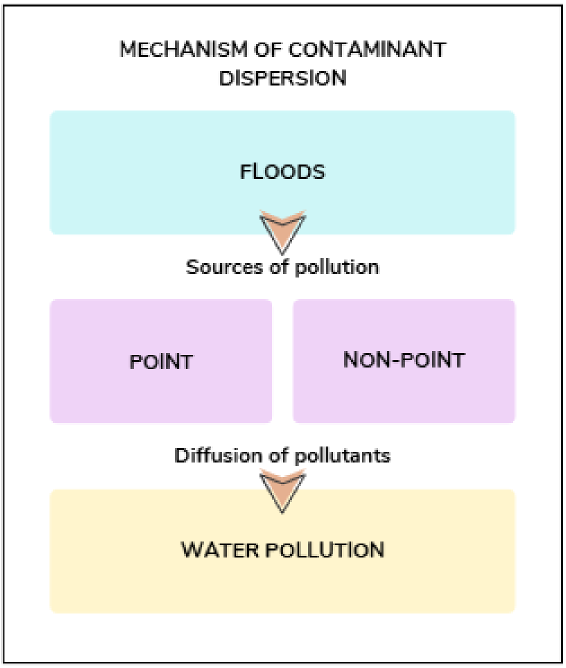
After reading the selected articles in full, the results were systematized and organized into four main categories, which structure the discussion throughout this study. The topics covered include the types of contaminants investigated, microorganisms used in biological processes, and approaches and technologies employed in bioremediation.

4 EMERGING CONTAMINANTS

The intensification of climate change has increased the frequency of floods globally, which, in addition to compromising the economy and health of populations, has significant impacts on the environment (Zhang et al., 2024).

During flood events, various contaminants from point sources (PFs) and nonpoint sources (NPSs) are rapidly released and dispersed, especially in high-velocity floods, significantly increasing the extent of water pollution and impacting large areas (Zhang et al., 2024).

Figure 3-Dispersion mechanism of emerging contaminants.



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4.1 Agrochemicals

Substances used to protect crops can leach and contaminate water bodies, especially during extreme weather events. Agrochemicals can reach the human body, where they are metabolized, eliminated, or accumulated, potentially causing clinical effects and disrupting ecosystems and affecting non-target species (González-González et al., 2022).

According to Hernández-Alomia et al. (2022), glyphosate, a phosphonate widely used as a herbicide, impacts aquatic ecosystems by promoting eutrophication through increased total phosphorus concentrations resulting from its leaching, which stimulates the proliferation of cyanobacteria and the consequent release of toxins, compromising water quality.

Additionally, organophosphates (OPs), according to Dash et al. (2023), constitute one of the main classes of pesticides, widely used as insecticides in agriculture and accounting for more than 34% of global consumption.

Fipronil, a compound frequently detected in surface waters due to agricultural and urban runoff, has severe effects on aquatic organisms, including neurological, reproductive, and oxidative changes in fish and invertebrates (Bhatt et al., 2023).

4.2 Personal Care Products and Pharmaceuticals

According to Ravikumar et al. (2024), substances used for medicinal, cosmetic, hygiene, and healthcare purposes are included in the category of pharmaceutical and personal care products (PFCPs).

PFCPs have high environmental mobility due to their hydrophilic nature, low volatility, and strong polarity, increasing their risk of contamination from sewage overflows, wastewater, and urban leachate (Ravikumar et al., 2024). According to Couto et al. (2022), the presence of such contaminants in aquatic environments is a global concern, as they have high intrinsic toxicity, persistence, and bioaccumulation potential, potentially causing significant impacts on both human health and ecosystems.

Kock et al. (2023) evaluated the impacts of pharmaceuticals on aquatic ecosystems, demonstrating that diatoms suffered a 40–60% reduction in their diversity and exhibited morphological changes when exposed to environmental concentrations of drugs, compromising essential processes such as photosynthesis and nutrient assimilation.

According to Bhaskaralingam et al. (2025), reported studies indicate that antibiotics, such as ciprofloxacin and sulfonamides, are associated with increased microbial resistance and bioaccumulation in aquatic organisms.

4.3 Plastics and Microplastics

The massive use of plastics in recent decades has made them a major environmental pollutant, due to their high durability, versatility, and low natural degradation rates. In this context, different types of synthetic polymers have been studied, notably low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polyethylene terephthalate (PET), and polystyrene (PS), which degrade extremely slowly through natural processes (Salinas et al., 2024).

In addition, tire wear particles (TWP) account for approximately 85% of urban microplastics and release heavy metals and toxic compounds, such as 6-PPD-quinone, which is lethal to fish (Bodus et al., 2024).

4.4 Heavy Metals

Mercury is one of the most hazardous heavy metals, exhibiting high toxicity and environmental persistence, which is why it is classified as a priority pollutant. Furthermore, its presence in water sources, whether surface or groundwater, poses a serious concern, primarily because it can penetrate the food chain and bioaccumulate at higher trophic levels, resulting in progressively higher concentrations (Adewuyi, 2025).

In addition to mercury, Cr(VI) can be attributed to several diffuse sources, including the release of industrial and urban effluents and agricultural and livestock activities. It stands out for its high solubility and toxicity, posing risks to both human health and various living organisms (Morales-Pontet et al., 2025).

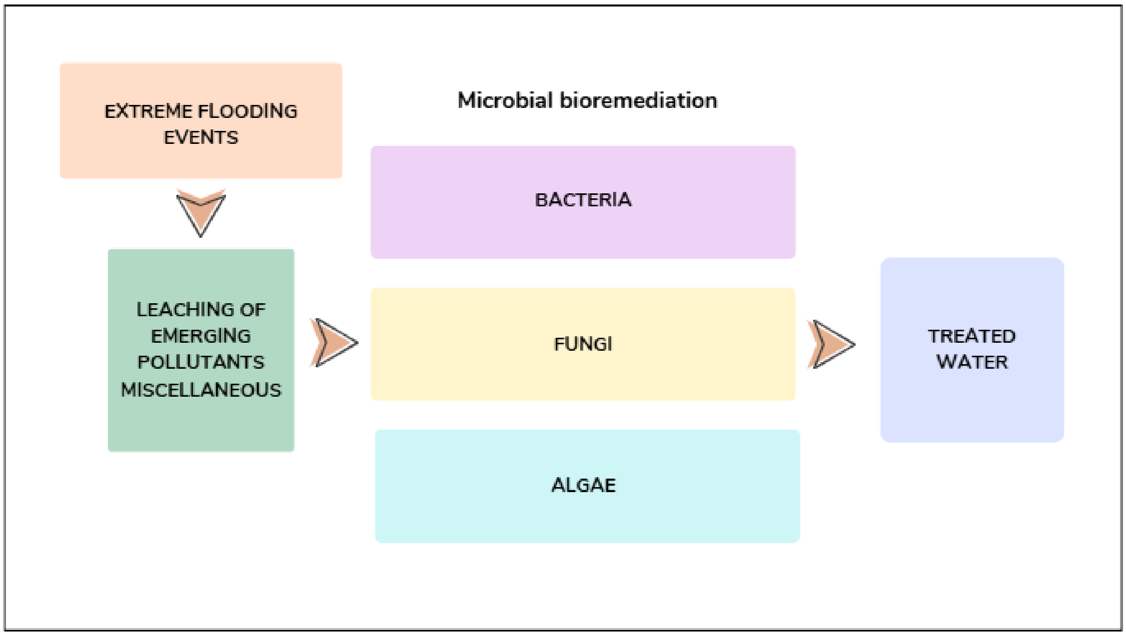
It is essential to note that other heavy metals, such as Cd (Cadmium), Co (Cobalt), Cu (Copper), Ni (Nickel), and Pb (Lead), can be detected in wastewater following extreme weather events.

5 MICROORGANISMS

According to Mishra et al. (2023), the use of enzymatic pathways in bioremediation to accelerate biochemical degradation enables the removal of contaminants from polymers, personal care products, and medical and household waste. This is enhanced by the addition of nutrients that stimulate natural microbial activity, constituting a promising strategy for treating emerging pollutants (EPs) in water.

Microbial bioremediation, using bacteria, fungi, or algae, has demonstrated effectiveness in removing EPs. In this scenario, advanced bioremediation techniques stand out for offering benefits such as environmental sustainability, the absence of adverse side effects, low implementation costs, and broad social acceptance (González-González et al., 2022).

Figure 4-Main groups of microorganisms used in Bioremediation.



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5.1 Bacteria

Hernández-Alomia et al. (2022) described three strains of degrading bacteria in Ecuadorian water bodies, including *Pseudomonas sp.*, *Pantoea stewartii*, and *Klebsiella variicola*, which can utilize glyphosate as the sole source of carbon, phosphorus, and nitrogen. These strains also included other species found in aquatic sediments and agricultural soils, including genera such as *Pseudomonas, Arthrobacter, Enterobacter, Geobacillus, Flavobacterium*, and *Bacillus.*

Additionally, Bhaskaralingam et al. (2025) identified that the *Achromobacter xylosoxidans* strain exhibited remarkable pesticide-degrading capacity, decomposing 94.12% of α-endosulfan, 84.52% of β-endosulfan, and 80.10% of endosulfan, compounds derived from organochlorine pesticides.

Several bacteria, such as *Escherichia coli, Fusobacterium sp., Bacillus sp.,* and *Brevibacterium cysticus,* are capable of removing mercury (Hg) from contaminated water through the presence of the mer operon gene, which produces enzymes such as mercury reductase (MerA) and organomercury lyase (MerB), which reduce Hg^{2+} to Hg^{0} and break carbon-mercury bonds, making mercury less toxic and aiding in environmental detoxification. (Adewuyi, 2025)

According to the review by Bhaskaralingam (2025), bacteria such as *Comamonas aquatica* and *Bacillus sp.* are capable of degrading antibiotics and anti-inflammatories, such as ibuprofen, achieving, in some cases, removal rates equivalent to 92%.

Bacterial consortia have shown even greater efficiency through metabolic cooperation among different species. Using bacterial consortia, paracetamol was removed at 76–100% by strains of *Stenotrophomonas* sp. and *Delftia tsuruhatensis*, while sulfamethoxazole was removed at approximately 99% by species such as *Nannochloris sp.* (Singh et al., 2024).

The bacteria *Serratia marcescens* and *Serratia sp.* demonstrated high potential for antibiotic degradation, removing, respectively, 89.5% of tetracycline in 48 hours and 84.03% of penicillin in 336 hours (González-González et al., 2022).

According to Ahmaruzzaman et al. (2024), bacterial consortia cultivated in microbial fuel cells (MFCs) achieved greater than 95% phenol removal within 60 hours, with the added advantage of generating electricity. Furthermore, halophilic bacterial communities, composed of genera such as *Formosa, Stappia, Luteococcus, Treponema,* and *Syntrophus,* demonstrated removal efficiencies above 99% for 4-chlorophenol in anaerobic biofilm reactors supplemented with hydrogen.

In the context of polyaromatic hydrocarbon (PAH) removal, *Pseudomonas putida* eliminated 71% of naphthalene, while *Rhodococcus wratislaviensis* degraded 53% of heavy PAHs in just 5 days;

when combined in a mixed bacterial biomass, PAH degradation efficiency increased to 95.5% (Ragini et al., 2024).

In estuarine microbial mats evaluated by Morales-Pontet et al. (2025), the consortium of heterotrophic bacteria in the deeper layers played a crucial role in Cr(VI) removal, achieving 98.82% efficiency in unmodified live consortia and 98.24% in autoclaved mats, highlighting their importance in the metal adsorption and reduction processes.

Regarding heavy metal removal, *Aeribacillus pallidus* achieved a Pb removal rate of 96.78%. At the same time, *Bacillus megaterium* and *Rhodotorula sp.* were able to remove, respectively, 79% and 80% of Cd, *Cellulosimicrobium sp.* achieved 99.33% removal of hexavalent chromium (Cr(VI)), *Sporosarcina saromensis* achieved 100% removal of Cr(VI), and *Vibrio parahaemolyticus* promoted the removal of 89.4% of Hg (Abu-Tahon et al., 2025).

Regarding the bioreduction of microplastics, *Ideonella sakaiensis* stood out for its ability to degrade PET in up to six weeks through hydrolyzing enzymes, while *Bacillus cereus* and *Bacillus gottheilii,* isolated from mangroves, also promoted significant mass loss of different polymers (Ahmed et al., 2024).

In bioaugmentation tests, bacterial consortia composed of *Microbacterium sp.* and *Rhodococcus ruber* removed 96.4% of the PCB Sovol and 72.2% in 90 days, while the combination of *Arthrobacter sp.* and *Ralstonia eutropha* achieved a 57% reduction of Aroclor (Hassan et al., 2023).

Microbial communities extracted from the rhizomicrobiome showed great potential for treating contaminated water. Consortia involving the bacteria *Gordonia amicalis, Pseudomonas aeruginosa, Rhodococcus ruber,* and *Ochrobactrum anthropi* achieved a similar degradation rate of 67% of hydrocarbons. In contrast, the association of C*orynebacterium sp., Sphingobacterium gobiense,* and *Kocuria flava* achieved 71.22% removal of the insecticide chlorpyrifos (Aryal, 2024).

The consortium composed of *Bacillus subtilis* and *Pseudomonas alloputida* achieved 11.11% and 16.94% reductions in recycled LDPE and virgin LLDPE, respectively (Salinas et al., 2024).

Table 1-Literature data on bacteria used in the bioremediation of emerging pollutants.

Biological Agent	Emerging Pollutant	Removal Efficiency	Literature Reference
Achromobacter xylosoxidans	α-endosulfan β-endosulfan endosulfan	94.12% 84.52% 80.10%	(Bhaskaralingam et al., 2025)
Comamonas aquática and Bacillus sp.	Ibuprofen	92%,	(Bhaskaralingam et al., 2025)
Stenotrophomonas sp. and *Delftia tsuruhatensis*	Paracetamol	76–100%	(Singh et al., 2024)
Nannochloris sp.	Sulfamethoxazole	99%	(Singh et al., 2024)
Serratia marcescens and *Serratia* sp.	Tetracycline Penincillin	89.5% 84.03%	(González-González et al., 2022)
Formosa, *Stappia*, *Luteococcus*, *Treponema*, and *Syntrophus*	Phenol 4-clorophenol	95% 99%	(Ahmaruzzaman et al.,2024)
Pseudomonas putida	Naphthalene	71%	(Ragini et al., 2024)
Rhodococcus wratislaviensis	Polyaromatic Hydrocarbons	53%	(Ragini et al., 2024)
Aeribacillus pallidus	Pb	96.78%,	(Abu-Tahon et al., 2025)
Bacillus megaterium	Cd	79%	(Abu-Tahon et al., 2025)
Rhodotorula sp	Cd	80%	(Abu-Tahon et al., 2025)
Cellulosimicrobium sp.	Cr (VI)	99.33%	(Abu-Tahon et al., 2025)
Sporosarcina saromensis	Cr(VI)	100%	(Abu-Tahon et al., 2025)
Vibrio parahaemolyticus	Hg	89.4%	(Abu-Tahon et al., 2025)
Microbacterium sp. and *Rhodococcus ruber*	Polychlorinated biphenyl	72.2%	(Hassan et al., 2023)
Arthrobacter sp. and *Ralstonia*	Aroclor	57%	(Hassan et al., 2023)
Gordonia amicalis, *Pseudomonas aeruginosa*, *Rhodococcus ruber*, and *Ochrobactrum anthropi*	Hydrocarbons	67%	(Aryal, 2024)
Corynebacterium sp., *Sphingobacterium gobiense*, and *Kocuria flava*	Chlorpyrifos	71.22%	(Aryal, 2024)
Halomonas, *Marinospirillum*, *Acinetobacter* and *Pseudomonas*	Hydrocarbons	98.3%	(Zhang et al., 2025)
Bacillus subtilis and *Pseudomonas alloputida*	Recycled LDPE Virgin LLDPE	11.11% 16.96%	(Salinas et al., 2024)
Pseudomonas putida immobilized	Phenol Cd Cu	92% 99% 97%	(Mehrotra et al., 2021)
Pseudomonas sp. immobilized	Textile Dyes	75–83%	(Mehrotra et al., 2021)
Pseudomonas sp., *Comamonas sp.*, and *Rhodococcus sp.* immobilized	Benzene Toluene	100%	(Mehrotra et al., 2021)

5.2 Fungi

Mycoremediation of water containing pharmaceutical residues by white-rot fungi, such as *Trametes versicolor,* has shown high potential for degrading analgesics, recalcitrant antibiotics, and psychotropic drugs, thanks to the production of oxidative enzymes capable of acting on highly persistent molecules (Singh et al., 2024).

Some filamentous and symbiotic fungi, such as *Trichoderma viride, Gliocladium arborescens*, and *Metarhizium robertsii*, have shown potential for removing Hg^{2+} and methylmercury compounds in aquatic environments through biosorption and the transformation of the metal into less toxic forms, using enzymatic mechanisms and the ability to accumulate Hg in their hyphae (Adewuyi, 2025).

Abu-Tahon et al. (2025) highlighted the efficiency of fungal species in the bioremediation of heavy metals, especially *Aspergillus niger*, which removed 80% of Uranium, *Aspergillus tubingensis* removed 90.8% of Pb, 68.4% of Zn, and 64.5% of Cr, *Phanerochaete chrysosporium* obtained 96.2% of Cd and 89.4% of Ni, *Phlebia brevispora* reached 97.5% of Pb, 91.6% of Cd, and 72.7% of Ni, while *Trametes pubescens* reached 99.56% of Pb and 67.1% of Zn. The fungus *Phlebia acanthocystis* was highly efficient in degrading pentachlorophenol (PCP), achieving 100% removal in low-nitrogen media, resulting in the formation of intermediate metabolites such as tetrachlorohydroquinone and tetrachlorocatechol, indicating complete degradation by oxidative pathways (Ahmaruzzaman et al., 2024).

In the review by Bhaskaralingam et al. (2025), *Pleurotus ostreatus* was found to eliminate 83%-91% of the antibiotics sulfamethoxazole, sulfadiazine, sulfathiazole, sulfapyridine, and sulfamethazine over 2 weeks.

The fungus *Umbelopsis isabellina* degraded over 90% of endocrine disruptors, including nonylphenol, 4-tert-octylphenol, and 4-cumylphenol, within 12 h. In comparison, *Trametes versicolor* removed 100% of the organophosphate pesticide Malathion and 98.7% of the herbicide Diuron in 840 h (González-González et al., 2022).

In Ragini's (2024) article, white rot fungi, when combined with zero-valent nano-iron, achieved 92–96% degradation of phenanthrene, anthracene, and benzo[a]pyrene after 42 days, while *basidiomycetes* reduced naphthalene by up to 70% and pyrene by 29%. (Ragini et al., 2024)

Furthermore, the application of white rot fungus in constructed wetlands, systems used for stormwater treatment, removed 82% of acetanilide and 70% of HMMM (hexamethoxymethylmelamine), toxic compounds derived from PDP (Bodus et al., 2024).

In laboratory and field trials (Hassan et al., 2023), polychlorinated biphenyl (PCB) was removed in trickle-bed reactors with *Pleurotus ostreatus*, reaching 82% for dichlorobiphenyl (diCB), 80% for trichlorobiphenyl (triCB), and 65% for tetrachlorobiphenyl (tetraCB).

In the removal of microplastics, the species *Aspergillus niger* and *Aspergillus fumigatus* showed polypropylene (PP) degradation rates of 71.1% and 53.1%, respectively, over 90 days, while the marine fungus *Zalerion maritimum*, under co-metabolism conditions, achieved 56% polyethylene (PE) removal (Li et al., 2023).

Table 2-Literature data on fungi used in the bioremediation of emerging pollutants.

Biological Agent	**Emerging Pollutant**	**Removal Efficiency**	**Literature Reference**
Aspergillus niger	U	80%	(Abu-Tahon et al., 2025)
Aspergillus tubingensis	Pb Zn Cr	90.8% 68.4% 64.5%	
Phanerochaete chrysosporium	Cd Ni	96.2% 89.4%	
Phlebia brevispora	Pb Cd Ni	97.5% 91.6% 72.7%	
Trametes pubescens	Pb Zn	99.56% 67.1%	
Phlebia acanthocystis	Pentachlorophenol	100%	(Ahmaruzzaman et al., 2024)
Pleurotus ostreatus	Sulfamethoxazole, Sulfadiazine, Sulfathiazole, Sulfapyridine and Sulfamethazine	83-91%	(Bhaskaralingam et al., 2025)
Umbelopsis isabellina	Nonylphenol, 4-tert-octylphenol and 4-cumylphenol	90%	(González-González et al., 2022)
Trametes versicolor	Malation Diuron	100% 98.7%	
Basidiomicetos	Naphthalene Pirene	70% 29%	(Ragini et al., 2024)
Pleurotus ostreatus	diClorobifenil triClorobifenil tetraClorobifenil	82% 80% 65%	(Hassan et al., 2023)
Aspergillus niger and *Aspergillus fumigatus*	Polypropylene	53.1-71.1%	(Li et al., 2023)
Zalerion maritimum	Polyethylene	56%	
Pleurotus sapidus	Paracetamol 2-mercaptobenzothiazole	90% 99% 100%	(Abushahab et al. 2024)

	Meloxicam, Furosemide Venlafaxine	84% 81%	
Trichoderma harzianum e *Trametes trogii*	Acetaminophenol Aminophenol Sulfanilamide	62-77% 30-46% 27-70%	(Gorin et al., 2024)
Schizophyllum commune immobilized	Solar Brilliant Red 80	100%	(Khan et al., 2022)

5.3 Algae

More recently, studies have evaluated the effectiveness of algae in removing PPCPs, including antibiotics, analgesics, endocrine disruptors, and microbial agents or disinfectants. They highlight that macroalgae, belonging to the classes *Chlorophyta, Xanthophyta, and Rhodophyta,* act as pollutant sinks (Ravikumar et al., 2024).

In a study by Bhaskaralingam et al. (2025), microalgae such as *Chlorella pyrenoidosa, Chlorella vulgaris,* and *Scenedesmus obliquus* removed between 70% and 90% of pharmaceuticals such as ibuprofen, diclofenac, and estrogen hormones in high-rate ponds or combined culture systems, where, in addition to biodegradation, bioadsorption and bioaccumulation occur. In hybrid systems, the association with bacteria and fungi enhanced the results through synergistic processes, such as biofilm formation. Furthermore, photosynthetic microorganisms, such as *Chlorella vulgaris* and *Spirulina platensis*, removed ciprofloxacin and tetracycline at rates exceeding 75% and up to 99%, respectively (Singh et al., 2024).

Furthermore, experimentally, Couto et al. (2022) showed that microalgae species of *Chlorella vulgaris, Scenedesmus quadricauda*, and *Selenastrum capricornutum* achieved removal rates of 43%, 89%, and 63%, respectively, for 17α-ethinylestradiol, a synthetic estrogen widely used in hormonal medications.

They also showed potential for valorizing the biomass produced, which could be redirected to the production of bioenergy, biofertilizers, and bioplastics. Pharmaceuticals such as ibuprofen can be removed with 100% efficiency by *Chlorella sorokiniana,* while naproxen can be removed up to 97% by microalgae of the genus *Cymbella sp.* (Singh et al., 2024).

Regarding antibiotic removal, *Chlorella spp.* demonstrated the ability to eliminate up to 100% of tetracyclines, while *Chromochloris zofingiensis* removed 97% of levofloxacin, and *Nannochloris sp.* was able to degrade approximately 100% of ciprofloxacin and triclosan (González-González et al., 2022).

In the study by Ragini et al. (2024), microalgae demonstrated significant removal of PAHs, with *Kirchneriella sp.* capable of degrading up to 80% of benzo[a]pyrene. In the surface layer of estuarine microbial mats studied by Morales-Pontet et al. (2025), diatoms such as *Nitzschia sp.* demonstrated high efficiency in Cr(VI) removal, achieving a removal rate of 87-99%. This efficiency was attributed to photosynthetic activity and the release of extracellular substances, which favored both the adsorption and reduction of chromium to its less toxic form, Cr(III).

In the study by Ahmaruzzaman et al. (2024), *Scenedesmus obliquus* removed approximately 9% of phenol and up to 90% of pentachlorophenol in five days, while *Chlorella pyrenoidosa* achieved 97% phenol degradation in just four days, and the macroalgae *Ulva lactuca* achieved up to 90% removal of this compound in contaminated effluents.

The microalgae *Cyanothece sp*. was able to act as a natural bioflocculant, producing extracellular polymeric substances (EPS) that promote the aggregation of micro- and nanoplastics, with greater efficiency on fractions <300 μm, at concentrations of 1–10 mg/L, demonstrating potential for the removal of plastic particles in aquatic systems (Ahmed et al., 2024).

The most impressive results reported by Das et al. (2023), Li et al. (2023), and Abu-Tahon et al. (2025) were obtained with *Scenedesmus abundans*, which demonstrated high efficiency in the removal of microplastics, achieving 98% removal of polymethyl methacrylate (PMMA), 87% of polylactic acid (PLA), and 84% of polystyrene (PS) in a period of just six days.

Table 3-Literature data on algae used in the bioremediation of emerging pollutants.

Biological Agent	Emerging Pollutant	Removal Efficiency	Literature Reference
Chlorella pyrenoidosa, *Chlorella vulgaris* and *Scenedesmus obliquus*	Ibuprofen Diclofenac	70-90%	(Bhaskaralingam et al., 2025)
Chlorella vulgaris and *Spirulina platenses*	Ciprofloxacin Tetracycline	75-99%,	(Singh et al., 2024).
Chlorella sorokiniana,	Ibuprofen	100%	
Cymbella sp.	Naproxen	97%	
Chlorella vulgaris, *Scenedesmus quadricauda* and *Selenastrum capricornutum*	17α-ethinylestradiol	43% 89% 63%	(Couto et al., 2022)

Chlorella spp.	Tetracyclin	100%	(González-González et al., 2022)
Chromochloris zofingiensis	Levofloxacin	97%	
Nannochloris sp.	Ciproflozacin Triclosan	100%	
Kirchneriella sp.	Benzo[a]pyrene	80%	(Ragini et al., 2024)
Nitzschia sp.	Cr (VI)	87-99%	(Morales-Pontet et al., 2025)
Scenedesmus obliquus	Pentachlorophenol	90%	(Ahmaruzzaman et al., 2024)
Chlorella pyrenoidosa	Phenol	97%	
Ulva lactuca	Phenol	90%	
Scenedesmus abundans	Polymethylethacrylate Lactic polyacid Polystyrene	98% 87% 84%	(Das et al., 2023), (Li et al., 2023), (Abu-Tahon et al.,2025)
Prototheca zopfii	n-alkanes	100%	(Mehrotra et al., 2021)

5.4 Mixed Microbial Consortia

The use of mixed microbial cultures increases the efficiency of treatment processes, since different species can degrade distinct compounds or act in complementary metabolic chains (Sathya et al., 2023).

The study by Salinas et al. (2024) investigated the effectiveness of microbial consortia composed of bacteria and fungi in degrading different types of plastics, using qualitative enzymatic assays focused on esterase and ligninase activities associated with biodegradation.

The results demonstrated that the consortium formed by *Bacillus subtilis*, *Fusarium oxysporum*, and *Alternaria alternata* showed the most pronounced performance, degrading 17.65% of recycled LDPE and 15.27% of virgin LLDPE, and promoting approximately 6% degradation in recycled PET. In comparison, the consortium composed of *Bacillus subtilis* and *Pseudomonas alloputida* achieved 11.11% reduction in recycled LDPE and 16.94% in virgin LLDPE (Salinas et al., 2024).

Consortia of bacteria and microalgae enhance the removal of PPCPs through co-metabolism, biofilm formation, and metabolic synergy, primarily through the exchange of dissolved oxygen, showing greater efficiency in the degradation of β-estradiol compared to pure cultures, achieving removal of over 90% for nine pharmaceuticals in high-rate lagoons (Ravikumar et al., 2024).

Microalgae-bacteria consortia (MABC), composed of photosynthetic microalgae and heterotrophic bacteria from activated sludge, demonstrated high efficiency in removing emerging contaminants, achieving 97.6% removal of linear alkylbenzene sulfonate (LAS). Their main advantage is passive photosynthetic aeration, which eliminates the need for energy in conventional aerobic systems (Thayyil et al., 2024).

Integrated algae and bacteria systems, when applied to algal-bacterial granular sludge (ABGS) systems, achieved over 96% removal of polystyrene (PS) (Li et al., 2023).

Table 4-Literature data on mixed microbial consortia used in the bioremediation of emerging pollutants.

Mixed Consortia	**Emerging Pollutant**	**Removal Efficiency**	**Literature Reference**
Bacillus subtilis, *Fusarium oxysporum* and *Alternaria alternata*,	Recycled LDPE Virgin LLDPE Recycled PET	17.65% 15.27% 6%	(Salinas et al., 2024)
Pseudomonas, Bacillus, Acinetobacter, Sphingomonas, Rhodococcus, Alcaligenes, Burkholderia, Klebsiella, Stenotrophomonas, Aspergillus, and *Penicillium.*	Hydrocarbons Phenol Dyes Cr, Cd, Pb, and Hg	90% 80–95 70–98% 60–85%	(Wani et al., 2022)
Pseudomonas aeruginosa, *Bacillus subtilis*, and *Candida bombicola*	Hydrocarbons Pb	80.9% 99.6%	(Ng et al., 2022)

6 APPROACHES AND TECHNOLOGIES

6.1 Immobilization

From a technological perspective, the application of isolated enzymes, such as immobilized laccases in membrane bioreactors, has stood out for its high performance, achieving removals of over 90% of compounds such as carbamazepine and estradiol in short periods. Innovative systems, such as microbial fuel cells, have been investigated for simultaneous antibiotic removal and energy generation, although they still face operational limitations at high pollutant concentrations (Bhaskaralingam et al., 2025).

Immobilized bacteria have demonstrated high efficiency in bioremediation, achieving 92% removal of phenol, over 99% for cadmium, and 97% for copper using *Pseudomonas putida* on silica-alginate, and 75–83% removal of textile dyes using *Pseudomonas sp.* in silica, ~90% of arsenic by oxidizing bacteria in polyvinyl alcohol (PVA), and up to 100% of benzene and toluene by *Pseudomonas sp., Comamonas sp.,* and *Rhodococcus sp.* (Mehrotra et al., 2021).

In the case of immobilized algae, the main highlight was *Prototheca zopfii*, which, encapsulated in alginate and polyurethane matrices, achieved 100% removal of n-alkanes (Mehrotra et al., 2021).

In the study by Zhang et al. (2025), the bacterial immobilization strategy used polyvinyl alcohol (PVA) and sodium alginate (SA) supports associated with iron-humus complexes, allowing the fixation of the bacteria *Zoogloea sp.* This approach resulted in efficient heavy metal removal, achieving final cadmium concentrations below 0.01 mg/L, with copper and zinc reduced to 0.10–0.11 mg/L and 0.08–0.10 mg/L, respectively.

Similarly, when immobilized, white-degrading fungi, such as *Trametes versicolor* and *Phanerochaete chrysosporium*, showed even more impressive performance, achieving removals close to or exceeding 95% due to continuous secretion of laccases and peroxidases (Fu et al., 2020).

When applied to filtration systems, biochar achieved up to 93% removal of the pesticide fipronil, nearly twice the performance of conventional filters, and offered additional advantages, such as low cost, sustainability, and the absence of toxic byproducts (Bhatt et al., 2023).

Bioaugmentation, a technique that introduces native or allochthonous strains to accelerate degradation, demonstrated high efficiency, with species of the genus *Bacillus* achieving 93% removal in 5 days and the white-rot fungus *Trametes versicolor* achieving 96.5% in 9 days (Bhatt et al., 2023).

Khan et al. (2022) reported in their studies that the use of immobilized fungal enzymes showed significant efficiency in degrading contaminants, highlighting the species *Pleurotus ostreatus*, which achieved 100% removal of textile dyes through manganese peroxidase, *and Schizophyllum commune*, responsible for almost 100% discoloration of the dye Solar Brilliant Red 80.

Fu et al. (2020) highlight that immobilizing microorganisms in beads significantly increased the efficiency of bioremediation of phenolic compounds, achieving removal rates exceeding 90% in laboratory tests. Bacteria such as *Pseudomonas putida* and *Bacillus subtilis*, encapsulated in calcium alginate beads, maintained high metabolic stability and high phenol oxidation performance over multiple cycles.

High-throughput microalgae ponds, capable of promoting high removal of organic matter and nutrients, and constructed wetlands (FTW), in which plants and microorganisms act synergistically to retain nutrients and heavy metals, stand out as approaches for wastewater remediation (Sathya et al., 2023).

Among emerging technologies, autotrophic bioflocs (ABFT) stand out, a technology based on the formation of microbial aggregates that can achieve up to 97% reduction in eutrophication, in addition to significantly increasing the efficiency of removing emerging contaminants, constituting sustainable and high-potential alternatives for wastewater treatment (Sathya et al., 2023).

6.2 Membranes and Bioreactors

One of the main advances reported is the integration of membranes with algae-based biological processes, which, in addition to enabling the removal of nutrients and contaminants, allows the use of the generated biomass for various applications. Species such as *Chlorella vulgaris*, *Scenedesmus obliquus*, and *Spirulina platensis* stand out for their high efficiency in nutrient assimilation and the production of value-added biomass (Thanigaivel et al., 2025).

Zhang et al. (2025) investigated the application of an anaerobic/anaerobic/anoxic/oxic membrane bioreactor (An2AO-MBR) associated with a microbial community in wastewater treatment, achieving 98.3% removal of petroleum fractions. The microbiota consisted predominantly of halotolerant bacteria, notably the genera *Halomonas, Marinospirillum, Acinetobacter,* and *Pseudomonas,* which played a central role in hydrocarbon degradation.

6.3 Biosurfactants

Produced by bacteria such as *Pseudomonas aeruginosa* and *Bacillus subtilis,* as well as by fungi such as *Candida bombicola,* biosurfactants act in the emulsification of hydrophobic pollutants by reducing surface tension; in addition, their application can increase the degradation of hydrocarbons by up to 80.9% and the removal of heavy metals such as lead by 99.6% (Ng et al., 2022).

6.4 Identification of degrading genes

Hernández-Alomía et al. (2022) identified microorganisms capable of degrading glyphosate using the molecular PCR technique applied to genetic material released by organisms into the environment of different bodies of water, focusing on the phnJ gene, essential for breaking the carbon-phosphorus bond of glyphosate, allowing the detection of gene sequences even at low concentrations, expanding the available genetic repertoire and enabling the identification of degrading genes directly in environmental DNA, even before the isolation of microorganisms.

6.5 Genetic Engineering and Metagenomic Analysis

Dash and Osborne (2023) demonstrated that the use of biotechnologies for the bioremediation of organophosphate pesticides, including genetic engineering, gene editing (CRISPR/Cas9), and enzyme enhancement, can significantly enhance microorganisms' ability to degrade these pollutants. Furthermore, genes encoding hydrolases have been extensively studied in microorganisms such as *Pseudomonas pseudoalcaligenes, Escherichia coli, Streptomyces lividans, Yarrowia lipolytica,* and *Pichia pastoris*.

The study by Abushahab et al. (2024) demonstrated that recombinant DyP peroxidase (rPsaDyP), obtained through genetic engineering from the gene of the fungus *Pleurotus sapidus*, has high potential for thermophilic bioremediation, achieving removals of over 90% for paracetamol, 99% for 2-mercaptobenzothiazole (MBT), and 100% for meloxicam, in addition to significant reductions of 84% for furosemide and 81% for venlafaxine.

The use of metagenomics to analyze microbial consortia has become a powerful tool for identifying the genes and metabolic pathways of key microorganisms involved in contaminant degradation.

The bacterial consortia studied through metagenomic analysis by Wani et al. (2022) showed high efficiency in bioremediation, removing up to 90% of polycyclic aromatic hydrocarbons, 80–95% of phenols, 70–98% of dyes, 60–85% of metals such as Cr, Cd, Pb and Hg, and 75–90% of antibiotics, with predominant microorganisms from the genera *Pseudomonas, Bacillus, Acinetobacter, Sphingomonas, Rhodococcus, Alcaligenes, Burkholderia, Klebsiella* and *Stenotrophomonas,* in addition to the fungi Aspergillus and Penicillium, all associated with the degradation of dyes and aromatic compounds.

6.6 Fuel Cells

Fungal microbial fuel cells (FMFCs) are an innovative technology that combine bioremediation of pharmaceutical effluents with energy generation. The system proposed by Gorin et al. (2024), with *Trichoderma harzianum* at the anode and *Trametes trogii* at the cathode, promoted the mineralization of recalcitrant compounds, biofilm formation, and energy recovery, achieving removals of 62-77% of acetaminophen, 30-46% of para-aminophenol, and a rate of 27-70% for sulfanilamide.

Bacterial fuel cells (BMFCs), based on the activity of manganese-oxidizing bacteria, stand out as an innovation in bioremediation by combining the removal of heavy metals with energy generation, reaching 91.2% for Cu^{2+}, 99.9% for Co^{2+} , and 99.97% for Ni^{2+} (Liu et al., 2024).

7 FINAL CONSIDERATIONS

Bioremediation has established itself as one of the most promising and sustainable strategies for treating and recovering contaminated water, especially given the environmental challenges posed by climate change and increased flooding. Recent advances highlight the potential of diverse microbial groups, including bacteria, fungi, algae, and mixed consortia, for degrading and immobilizing emerging contaminants such as pharmaceuticals, pesticides, microplastics, and heavy metals. High removal rates, often exceeding 90%, demonstrate the effectiveness of biological processes.

In the technological context, the application of innovative techniques such as microbial immobilization, autotrophic bioflocs (ABFT), microbial fuel cells (MFCs), membrane bioreactors, and hybrid algae-bacteria systems has increased the efficiency and operational stability of treatment systems. These technologies offer advantages such as low cost, generation of non-toxic byproducts, biomass reuse, and reduced energy consumption, reinforcing the practical feasibility of large-scale bioremediation. Despite this, challenges remain regarding application in complex natural environments, the variability of climatic conditions, and the need for microorganisms to adapt to different types of contaminants and substrates.

In terms of feasibility, bioremediation proves technically applicable and economically favorable, especially in water body restoration projects and areas degraded by flooding.

For future research, we recommend further metagenomic and genetic engineering studies to identify and optimize degrading genes, the development of sustainable supports for microbial immobilization, the integration of bioelectrochemical processes for simultaneous energy generation and treatment, and the evaluation of pilot systems across different climatic and hydrological contexts. Furthermore, it is recommended that public policies be created and incentives be provided for applied research on the removal of secondary pollutants from floods, with the aim of incorporating bioremediation as an effective tool in strategies to manage and mitigate environmental impacts associated with climate change.

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