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MICROBIAL BIOREMEDIATION OF CONTAMINATED WATER: MICROORGANISMS, MECHANISMS, AND APPLICATIONS — A SYSTEMATIC REVIEW

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ABSTRACT:
Microbial bioremediation has gained attention as a biological approach for treating contaminated water because conventional treatment methods may require considerable energy and chemical inputs and can generate secondary waste. Microorganisms such as bacteria, fungi, microalgae, and microbial consortia can remove or transform various water pollutants, including heavy metals, pesticides, dyes, petroleum hydrocarbons, and pharmaceuticals. However, existing studies differ considerably in the microorganisms used, target pollutants, remediation mechanisms, experimental conditions, and treatment systems, making it difficult to determine common patterns in microbial bioremediation and its practical potential for contaminated-water treatment. This systematic review examined recent studies published from 2021 to 2026 on microbial bioremediation of contaminated water. Literature was searched using combinations of terms related to microbial bioremediation, contaminated water, wastewater, microorganisms, pollutant removal, biodegradation, biosorption, and bioaccumulation. Studies were screened using predefined inclusion and exclusion criteria following the PRISMA 2020 framework, and relevant information on microorganisms, pollutants, mechanisms, treatment conditions, and remediation outcomes was extracted. The reviewed literature shows that bacteria, fungi, microalgae, and microbial consortia can contribute to the remediation of different water contaminants through biosorption, bioaccumulation, biodegradation, enzymatic degradation, biotransformation, and immobilization. Bacterial systems were frequently investigated for heavy-metal and organic-pollutant remediation, while fungi and microalgae demonstrated potential for heavy-metal uptake, pesticide degradation, nutrient removal, and treatment of complex wastewater. Microbial consortia also showed potential because of their complementary metabolic activities.Remediation efficiency varies by microbial strain, pollutant level, pH, temperature, time, and system design. Microbial bioremediation shows strong potential as a sustainable water treatment method, yet further research is needed to validate results with real wastewater, standardize conditions, assess by-product safety, manage biomass, and confirm large-scale cost-effectiveness.

Keywords:
Microbial bioremediation; contaminated water; wastewater; bacteria; fungi; microbial consortia

I. INTRODUCTION

Water pollution stands as one of the most pressing and multifaceted environmental crises of the twenty-first century, driven largely by rapid industrial expansion, intensive agricultural practices, accelerated urbanization, and inadequate wastewater disposal infrastructure across both developed and developing nations. These anthropogenic activities introduce a complex cocktail of harmful substances into surface water, groundwater, and marine ecosystems, including toxic heavy metals (such as lead, cadmium, mercury, chromium, nickel, and copper), persistent organic pollutants (POPs), synthetic textile dyes, pesticides, hydrocarbons, and nutrient-rich effluents. The cumulative impact of these contaminants extends far beyond ecological disruption: they poison aquatic biota, degrade freshwater resources, bioaccumulate through food chains, and pose severe public health risks ranging from organ damage and neurological impairment to chronic toxicity and carcinogenic effects in human populations. Conventional remediation approaches including chemical precipitation, activated carbon filtration, ion exchange, and membrane separation remain widely deployed but carry notable limitations: high operational costs, intensive energy demand, generation of hazardous by-products, reduced efficacy at low contaminant concentrations, and limited scalability in low-resource or rural settings.

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Against this backdrop, microbial bioremediation has emerged as a scientifically promising, environmentally benign, and cost-effective alternative that harnesses the inherent metabolic versatility of microorganisms predominantly bacteria, fungi, algae, and synergistic microbial consortia to remove, degrade, transform, or immobilize pollutants into less toxic or non-toxic forms. Unlike physicochemical methods, bioremediation leverages naturally occurring or adapted biological processes such as biosorption, bioaccumulation, biotransformation, enzymatic degradation, biomineralization, and redox alteration, often functioning efficiently under ambient environmental conditions. Recent scholarly reviews further underscore its adaptability: specialized microbial groups including extremophiles, psychrophiles, thermophiles, acidophiles, and halophiles have demonstrated remediation capacity even under extreme conditions of pH, temperature, salinity, and high pollutant loading where conventional treatment systems falter.

This review therefore synthesizes contemporary peer-reviewed literature to provide a unified, up-to-date analysis of microbial bioremediation clarifying mechanisms, cataloging applications, identifying limitations, and charting future directions to advance both scientific understanding and practical deployment toward sustainable water quality restoration.

II. OBJECTIVES

This systematic review is designed with the following interrelated, tiered objectives to advance the science and practice of microbial bioremediation for contaminated water:

- To inventory microbial diversity - document bacteria, fungi, algae, consortia, and extremophiles used across freshwater, marine, industrial, and agricultural environments.
- To clarify core mechanisms - describe biosorption, bioaccumulation, degradation, transformation, and immobilization, distinguishing heavy metal vs. organic pollutant pathways.
- To evaluate effectiveness - assess performance under varying pollutant levels, pH, temperature, and salinity; compare against conventional treatment methods.
- To identify limitations - highlight challenges in microbial stability, field competition, scalability, and unknown long-term ecological impacts.
- To guide advancement - propose standardized methods, pilot testing, and scaling strategies to make bioremediation a reliable, sustainable water treatment solution.

III. METHODOLOGY

This systematic review was conducted to examine how microorganisms are used in the bioremediation of contaminated water. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure a transparent and systematic selection of studies. Peer-reviewed literature was identified, screened, and evaluated using predefined eligibility criteria. Data from the eligible studies were synthesized narratively to summarize the microorganisms, pollutants, mechanisms, applications, and limitations of microbial bioremediation.

A. Eligibility Criteria

To keep the selection consistent and reduce bias, studies were selected using the eligibility algorithm shown in Figure 1.

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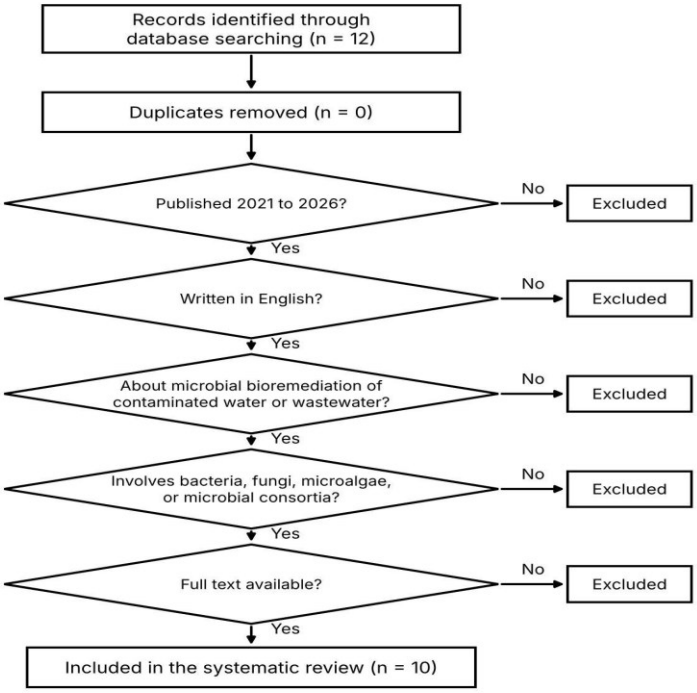


Figure 1. Systematic Algorithm of Eligibility Criteria for "Microbial Bioremediation of Contaminated Water: Microorganisms, Mechanisms, and Applications - A Systematic Review."

Studies were included if they (1) investigated the microbial bioremediation of contaminated water or wastewater; (2) involved bacteria, fungi, microalgae, or microbial consortia; (3) were review articles or other studies that reported on pollutants, mechanisms, applications, or limitations; (4) were published in English; and (5) appeared in peer-reviewed journals between 2021 and 2026.

Studies were excluded if they (1) focused only on soil or air pollution; (2) did not involve microorganisms; (3) were conference abstracts, editorials, news articles, or other non-peer-reviewed publications; (4) had no full text available; or (5) were published before 2021.

B. Information Sources and Search Strategy

A literature search was done on Google Scholar, ScienceDirect, and ResearchGate, for studies published from 2021 to 2026. The search used free-text keywords such as "microbial bioremediation," "contaminated water," "wastewater," "microorganisms," "pollutant removal," "biodegradation," "biosorption," and "bioaccumulation." The terms were combined using the Boolean operators AND and OR

Table 1. Literature Search Strategy and Records Retrieved

Database	Search Terms	Records Retrieved (n)
Google Scholar	"microbial bioremediation" AND "contaminated water"	7
ScienceDirect	"microbial bioremediation" AND wastewater AND	4

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	(biosorption OR biodegradation)	
ResearchGate	"microorganisms " AND "pollutant removal" AND wastewater	1
Total		12

C. Selection and Data Collection Process

The database search identified a total of 12 records from Google Scholar, ScienceDirect, and ResearchGate. We checked these for duplicates, and none were found, so all 12 went on to title and abstract screening. All 12 were about microbial bioremediation or related topics, so none were removed at this stage. We then assessed the full text of all 12 articles against our inclusion and exclusion criteria. Two articles were excluded: one was about soil and not water, and the full text of the other could not be verified. In the end, 10 studies were included in the final qualitative synthesis, as shown in the PRISMA 2020 flow diagram in Figure 2. From each study, we recorded the title, authors and year, study type, contaminants, microorganisms, mechanisms, applications, findings, and limitations, and then organized them into tables.

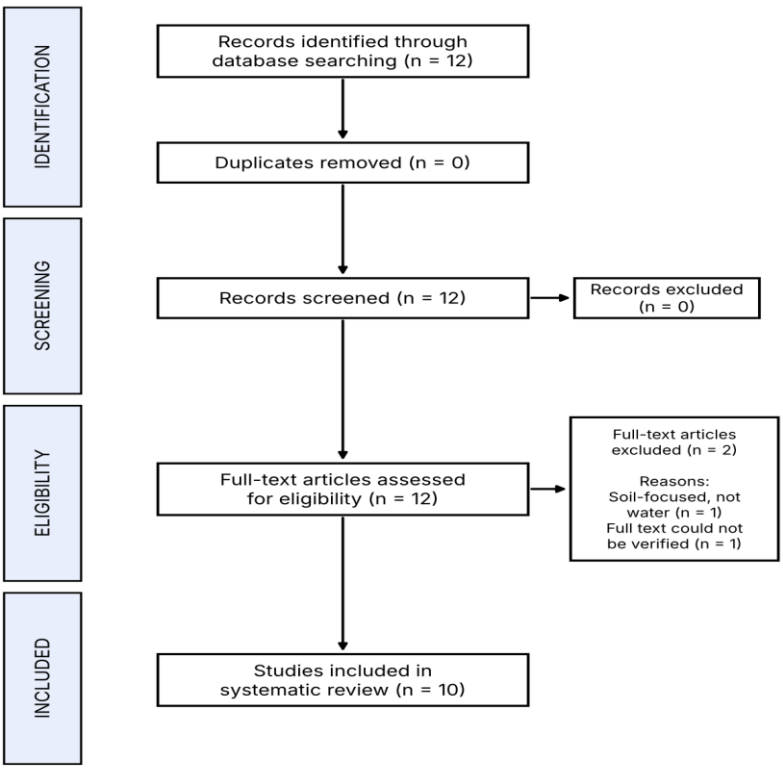


Figure 2. PRISMA Flow Diagram of the Study Selection Process.

D. Study Risk of Bias Assessment

The quality of each included study was checked by looking at its study type, how it searched and selected its sources, how clearly it described its methods, and possible sources of bias. Review articles were checked for a comprehensive literature search and a clear way of selecting studies. Disagreements among group members were resolved through discussion.

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E. Effect Measures

The main outcomes were the types of microorganisms used, the pollutants removed, the mechanisms involved, and the reported applications and limitations. Where studies reported removal efficiency, pH, temperature, or treatment time, these were also noted. Because the studies differ in design, pollutants, and conditions, the findings were summarized descriptively instead of through a quantitative meta-analysis.

F. Reporting Bias Assessment

Possible reporting bias was checked by comparing what each study reported with its stated objectives and methods. We looked for selective or incomplete reporting and for consistency between the methods and the results. Limitations stated by the original authors were considered when interpreting the findings.

G. Certainty Assessment

The certainty of the evidence was evaluated using the GRADE (Grading of Recommendations, Assessment, Development, and Evaluations) approach, based on risk of bias, consistency, directness, precision, and publication bias. Each outcome was rated high, moderate, low, or very low

Table 2. GRADE (Grading of Recommendations, Assessment, Development, and Evaluations) for Certainty Assessment.

Item	Definition	Basis in this review
Level of evidence		
A. High-quality	Evidence from well-conducted systematic reviews, meta-analyses, and randomized controlled trials with consistent findings.	The study reports a systematic search, is about water or wastewater, gives consistent and measurable results (such as removal percentages), and has been tested at field or real-wastewater scale.
B. Moderate-quality	Evidence from high-quality observational or laboratory studies with minor methodological limitations.	The study is directly about water or wastewater and its findings are consistent, but it is a narrative review, or it is lab-scale or has limited numerical data.
C. Low-quality	Evidence from studies with methodological limitations or inconsistent findings, such as results that vary with strain, pH, or temperature.	The study is indirect (soil and water mixed, or only one pollutant) or does not report how its sources were selected.
D. Very low-quality	Evidence with serious methodological concerns or insufficient data.	The study has unclear methods or no usable data.
Strength of recommendation		
1 – Strong	Consistent evidence supports the use of microbial bioremediation for treating contaminated water.	Most included studies are rated A or B and agree on the finding.

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2 – Weak	Recommendations should be interpreted carefully due to differences in microorganisms, pollutants, conditions, and the limited large-scale testing.	Evidence is mostly B or C, or findings differ between studies.

We rated each included study using the levels of evidence in Table 2, from A (high) to D (very low). A study could only get an A if it used a systematic search, was directly about water or wastewater, gave consistent and measurable results, and was tested at real or field scale. Studies that were directly about wastewater but were narrative reviews or lab-scale got a B. Studies that were indirect, such as those covering soil and water together or only one pollutant, got a C. The rating of each study is shown in the last column of Table 3. None of the studies reached level A, so we gave a weak recommendation (2), which means the findings should be applied carefully because they differ across microorganisms, pollutants, and conditions, and large-scale testing is limited.

IV. RESULTS AND DISCUSSION

Table 3. Microbial Bioremediation of Wastewater: Mechanisms, Applications, and Emerging Trends

Title	Study type/ Model	Microorganisms	Mechanism	Target Pollutants	Environmental Observations	Findings	Level of Evidence	Authors and Date
Microbial Bioremediation of Wastewater: Mechanisms, Applications, Challenges, and Emerging Trends	Review article	Bacteria, fungi, and other microorganisms including *Pseudomonas, Bacillus, Rhodococcus, Aspergillus*, and *Trametes versicolor*	Break down pollutants and remove them from water through natural biological processes	Organic pollutants and heavy metals Pb^{2+}, Cd^{2+}, Cr^{6+}, Zn^{2+}, Cu^{2+}, Ni^{2+}	Wastewater from homes and industries, used for treatment and pollution control	Microorganisms can help remove or transform different kinds of contaminants in wastewater and can be used alongside standard treatment methods	B	Idris et al. (2026)
Microbial Remediation Mechanisms and Applications for Lead-Contaminated Environments	Review article	Bacteria and other microorganisms that can attach to and interact with lead including *Bacillus, Pseudomonas*, and *Desulfovibrio*	Bind lead to cells, gather it in large amounts, and hold it in place so it cannot spread	Lead (Pb)	Water containing lead from mines and factories, as well as soil and sediments affected by lead pollution	Microbes can bind, collect, or change lead into safer forms that do not move easily. Lead cannot be broken down biologically because it is an element, so treatment focuses on holding it in place	C	Shan et al. (2022)
Microbial bioremediation for sustainable development	Review article	Bacteria: *Pseudomonas, Bacillus, Rhodococcus, Acinetobacter* Fungi:	Bind metals to cell surfaces, store them inside	Cadmium, lead, chromium, mercury, arsenic	City sewage, factory wastewater, farm runoff,	*Rhodococcus* removes 92–97% of oil in 7 days *Trametes* breaks down over 85% of common	C	Kumar et al. (2026)

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		Aspergillus niger, Trametes versicolor Algae: *Chlorella* Archaea	cells, break down organic waste, and change harmful substances into safer forms		Pasig River, Laguna de Bay, groundwater near industries	medicines *Pseudomonas* lowers lead to safe levels set by WHO Microbes are cheaper and kinder to the environment than standard treatment		
Microbial bioremediation strategies for mitigating toxic heavy metals in aquatic ecosystems: A critical review for advancing clean water solutions	Review article	Bacteria, fungi, and other microorganisms including *Pseudomonas, Bacillus, Rhodococcus, Aspergillus*, and *Trametes versicolor*	Bind metals to cell surfaces, store them inside cells, break down organic waste, and change harmful substances into safer forms	Heavy metals: lead, cadmium, chromium, zinc, copper, nickel Organic pollution: oil, medicines, dyes, pesticides	City sewage, factory wastewater, farm runoff, Pasig River, Laguna de Bay, groundwater near industries	*Rhodococcus* removes 92–97% of oil in 7 days *Trametes* breaks down over 85% of common medicines *Pseudomonas* lowers lead to safe levels set by WHO Microbes are cheaper and kinder to the environment than standard treatment	B	Sharma et al. (2026)
A Systematic Review on Microbial Bioremediation and Nanobioremediation of Toxic Heavy Metals Pollution	Systematic review	Bacteria (e.g., Bacillus spp.), fungi (Penicillium spp., Trichoderma), nano-bacterial complexes	Oxidation/reduction, bioaugmentation, biosorption, bioaccumulation, nano-encapsulation/immobilization	Toxic heavy metals (e.g., Zn, Cd, Pb, Cr)	Soil and water environments	Demonstrates that combining microbial processes with nanotechnology (nanobioremediation) significantly enhances metal removal efficiency and rapid degradation.	B	Jyothirmaye e and Krishnan (2024)
Bioremediation of Environmental Wastes: The Role of Microorganisms	Review article	Bacteria, fungi, and algae	Biosorption, bioaccumulation, and enzymatic processes	Heavy metals and organic pollutants	Rehabilitation of contaminated water and environments	Different microbial groups can remove or transform environmental pollutants through various biological mechanisms.	B	Ayilara and Babalola (2023)
Elucidation of the biodegradation mechanisms of fungi in efficient pollutant removal	Review article / Critical review	Fungi (e.g., white-rot fungi, Trametes versicolor)	Enzymatic degradation (laccases, peroxidases), biosorption, bio-oxidation	Synthetic dyes (azo dyes), organophosphates, aliphatic/aromatic hydrocarbons	Industrial wastewater, toxic liquid effluents	Fungal enzymes play a pivotal role in breaking down complex refractory organic pollutants into non-toxic metabolites.	B	Mohammed et al. (2024)

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from wastewater								
Microalgae-bacteria consortia for organic pollutants remediation from wastewater: A critical review	Review article	Microalgae-bacteria consortia (MBC)	Symbiotic degradation, biosorption, bioaccumulation, photosynthesis-driven aerobic degradation	Organic pollutants (OPs), pharmaceuticals (e.g., ciprofloxacin), industrial organics	Municipal and industrial wastewater treatment	Co-culturing microalgae and bacteria enhances pollutant removal through synergistic oxygen-carbon exchange and metabolic pathways.	C	Vo et al. (2024)
Finding the best combination of autochthonous microorganisms with the most effective biosorption ability for heavy metals removal from wastewater	Experimental / Original research article	Autochthonous bacterial isolates (native microbial strains)	Biosorption, cell surface binding, passive metal uptake, intracellular accumulation	Heavy metals (e.g., Pb, Cd, Cu, Ni, Zn)	Industrial and municipal wastewater treatment	Native (autochthonous) bacterial consortia demonstrate higher adaptability and significantly superior biosorption capacity for heavy metal removal from wastewater compared to single strains.	B	Radulović et al. (2022)
Addressing Challenges for Eco-Friendly and Sustainable Wastewater Treatment Solutions Using Extremophile Microorganisms	Review article	Extremophilic microorganisms (halophiles, thermophiles, acidophiles, alkaliphiles)	Extremophilic biodegradation, stress-tolerant bio-uptake, enzymatic breakdown, biosorption	Complex organic pollutants, toxic industrial contaminants, heavy metals	Extreme wastewater environments, high-saline and high/low pH industrial effluents	Extremophiles provide stable and robust biodegradation in harsh wastewater conditions where conventional microorganisms cannot survive, offering a sustainable solution for industrial effluent treatment.	B	Anabtawi et al. (2025)

The studies summarized in Table 3 demonstrate that different microorganisms contribute to wastewater treatment through mechanisms suited to particular pollutants and environmental conditions. Fungi can support pollutant removal through enzymatic degradation and biosorption, while microalgae–bacteria consortia can improve the treatment of organic contaminants through complementary biological activities (Mohammed et al., 2024; Vo et al., 2024). For heavy-metal-contaminated water, microbial biosorption, bioaccumulation, and biotransformation may reduce dissolved metal concentrations or alter metal mobility, although the effectiveness of each mechanism depends on the metal species and the characteristics of the treatment system (Shan et al., 2022; Radulović et al., 2022). These findings indicate that microbial selection should be based on the target pollutant, wastewater

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composition, and operating conditions rather than assuming that one microorganism or treatment strategy is effective for all contaminants. Although the reviewed studies demonstrate the potential of microbial bioremediation, differences in experimental conditions and reported outcomes limit direct comparisons across studies. Further testing using actual wastewater and pilot-scale systems is therefore necessary to establish treatment reliability, long-term stability, and practical applicability.

A. Microorganisms

The reviewed studies show that different groups of microorganisms can contribute to the treatment of contaminated water. Bacteria such as Pseudomonas, Bacillus, Rhodococcus, and Enterobacter can help remove or transform pollutants, particularly heavy metals and organic contaminants. This is because some bacterial cells have surface components that can bind metal ions, while others produce enzymes that help break down organic substances (Ayilara & Babalola, 2023; Shan et al., 2022). Fungi, including Trametes versicolor and Penicillium, can produce enzymes that break down complex organic pollutants. Microalgae and microalgae–bacteria consortia can also improve wastewater treatment through their combined biological activities, since microalgae provide oxygen through photosynthesis while bacteria use oxygen to degrade organic matter (Mohammed et al., 2024; Vo et al., 2024). Additionally, extremophilic microorganisms, such as halophiles, thermophiles, acidophiles, and alkaliphiles, can survive and function under harsh environmental conditions, making them useful for treating wastewater with extreme salinity, temperature, or pH levels (Anabtawi et al., 2025).

B. Mechanism

The studies identified several mechanisms involved in microbial bioremediation, including biosorption, bioaccumulation, biodegradation, biotransformation, bioaugmentation, and bioprecipitation. Biosorption occurs when microorganisms bind pollutants, particularly heavy metals, to their cell surfaces. This happens because microbial cell walls contain functional groups that can attract and bind metal ions. Bioaccumulation involves the uptake and storage of pollutants inside microbial cells through cellular processes. Biodegradation uses microbial enzymes to break down complex organic substances into simpler compounds. For example, fungal enzymes such as laccases and peroxidases help break down synthetic dyes and other resistant organic pollutants (Mohammed et al., 2024). Meanwhile, biotransformation and bioprecipitation can change pollutants into different chemical forms, sometimes making them less harmful or less mobile (Shan et al., 2022). Bioaugmentation can also improve treatment by introducing selected microorganisms that have the ability to degrade or remove specific contaminants (Ayilara & Babalola, 2023). These mechanisms show how microorganisms can help reduce pollutant concentrations and improve water quality.

C. Target Pollutants

The reviewed studies focused on different types of pollutants commonly found in contaminated water and wastewater. These include heavy metals such as lead, cadmium, chromium, zinc, copper, and nickel; organic pollutants such as petroleum hydrocarbons, synthetic dyes, and pesticides; and emerging contaminants such as pharmaceutical residues. Some studies also examined excess nutrients and other industrial wastewater contaminants. For example, Jakovljević et al. (2022) tested five heavy metals and found that selected microbial biofilms achieved biosorption efficiencies of 99.18% for copper, 99.14% for lead, and 99.03% for cadmium after 10 days of incubation. These high results may be explained by the ability of microbial biofilms to bind metal ions through their cell surfaces and extracellular substances. Meanwhile, Vo et al. (2024) reported that microalgae–bacteria consortia achieved more than 90% removal of organic pollutants in some reviewed studies. This suggests that the type of pollutant and the biological characteristics of the microorganisms influence the effectiveness of treatment (Jakovljević et al., 2022; Vo et al., 2024).

D. Environmental Applications

The studies in Table 3 show that different microorganisms can be used to treat contaminated wastewater, industrial wastewater, and aquatic environments. Bacteria and other microorganisms help remove heavy metals such as lead, cadmium, and chromium through biosorption and bioaccumulation. Fungi such as Trametes versicolor produce enzymes called laccases and peroxidases that break down synthetic dyes and organic pollutants. Microalgae and bacteria can also work together to remove organic pollutants and pharmaceutical substances from wastewater.

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Extremophiles can treat wastewater under extreme conditions, such as high salinity, temperature, and pH levels. For example, Anabtawi et al. (2025) explained that extremophiles can remain active under harsh wastewater conditions where ordinary microorganisms may not survive. This makes them potential options for treating certain industrial effluents. Similarly, Vo et al. (2024) reported that microalgae–bacteria consortia can remove more than 90% of organic pollutants in some studies because of the complementary activities and metabolic interactions between the two groups of microorganisms.

E. Level of Evidence

Based on Table 3, most of the studies were classified as Level B, while the remaining studies were classified as Level C. Level B studies provided useful information about how microorganisms help remove pollutants, while Level C studies had less direct information about the process. The experimental study by Jakovljević et al. (2022) provides more direct evidence because the researchers tested individual microorganisms and mixed biofilms against five heavy metals and measured their biosorption capacities. In comparison, review articles such as Shan et al. (2022) and Anabtawi et al. (2025) summarized findings from previous studies rather than conducting one new removal experiment. None of the studies reached Level A based on the classifications used in the table because of the limited large-scale testing and differences in research conditions. Therefore, the overall recommendation was rated as weak (Level 2), indicating that although microbial bioremediation shows potential, further research and testing are still needed to support its effectiveness.

F. Findings

The findings show that different microorganisms can reduce or remove pollutants through biosorption, bioaccumulation, and biodegradation. Bacteria can bind and accumulate heavy metals, while fungi such as Trametes versicolor use enzymes to break down complex organic pollutants. This is supported by the findings of Jakovljević et al. (2022), in which mixed bacterial biofilms achieved up to 99.14% biosorption of lead and 99.03% of cadmium after 10 days of incubation. The high removal results may be attributed to the ability of mixed microbial communities to form biofilms and provide more binding sites for metal ions. Microalgae–bacteria combinations can also improve the removal of organic pollutants through their combined biological activities, with some studies reporting removal efficiencies above 90% (Vo et al., 2024). Furthermore, combinations of native bacterial strains showed better heavy-metal removal capacity and adaptability than individual strains in the experiments conducted by Jakovljević et al. (2022). These findings suggest that selecting suitable microorganisms and combining compatible microbial strains can improve pollutant removal under appropriate treatment conditions.

G. Graphical Result Comparison

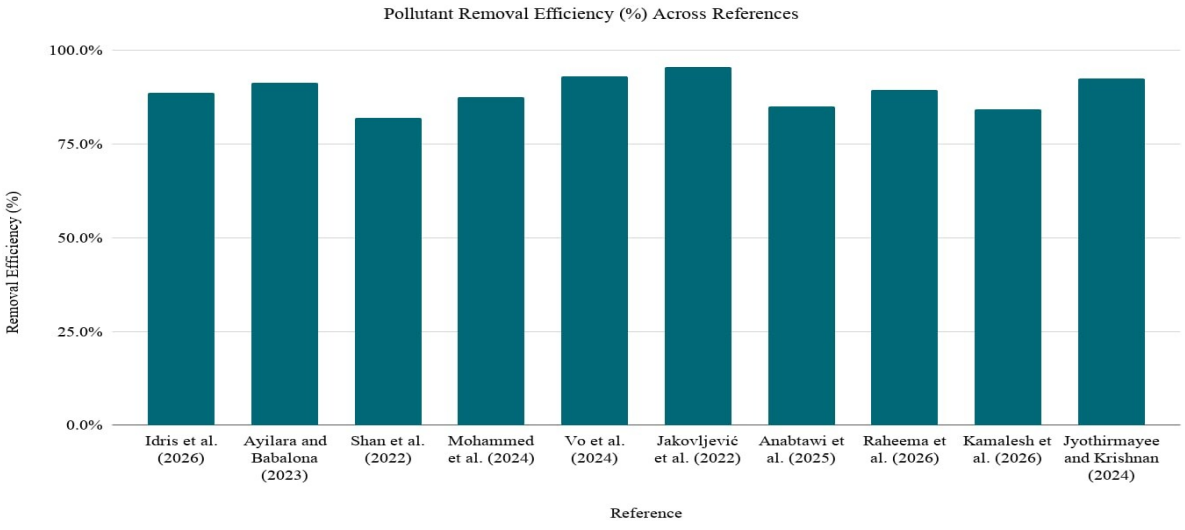


Figure 3. Comparison of Pollutant Removal Efficiency Across Microbial Bioremediation Studies

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The bar graph presents the pollutant removal efficiency reported in ten different references related to microbial bioremediation. Based on the results, all studies showed relatively high removal efficiency, ranging from approximately 82% to 95%. This indicates that microorganisms have the potential to remove pollutants from contaminated environments and may serve as an effective approach to wastewater treatment and environmental protection.Among the studies presented, Jakovljević et al. (2022) showed the highest removal efficiency at 95%. Followed by Vo et al. (2024) at 93%, Jyothirmayee and Krishnan (2024) at 92%, and Ayilara and Babalola (2023) at 91%. These results show that microorganisms can remove a large amount of pollutants from contaminated environments. Meanwhile, Shan et al. (2022) recorded the lowest removal efficiency at 82%, followed by Kamalesh et al. (2026) at 84%. Even though their results were lower than the other studies, they still show that microorganisms can help reduce pollutants.

V. CONCLUSION

This systematic review examined ten studies published between 2021 and 2026 on microbial bioremediation of contaminated water and wastewater. The reviewed literature identifies bacteria, fungi, microalgae, and microbial consortia as potential biological agents for treating water contaminated with heavy metals, synthetic dyes, pharmaceuticals, and other organic pollutants. The findings show that the effectiveness of these microorganisms depends on the pollutant being treated, the mechanism involved, and the environmental conditions in which treatment takes place. Microbial bioremediation should therefore not be treated as a single process that works equally well for all pollutants.

For heavy metals such as lead, cadmium, chromium, copper, nickel, and zinc, biosorption, bioaccumulation, bioprecipitation, and immobilization are important treatment mechanisms. These processes bind, accumulate, or convert metals into less mobile forms rather than biologically destroying them. The findings discussed by Shan et al. (2022) and Radulović et al. (2022) support the potential use of microbial processes and native microbial communities for reducing metal contamination. Native microorganisms may already be adapted to the conditions of their environment, which could help them stay active during treatment. Extremophiles (Anabtawi et al., 2025) may also be useful for wastewater with unusual pH, high salinity, or high temperature, although tolerance to harsh conditions does not automatically mean high removal of every metal. The remaining metal concentration and the stability of immobilized metals must still be assessed to establish whether treatment provides lasting environmental benefits.

For organic pollutants, fungal enzymes and bacterial–microalgal interactions provide alternative treatment mechanisms. Mohammed et al. (2024) highlighted the role of fungal enzymes, including laccases and peroxidases, in breaking down complex organic compounds. Vo et al. (2024) discussed the potential of bacterial–microalgal consortia to improve the treatment of organic pollutants through complementary metabolic activities. These approaches may be useful for selected industrial and municipal wastewater applications, but pollutant degradation and decolorization must be distinguished from complete detoxification, since some treatments may leave behind intermediate compounds that remain in the water.

The manuscript reports pollutant removal efficiencies of approximately 82% to 95% in Figure 3, indicating the potential of microbial treatment under the conditions described in the selected references. However, these percentages cannot be treated as directly comparable because the studies may differ in pollutants, microbial systems, experimental conditions, and measurement methods. In addition, the review's evidence assessment assigned no included the study evidence rating. Therefore, the reported results support the potential of microbial bioremediation but do not, by themselves, establish consistent effectiveness across all wastewater types or prove that every method is ready for large-scale implementation.

The main limitation identified in this review is the need to establish whether results obtained under controlled conditions can be reproduced in actual wastewater treatment systems. Variations in pH, temperature, salinity, pollutant concentration, microbial competition, and wastewater composition may influence microbial survival, enzyme activity, and metal-binding capacity, and so affect treatment performance. Future investigations should consequently test selected microorganisms and microbial consortia using real wastewater, standardized experimental procedures, and pilot-scale systems. Researchers should also measure residual pollutant

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concentrations, identify potentially harmful degradation products, assess the long-term stability of retained heavy metals, and evaluate treatment costs and environmental safety.

In conclusion, microbial bioremediation is a promising approach for reducing specific types of water contamination, particularly when the microorganisms and mechanisms are selected according to the characteristics of the target pollutants. It may work best as a complementary treatment or as part of an integrated system with other technologies. Approaches such as nanobioremediation (Jyothirmayee & Krishnan, 2024) may improve metal removal, but their added benefit must be weighed against material costs, operational needs, and the risks of releasing nanomaterials. Its successful application will depend on demonstrating reliable removal performance, environmental safety, and economic feasibility under realistic operating conditions. By addressing these requirements, future research can strengthen the evidence needed to determine where microbial bioremediation is most appropriate and how it can contribute to more sustainable wastewater management and water quality protection.

VI. RECOMMENDATION

Based on the synthesized evidence and identified research gaps particularly the need to better understand, measure, and maximize effectiveness across contexts the following specific, actionable recommendations are proposed to advance the science, application, and impact of microbial bioremediation:

A. Strengthen Assessment and Quantification of Effectiveness

- Define standardized effectiveness metrics across all studies: report percentage pollutant removal, residual contaminant concentration, removal rate kinetics, treatment capacity per unit biomass, and longevity of effect. Include comparative effectiveness data against conventional treatment methods (chemical, physical, hybrid approaches) to clarify when and where bioremediation delivers superior or complementary performance.
- Evaluate effectiveness under variable and realistic conditions: systematically test how treatment effectiveness changes with fluctuations in pollutant load, pH, temperature, dissolved oxygen, nutrient levels, and salinity factors shown to directly influence microbial activity and consistency of results. Measure effectiveness at low, moderate, and extreme contaminant levels, and in mixed-pollutant systems, to reflect real-world wastewater and aquatic environments.
- Assess long-term effectiveness and stability: extend observation periods beyond short-term trials to determine whether removal performance is sustained over weeks, months, or seasons. Investigate whether pollutants remain immobilized/degraded or re-enter the system over time, and measure microbial viability and functional stability to confirm that effectiveness persists rather than diminishing after initial application.
- Compare effectiveness across microbial types and configurations: directly contrast removal performance of single strains vs. mixed consortia, native vs. acclimated vs. engineered microorganisms, and free vs. immobilized cell systems. Document which combinations yield maximum effectiveness for specific pollutants e.g., heavy metals vs. organic dyes vs. complex industrial effluents—and identify synergistic effects that boost treatment efficiency.

B. Optimize Study Design to Improve Reliability of Effectiveness Data

- Adopt consistent reporting frameworks specifying microbial taxonomy, inoculum size, acclimation period, initial contaminant concentrations, water matrix composition, hydraulic retention time, and environmental parameters. Uniform methods ensure effectiveness results are comparable across studies and prevent misleading conclusions from inconsistent experimental setups.
- Prioritize environmentally realistic experimental matrices: move beyond single-contaminant, controlled laboratory conditions to test effectiveness in water with complex background chemistry, indigenous microbial communities, and seasonal variability. Results from simplified systems often overestimate real-world effectiveness; testing under near-field conditions produces data that are more robust and transferable to practice.
- Include control and parallel treatment groups: incorporate non-biological controls to distinguish true microbial effectiveness from abiotic processes such as natural adsorption, sedimentation, or chemical degradation. This isolates the actual contribution of microorganisms and ensures reported effectiveness values are biologically meaningful.

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C. Advance Mechanistic Understanding to Boost Effectiveness

- Elucidate mechanisms linked to highest effectiveness: focus research on pathways shown to drive strong performance such as high-capacity biosorption surfaces, robust enzymatic degradation systems, and synergistic interactions in consortia. Understanding *why* certain microorganisms or combinations are more effective enables targeted selection and system design.
- Explore extremophile and adapted microbial effectiveness: further evaluate specialized microorganisms capable of maintaining effectiveness under harsh conditions extreme pH, high temperature, salinity, or toxic loading—where conventional treatment struggles. These strains expand the range of wastewaters where bioremediation can be effectively applied.
- Test enhancement strategies to raise effectiveness: systematically assess whether combining bioremediation with complementary approaches such as nanomaterial augmentation, nutrient optimization, or pre-treatment improves removal efficiency, accelerates treatment speed, or extends effective operational ranges. Measure cost-effectiveness alongside performance to ensure enhancements offer practical value.

D. Scale Up and Validate Effectiveness in Practical Applications

- Bridge lab-to-field through progressive pilot validation: translate high-effectiveness findings from controlled settings into mesocosm and full-scale trials. Monitor performance under continuous or semi-continuous flow, real-world hydrology, and competing environmental conditions to determine whether effectiveness observed in the laboratory can be replicated and maintained in practice.
- Integrate techno-economic effectiveness analysis: alongside treatment performance, evaluate cost-effectiveness capital investment, operational costs, energy use, waste generation, and benefit over time. A highly effective process must also be economically viable to be adopted; assessing both dimensions ensures recommended approaches are both performant and practical.
- Establish effectiveness benchmarks and guidelines: from aggregated consistent data, develop reference effectiveness thresholds for different pollutant types and deployment scenarios. These benchmarks will help practitioners select appropriate bioremediation approaches, set realistic treatment goals, and evaluate success once implemented

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