Ecological Risk and Security Research (2024) Volume 2 Issue 2
doi: 10.59429/ersr.v2i2.10224

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RESEARCH ARTICLE

The use of microorganisms as a solution for environmental sanitation in urban slums in poor and developing countries

Estefan M. da Fonsecaa[1*], Christine C. Gaylardeb[2], Bruno S. Pierria[1], Jéssica de F. Delgadoa[1], Leonardo S. De Limaa[1], Bismarck Alcantarac[3], Letícia F. Garciac[3], José A. S. Aranhad[4], Mariana M. M. Lopese[5], Ana L. Astie[5]

[1] *Department of Geology and Geophysics/LAGEMAR – Laboratório de Geologia Marinha, Instituto de Geociências, Universidade Federal Fluminense, Avenida Litorânea s/n, 24210-340 Niterói, RJ, Brasil.*

[2] *Department of Microbiology and Plant Biology, Oklahoma University, 770 Van Vleet Oval, Norman, OK, 73019, USA. ORCID ID 0000-0002-7252-0211*

[3] *Instituto Singular - Praça Mahatma Gandhi, Edifício Odeon, nº 2, sala 917, Cinelândia, Rio de Janeiro -RJ.*

[4] *Pontifícia Universidade Católica do Rio de Janeiro - Rua Marquês de São Vicente, 225, no bairro da Gávea, Zona Sul do Rio de Janeiro*

[5] *Secretaria de Meio Ambiente e Sustentabilidade do Estados do Rio de Janeiro – SEAS - Av. Venezuela, 110 Saúde Rio de Janeiro*

*** Corresponding author:** Estefan M. da Fonsecaa, estefanmonteiro@id.uff.br

ABSTRACT

Accelerated urbanization in developing countries has driven the expansion of informal settlements, often without access to essential infrastructure such as water supply, sewage treatment, and waste management. These deficiencies contribute to the spread of waterborne diseases and the degradation of urban ecosystems. Streams in these areas are frequently used as open sewers, intensifying environmental contamination and health risks. Addressing these challenges requires integrated public policies focused on land regularization, sanitation infrastructure, and environmental justice. In this context, microbial bioremediation emerges as a sustainable and low-cost alternative. The use of specific microorganisms capable of degrading organic and chemical pollutants offers several advantages: they can adapt to different environments, require minimal maintenance, and do not produce secondary pollution. These biological agents improve water quality, reduce pathogen loads, and support the ecological restoration of contaminated urban waterways. Their application in decentralized and community-level interventions makes them particularly suitable for areas with limited infrastructure. By combining conventional urban planning with microbial-based strategies, it is possible to promote healthier environments and enhance public health in vulnerable communities affected by unregulated urban growth. Within this context, the primary objective of this article was to collect data from a wide range of available studies on the subject to provide insights that could encourage the development of microbiological research to support public policies for environmental sanitation in slums and other communities where infrastructure installation is particularly challenging.

ARTICLE INFO
Received: 12 July 2024 | Accepted: 7 Octoberl 2024 | Available online: 28 November 2024

CITATION
Estefan M. da Fonseca; C. C. Gaylarde; B. S. Pierri; J. de F. Delgado; L. S. De Lima; B. Alcantara; L. F. Garcia; J. A. S. Aranha; M. M. M. Lopes; A. L. Asti. The use of microorganisms as a solution for environmental sanitation in urban slums in poor and developing countries. *Ecological Risk and Security Research* 2024; 2(2): 10224.doi: 10.59429/ersr.v2i2.10224

Keywords: Urbanization; informal settlements; sanitation; public health; microorganisms; bioremediation; water quality; environmental restoration

1. Introduction

Poor and/or developing countries have faced a series of socioeconomic challenges that can, ultimately, result in negative impacts on the environment [1]. Unlike developed countries, underdeveloped nations do not have a history of gradual industrialization and consequent modernization. As a result, the impacts arising from the production and improper disposal of industrial waste have alarmingly affected local ecosystems, leading to the accumulation of pollutants [2] and resulting in disruptions to the trophic net [3].

In parallel, since the development of these countries is often based on the market demands of developed nations, driven by high consumption, they have been compelled to accelerate their extractive industries for minerals and other natural resources to supply the industries of the Global North. However, they fail to implement the same preventive measures and policies required in developed countries. A similar scenario is observed in the food industry, where less developed countries resort to more environmentally harmful methods to intensify their production, thereby ignoring the impacts on their own ecosystems [4].

One of the most pressing challenges faced by underdeveloped and developing nations, especially under conditions of significant socioeconomic pressure, is inadequate infrastructure in major urban centers, and particularly integrated transportation systems [5-7]. Thus, low-income workers, unable to afford housing near their workplaces, are forced to live in peripheral communities known as slums. These densely populated areas are usually located on steep, hard-to-access terrains, which makes the installation of basic sanitation infrastructure a significant logistical challenge [8]. The inability to extend sewage systems, water supply networks, and solid waste collection services to these regions leads to severe environmental and social consequences [9]. In most cases, streams and rivers in these areas are used as disposal sites for domestic sewage, compromising the well-being and health of the local population [10].

Conventional wastewater treatment methods, whether centralized or decentralized, face a range of technical and financial limitations that restrict their efficiency, especially in low-resource settings. Centralized systems often entail substantial capital investment for the construction of sewer networks, storage units, and operational facilities, along with the recruitment of qualified personnel for process management and monitoring [11-13]. In contrast, decentralized approaches may reduce logistical burdens but are frequently limited in capacity, making them unsuitable for handling large urban wastewater volumes [11, 14]. These conventional systems are typically energy-intensive and involve complex mechanical and chemical procedures, which not only increase the probability of system failure but also elevate operational expenses [15]. In addition, they often exhibit poor performance in eliminating persistent micro-pollutants, such as pharmaceutical residues and endocrine-disrupting compounds, now widely detected in domestic and industrial wastewater streams [16-18].

The success of treatment processes is heavily dependent on various factors, including the economic stability of the operating region, energy supply, the specific chemical nature of the pollutant, and the overall technical design [19]. Variables such as influent wastewater composition, system automation, chemical dosing accuracy, operator expertise, and real-time monitoring also play a critical role in determining treatment efficacy [20]. Altogether, the interaction of these elements reveals the inherent complexity and often inadequate performance of traditional wastewater technologies, reinforcing the necessity for innovative, context-appropriate, and resource-efficient solutions.

Countries in the Global North, particularly in Europe and North America, tend to impose stringent regulations on the use of microbial agents for bioremediation due to concerns regarding ecological safety and long-term environmental impacts. These nations often require comprehensive risk assessments prior to the release of microbial consortia or genetically modified organisms into natural environments. The primary concern lies in the potential for non-native or engineered strains to disrupt native microbial communities, alter nutrient cycles, or transfer genes to indigenous species [21]. Regulatory frameworks such as the European Union's REACH and directives from the U.S. Environmental Protection Agency (EPA) demand rigorous testing to ensure biosafety, including evaluation of persistence, pathogenicity, and horizontal gene transfer [22]. In contrast to many developing regions where regulations may be less defined or enforced, these precautionary measures reflect a high level of environmental governance and a more cautious approach to microbial biotechnology applications [23, 24]. Consequently, while bioremediation offers a sustainable alternative to chemical treatments, its implementation in the Global North remains highly regulated due to the potential risks posed to complex and sensitive ecosystems.

From a geographical perspective, many underdeveloped countries possess climatic and environmental conditions that differ significantly from those of the nations from which socio-economic solutions and technologies are often imported. These imported solutions frequently overlook the natural capabilities and ecological particularities of the receiving countries [25]. A clear example of this is the warm and humid climate typical of tropical regions. These environmental conditions have supported the development of rich biodiversity, which relies on ecological competition to maintain the balance within ecosystems [26]. In this sense, environments with high biodiversity may be more resistant to biological invasions by alien species due to increased competition for limited resources. This idea is supported by the biotic resistance hypothesis, which suggests that diverse native communities are more effective at utilizing available ecological niches, leaving fewer opportunities for invaders to establish themselves. For instance, [27] Kennedy et al. (2002) demonstrated that plant communities with greater species richness showed increased resistance to invasion, likely because the native species occupied resource spaces more fully. Similarly, [28] Levine et al. (2004) conducted a meta-analysis which indicated that, although biotic resistance significantly reduces the success of invasive species, it rarely prevents invasions entirely. These findings imply that, while high biodiversity may act as a barrier to invasions, other ecological and environmental factors also influence the success of alien species.

Given this scenario, an important question arises: why not harness the natural conditions of tropical environments to develop more sustainable and cost-effective basic sanitation strategies? Tropical regions are characterized by warm and humid climates, which favor the accelerated growth and metabolic activity of microorganisms [29]. These conditions provide an ideal setting for the application of microbial-based technologies—such as bioremediation and constructed wetlands—capable of treating wastewater, degrading pollutants, and improving overall water quality with minimal energy input and infrastructure demand [30]. Unlike conventional sanitation systems, which are often energy-intensive, expensive, and poorly adapted to informal urban areas, microbial solutions can be decentralized, low-maintenance, and ecologically integrated [12, 13]. This approach not only addresses the technological gap faced by many developing countries but also leverages local biodiversity and climatic advantages to meet sanitation needs in a sustainable manner [31, 32]. The high microbial diversity found in tropical regions, combined with elevated temperatures and humidity, tends to accelerate the metabolic activity of native organisms—conditions that are particularly favorable for bioremediation processes [32]. It is within this framework that the present article was conceived: to explore how tropical nations can utilize microbial ecosystems as allies in advancing basic sanitation, thereby reducing environmental impacts while improving public health and resilience.

2. Challenges of sanitation infrastructure in informal settlements

The emergence of informal settlements, commonly known as "favelas" in Brazil, is largely rooted in rapid urbanization processes, socioeconomic inequality, and a chronic lack of affordable housing. As cities in developing countries expanded, often without proper urban planning, large segments of the population were forced to occupy peripheral or unregulated areas, giving rise to densely populated neighborhoods lacking legal land tenure and public services [7]. These settlements in Brazil frequently develop on steep hillsides, flood-prone zones, or other geologically unstable areas, further complicating the provision of basic infrastructure (Figure 1).

Figure 1. Image of a typical favela located in the city of Rio de Janeiro - Brazil (Source: Authors' owns).

The installation of traditional sanitation systems, such as centralized sewage networks and water supply grids, is significantly hindered in these environments. The absence of formal urban planning, irregular housing layouts, and narrow alleys restrict the access of construction equipment and limit the feasibility of large-scale civil works [33]. Moreover, the high population density in favelas exacerbates wastewater generation, while the lack of formal drainage and treatment systems leads to the direct discharge of untreated sewage into nearby rivers and streams.

In addition to logistical and financial barriers, public health considerations also limit the applicability of conventional sanitation methods in informal settlements. For instance, chlorination is one of the most widely used disinfection methods for drinking water and sewage worldwide. However, in unregulated settings, the improper use of chlorine or other chemical agents can pose serious health risks to local populations. Overdosing may lead to the formation of disinfection by-products, such as trihalomethanes (THMs), which are linked to carcinogenic and mutagenic effects [34]. In communities with limited environmental literacy or safety protocols, the handling, storage, and application of such substances present further hazards.

Another concerning example is the use of aluminum-based coagulants such as aluminum sulfate (alum) in water treatment. When improperly dozed, this can lead to elevated aluminum concentrations in drinking water. Chronic exposure to high levels of aluminum has been associated with neurological effects, raising concerns regarding its potential contribution to neurodegenerative diseases, such as Alzheimer's disease [35, 36].

These constraints underscore the need for context-sensitive, low-risk, and decentralized sanitation alternatives. Approaches based on natural biological processes, such as bioremediation using native microorganisms, offer a more sustainable solution for managing waste in such environments. These methods reduce reliance on hazardous chemicals and are more adaptable to the spatial and social realities of informal urban areas, aligning better with the principles of environmental justice and inclusive development [37]. Such strategies not only mitigate environmental pollution but also empower local communities by promoting low-cost, decentralized interventions that are compatible with their socio-environmental contexts.

3. Use of microorganisms in basic sanitation

Water is an essential resource for all living organisms, and its contamination poses a direct threat to both ecological systems and human health. The scarcity of safe, sustainable drinking water sources has been linked to factors such as climate change, rapid industrial growth, unsustainable agricultural practices, and population expansion. Despite technological advances, available water sources often contain trace amounts of persistent pollutants that may be hazardous to living organisms [38]. The growth of industrial and high-tech sectors, while beneficial for economic development and quality of life, has resulted in significant environmental repercussions, especially through the discharge of untreated effluents rich in organic substances.

When water is contaminated with organic or inorganic pollutants, pathogenic microorganisms, or industrial chemicals, it loses its original properties and becomes hazardous waste [39]. According to Crini & Lichtfouse (2019) [40], wastewater can carry proteins, fats, carbohydrates, surfactants, trace organic compounds, and emerging contaminants. Sources of wastewater include municipal, industrial, and agricultural activities. Municipal effluents commonly contain harmful biological agents such as coliforms, protozoa, and viruses, along with pharmaceuticals [41]. Industrial discharges, particularly from dyeing, mining, metal processing, and chemical production, liberate toxic metals, synthetic dyes, and chlorinated compounds into aquatic environments, affecting biodiversity and human health, as well as water aesthetics [42].

Conventional treatment methods, physical, chemical, and biological, vary in effectiveness and often create secondary pollution. Advanced oxidation processes (AOPs), particularly dielectric barrier discharge (DBD) systems, have shown potential in breaking down resilient organic contaminants [43]. Optimizing DBD under ambient conditions could offer a more effective, standalone solution for wastewater purification, eliminating pollutants through complete mineralization.

Microorganisms are remarkably versatile and ubiquitously distributed across diverse ecosystems, exhibiting the ability to thrive in extreme environments—from subzero temperatures to high heat, arid deserts to aquatic habitats, and both oxygen-rich and oxygen-depleted conditions, even amidst toxic substances and in wastewater [44]. This exceptional adaptability renders them valuable allies in the treatment of polluted aquatic systems, especially for the breakdown of contaminants. Bioremediation harnesses naturally occurring or externally introduced microbial communities that metabolize environmental pollutants, utilizing them as sources of carbon and energy [45]. The choice of microbial strains for bioremediation is highly contingent on the physicochemical nature of the target pollutant and the environmental parameters in the contaminated area [46]. Table 1 presents a series of scientific references as well as the results obtained from the use of microorganisms in maintaining environmental quality across the various studies presented, in particular, studies that address decentralized water treatment systems.

Table 1. Scientific articles addressing the use of microorganisms for environmental quality maintenance

Scientific Reference	Results
Wigginton et al., 2020 [47]	This study compares the nitrifying and denitrifying bacterial communities in nine onsite wastewater treatment systems (OWTS) and one wastewater treatment plant (WTP). Results show similar amoA diversity but higher nosZ diversity in the WTP. While both systems share a core group of N-transforming bacteria, OWTS and WTP promote distinct microbial communities, suggesting different management strategies may be needed for advanced N-removal OWTS.
Lozano Povis and Sanabria Pérez, 2023 [48]	The study evaluated microbial enzyme efficiency in wastewater treatment under different temperatures. Using synthetic wastewater (COD 800 mg/L), results showed that temperature control (20 °C) enhanced pollutant removal. The process followed Orozco's kinetic model, confirming temperature and treatment time as key factors for effective enzymatic remediation.
Koul et al., 2022 [49]	This review discusses various domestic wastewater treatment (DWWT) methods, including traditional physical, chemical, and biological approaches, as well as biosorption techniques using microorganisms, fungi, and algae, emphasizing the importance of considering waste type, clean-up requirements, and environmental impact in selecting effective and sustainable treatment methods.
Ruas et al., 2022 [50]	The study found that combining *Chlorella vulgaris* algae with activated sludge bacteria improved pathogen removal, with aeration and CO2 boosting efficiency, while a 24:0 light-dark cycle enhanced removal of *Enterococcus faecalis* but reduced *E. coli* and *P. aeruginosa* removal.
Wu et al., 2019 [51]	This global study analyzed 16S rRNA sequences from ~1,200 activated sludge samples across 269 wastewater treatment plants (WWTPs) in 23 countries. Despite identifying nearly 1 billion bacterial phylotypes, only 28 core taxa were consistently linked to treatment performance. Unlike macroorganisms, bacterial diversity in activated sludge shows no latitudinal gradient and is shaped by both stochastic (dispersal, drift) and deterministic (temperature, organic load) factors. These findings improve our understanding of microbial diversity and function in WWTPs worldwide.
Wu and Yin, 2020 [52]	Biological wastewater treatment remains vital but faces challenges from stricter discharge standards and emerging pollutants. A new concept—**microbial niche nexus**—is proposed to enhance treatment efficiency by tailoring microbial niches to support diverse communities. Strategies include co-enriching r/K-strategists and creating microenvironments with substrate gradients. Future directions involve advancing microbial enrichment, functional analysis, system design, and novel technologies for improved performance.
Zhang et al., 2018 [53]	Seasonal variation impacted the activated sludge bacterial community more than system differences, with the oxidation ditch process showing greater stability. Core genera included *Nitrospira*, *Pseudomonas*, and *Lactococcus* in domestic wastewater, and *Thauera* and *Thiobacillus* in industrial wastewater systems.
Ji et al., 2015 [54]	A pilot-scale sequencing batch biofilm filter (SBBF) efficiently treated domestic sewage, achieving high removal rates of COD (89.4%), ammonium nitrogen (83.3%), total nitrogen (62.9%), and total phosphorus (48.7%). Pyrosequencing identified *Acinetobacter* species as key players in denitrifying phosphorus removal
Mattew et al., 2022 [55]	This review explores the use of microalgae-bacteria consortia in wastewater treatment, highlighting

Scientific Reference	Results
	their ability to reduce nutrients, COD, and toxic metals, while enabling biofuel production. HRAPs offer energy-efficient, cost-effective treatment, with microbial synergy enhancing overall efficiency.
El-Khateeb et al., 2023 [56]	This study explores a new wastewater treatment system combining UASB reactors with aerobic treatment, achieving 40-66.67% parasite removal. It also links microbial communities to treatment performance and evaluates the system's economic feasibility for municipal plants.
David et al., 2018 [57]	This study used a microbial consortium in a pilot plant to treat biological-staining residues and domestic wastewater. Significant pollutant removal was achieved, and the treated effluent improved root growth in *Lolium perenne* plants.
Ma et al., 2015 [58]	This study demonstrated that intermittent aeration with low dissolved oxygen effectively suppressed nitrite-oxidizing bacteria (NOB) growth, enabling efficient nitrogen removal from domestic wastewater using anammox bacteria. The effluent total nitrogen (TN) was reduced to 6.6 ± 2.7 mg/L, compared to the influent TN of 62.6 ± 3.1 mg/L.
Numberger et al., 2019 [59]	This study analyzed bacterial communities in a WWTP in Berlin using 16S rRNA gene sequencing. It found distinct bacterial groups in the inflow and effluent, with most disease-associated bacteria reduced, except for Legionella and Leptospira, which increased. This suggests WWTPs may reduce enteric bacteria but could release other harmful pathogens, emphasizing the need for thorough bacterial characterization to assess health risks.
Visnevschi et al., 2025 [60]	This study improves wastewater treatment by using floating biofilm to enhance nitrification (99.3%) and denitrification (19.9–91.1%). The biofilm promotes denitrification by consuming COD and nutrients, especially at temperatures of 17.6 °C and 20.4 °C. This method was successfully applied at the Causeni Wastewater Treatment Plant in Moldova.
Dinh et al., 2021 [61]	This study examined the impact of salinity on wastewater treatment in a DHS reactor. As salinity increased from 0.5% to 3.0%, removal efficiencies for CODCr, BOD5, NH4+-N, and TN decreased, but the reactor still showed good potential for treating saline wastewater.
Shchegolkova et al., 2016 [62]	This study analyzed activated sludge (AS) in wastewater treatment plants, finding that microbial communities stabilized over time and varied by wastewater type. Pathogens were reduced, except in slaughterhouse wastewater. The tool XeDetect was developed to predict microbial metabolism, helping optimize bioreactor performance and reduce issues like bulking and foaming.
Li et al., 2022 [63]	This study shows that a passive aeration ditch (PAD) using polyester fabric effectively treats saline decentralized wastewater. Higher C/N ratios improve pollutant removal, while higher salinity boosts biofilm growth but reduces contaminant removal efficiency. Optimal performance occurs with salinity below 2% and a C/N ratio between 1 and 3. These findings demonstrate PAD's potential and offer a strategy for optimizing performance.
van den Brand et al., 2015 [64]	This study explores the benefits of sulfate-reducing bacteria (SRB) in domestic wastewater treatment, including reduced sludge, pathogen removal, heavy metal removal, and efficient COD removal. SRB are well-suited for treatment when sulfate is present, with favorable conditions like pH, organic substrates, and temperature.
Begmatov et al., 2022 [65]	This study examined microbial communities in activated sludge at nine Moscow WWTPs, showing

Scientific Reference	Results
	that treatment technology influences microbial composition. The UCT process was effective for removing organic matter, nitrogen, and phosphorus. Social, cultural, and environmental factors were found to be more significant than treatment technology in shaping microbial communities.
Shahid et al., 2020 [66]	This article highlights the role of microbes in floating treatment wetlands (FTWs) for pollutant removal. Microbes form biofilms on plant roots, aiding in the breakdown of nitrogen, phosphorus, metals, and organic compounds. Plant-microbe interactions enhance pollutant uptake and alleviate metal toxicity, with microbial inoculation potentially improving FTW efficiency.
Sharma et al., 2024 [67]	Genetically modified *E. coli* offers an efficient and safe alternative for environmental bioremediation, outperforming traditional methods and natural strains. Despite higher costs, these microbes show strong degradation abilities and adaptability to various pollutants.
Thirumalaivasan et al., 2024 [68]	This review highlights fungal and bacterial bioremediation as sustainable solutions to toxic waste accumulation, offering an alternative to costly and polluting traditional methods. It explores microbial mechanisms, recent innovations, scalability challenges, and future directions for effective environmental management.
Maglione et al., 2024 [69]	Bioremediation uses microbes to degrade pollutants, supporting circular bioeconomy goals. This review highlights key microorganisms, applications in agro-industrial waste, and challenges to implementation.
Huang et al., 2023 [70]	This study investigates the microbial diversity and nitrogen removal pathways in a decentralized wastewater treatment (WWT) system at an expressway service area using 16S rRNA high-throughput sequencing. The system efficiently removes COD, TN, NH3-N, and TP, with nitrification genes being more abundant than denitrification genes. The analysis identified 40 phyla, with Proteobacteria, Acidobacteria, and Nitrospirae being dominant. Nitrospirae, adapted to cold temperatures, play a key role in nitrification. The study highlights the microbial community's functional properties in decentralized WWT processes.
Mazurkiewicz et al., 2020 [71]	The article discusses how bioremediation improved water quality in the Słoneczko Reservoir, which had suffered from nutrient pollution and harmful bacteria. After bioremediation in 2017 and 2018, water transparency increased, odors disappeared, and bacteria levels became safe. The sediment, rich in nutrients, could potentially be used as fertilizer if managed sustainably. Water quality remained good until 2019.
Gao et al., 2018 [72]	This study highlights the successful use of microbial technology (MT) to improve the water quality of Chengnan River, without traditional methods like aeration or dredging. By applying microbial agents, the river saw increased oxygen levels and significant reductions in key pollutants. The water quality improved, showing the potential for MT to restore polluted urban rivers.

Table 1. (*Continued*)

Based on the studies presented and the positive results already recorded, it is understood that, despite being well explored, the field of microbiology in wastewater treatment still offers a vast horizon for development, which could help mitigate the impacts resulting from uncontrolled development, especially in developing countries, particularly those with hot and humid climates.

Microorganisms used in river restoration efforts are broadly categorized by their metabolic requirements. Aerobic microbes, which operate in oxygenated environments, effectively degrade substances such as alkanes, hydrocarbons, and polycyclic aromatic compounds [73]. In contrast, anaerobic species, though less frequently employed, show promise in breaking down persistent pollutants like polychlorinated biphenyls (PCBs) in oxygen-deprived sediments [74]. Ligninolytic fungi, such as Phanerochaete chrysosporium, demonstrate the capability to decompose complex toxic compounds. These fungi require organic substrates (e.g., straw, sawdust) to activate their enzymatic pathways [75]. Similarly, methylotrophs, mainly anaerobic organisms, initiate pollutant breakdown via methane monooxygenase and can target contaminants like trichloroethylene and dichloroethane [76].

Bacteria and fungi, known as nature's decomposers, offer a cost-effective, eco-friendly alternative to traditional chemical or physical remediation methods. As research continues, untapped microbial diversity holds great promise for advancing environmental biotechnology and enhancing water quality worldwide [77].

Bioremediation has gained prominence as a sustainable alternative to conventional remediation methods, primarily due to its economic feasibility and its ability to fully mineralize contaminants, thus offering a long-term solution to environmental pollution [78]. Unlike physical and chemical methods, which are often invasive and less effective at low contaminant concentrations, bioremediation presents a non-invasive approach that maintains ecological balance and can be effective even when pollutants are present in trace amounts [79].

Despite these advantages, the use of bioremediation is associated with certain limitations. The process tends to be slower than traditional techniques and often involves less predictable outcomes, which may hinder its application in time-sensitive or highly regulated scenarios [80]. These challenges highlight the importance of continuous monitoring and strategic planning when implementing bioremediation strategies.

In the context of river water remediation, the main approaches to bioremediation include: (i) Monitored Natural Recovery (MNR), which relies on natural attenuation processes; (ii) Biostimulation, involving the addition of nutrients or electron acceptors to enhance the activity of indigenous microbial communities; and (iii) Bioaugmentation, which consists of introducing specific microbial strains known for their degradative capabilities [81]. The combined application of these techniques can significantly enhance bioremediation efficiency, making it a promising solution for the restoration of contaminated aquatic environments.

3.1. Microbial strategies for enhancing aquatic environment quality

The use of biological processes to restore the ecological balance of aquatic systems has proven effective in reducing pollutant loads and improving overall water quality [23, 82]. Through the application of microbial communities, bioremediation facilitates the breakdown of organic matter, minimizing sediment accumulation and promoting greater oxygen diffusion throughout the aquatic environment [83]. These changes contribute to a healthier and more resilient riverine ecosystem [84].

For bioremediation to be effective, several critical biological functions must be fine-tuned. These include the regulation of nitrification processes to maintain minimal ammonia levels, the enhancement of denitrification to eliminate excess nitrogen, and the stimulation of carbon compound breakdown. Additionally, efficient sulfur compound oxidation and the stabilization of diverse microbial populations are essential for maintaining system functionality [85, 86, 87]. The approach also supports broader ecological productivity, including the growth of aquatic fauna such as shrimp and the cultivation of secondary aquatic crops [88, 89].

By aligning microbial activity with the specific biochemical dynamics of aquatic systems, bioremediation offers a sustainable and low-impact alternative for restoring degraded water bodies and supporting long-term environmental recovery [90]. A practical example of this approach can be found in the case of the Chengnan River in China, where researchers applied a tailored microbial agent (HP-RPe-3) directly to polluted water and sediments. This strategy led to marked improvements in water quality, dissolved oxygen levels to 5.0 mg/L, reducing ammonia nitrogen by 20%, lowering chemical oxygen demand (COD) by 38%, and decreasing total phosphorus by approximately 15% without artificial aeration or sediment dredging [91]. In the United States, bioremediation was effectively applied in aquaculture pond systems, where microbial treatments not only improved water quality by reducing organic waste and nutrient concentrations, but also increased shrimp production yields [88]. In India, decentralized systems utilizing microbial biofilters were implemented in informal settlements in Vadodara, significantly improving effluent quality through the removal of nitrogen and organic pollutants from domestic wastewater [82]. Similarly, in Ethiopia, facultative ponds harnessing native photosynthetic microorganisms provided a low-cost and effective solution for nutrient removal and water treatment in urban areas lacking centralized infrastructure [92]. These examples illustrate the versatility and effectiveness of microbial approaches in mitigating eutrophication and restoring ecological balance in diverse freshwater environments, including those in low-income regions where traditional infrastructure is limited.

3.2. Biotechnological approaches to organic waste degradation in aquatic environments

As noted previously, the rapid growth of industrial and domestic activities has brought undeniable benefits to modern society, yet it has simultaneously contributed to the degradation of aquatic ecosystems. One of the primary concerns is the increasing release of pollutants rich in both dissolved and suspended organic compounds, particularly carbon-based substances that serve as readily available substrates for microbial and algal growth [93].

Among the microbial taxa involved in the degradation of such organic detritus, species within the *Bacillus* genus have demonstrated significant bioremediation potential. Notable strains include *Bacillus subtilis*, *Bacillus cereus*, *Bacillus licheniformis*, *Bacillus coagulans*, as well as species from the *Paenibacillus* genus, such as *Paenibacillus polymyxa*, which have shown high efficiency in metabolizing organic pollutants [94]. In recent years, several successful applications of microbial bioremediation have been reported worldwide, particularly focusing on the removal of organic matter from aquatic systems. For instance, in China, a study conducted in the Buji River demonstrated that the combination of artificial oxygenation and exogenous microbial agents achieved an organic matter reduction of up to 22.3%, enhancing sediment quality without impairing the overlying water [95]. In developing countries, such applications are equally promising. In Ecuador, researchers identified two Gram-positive bacterial strains capable of significantly lowering biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in municipal wastewater, demonstrating the practicality of microbial treatment in urban tropical environments [96]. Similarly, in Indonesia, the application of a bacterial consortium known as BIO2000 led to a 95% decrease in organic content in shrimp aquaculture effluent within 72 hours [97]. In Malaysia, the indigenous strain *Ochrobactrum sp.* was able to remove 71% of COD from agricultural effluents after just six days of treatment, further supporting the feasibility of cost-effective microbial strategies in settings with limited infrastructure [98]. These cases illustrate the global relevance of microbial bioremediation as a sustainable and adaptable solution for reducing organic pollution, especially when aligned with the biochemical and climatic conditions of the targeted environments.

However, these beneficial microorganisms are often underrepresented in natural water bodies, necessitating their intentional introduction into affected environments in order to enhance bioremediation outcomes. Specific *Bacillus* strains are cultivated, immobilized using carriers such as sand or clay, and strategically dispersed in aquatic systems where they can compete with native microbial populations for organic substrates, including uneaten feed and waste materials from aquaculture [99]. Co-application of *Lactobacillus* species has been shown to accelerate the decomposition process. These bacteria produce a variety of hydrolytic enzymes capable of breaking down complex organic pollutants—such as proteins and polysaccharides—into simpler molecules. These smaller compounds are then further metabolized by other native microbial communities, facilitating a synergistic degradation process [100].

3.3. Biological remediation of nitrogenous pollutants in freshwater ecosystems

An overabundance of nitrogen-based compounds, particularly ammonia and nitrite, poses a major threat to freshwater systems, significantly impairing water quality and contributing to toxic environments for aquatic organisms such as fish and shrimp. These contaminants are introduced in various ways, including the excretion of aquatic fauna, human-related waste inputs, and the microbial decomposition of organic material accumulated in sediment layers [101, 102].

Among current remediation technologies, biologically driven nitrification has proven to be both effective and ecologically sound [47]. The oxidation of ammonia is carried out by specialized autotrophic bacteria belonging to genera such as *Nitrosomonas*, *Nitrosovibrio*, *Nitrosococcus*, *Nitrolobus*, and *Nitrospira*. This initial transformation is followed by the oxidation of nitrite into nitrate, a process mediated by other genera, including *Nitrobacter*, *Nitrococcus*, and again *Nitrospira* [103]. In parallel, some heterotrophic microorganisms are also capable of oxidizing nitrogen, albeit at a reduced efficiency, by utilizing organic nitrogen as a substrate [104]. During these biochemical transformations, the water pH can decrease slightly, which tends to enhance the solubility of nutrients and increase nitrate concentrations [105]. As nitrate accumulates in low-oxygen zones, anaerobic microbial communities become predominant. These organisms facilitate denitrification, reducing nitrate stepwise into inert nitrogen gas. Although the range of known denitrifying bacteria is relatively narrow, species from the genera *Pseudomonas*, *Bacillus*, and *Alcaligenes* are frequently observed to be highly effective in this process [106].

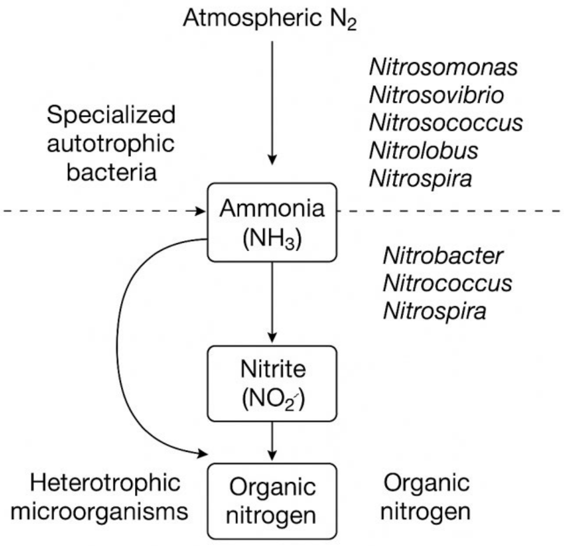

Figure 2. Bacterial role in nitrogen cycling

Recent studies have explored integrated strategies that combine microbial activity with phytoremediation. For instance, using *Nitrobacter* in conjunction with the grass species *Lolium perenne* has shown promising outcomes in the treatment of nutrient-enriched effluents, contributing significantly to water quality improvement [107].

Recent advances in decentralized wastewater treatment have highlighted the potential of anaerobic ammonium oxidation (anammox) processes as a sustainable alternative for nitrogen removal in low C/N environments typical of domestic sewage in tropical regions. Unlike conventional nitrification–denitrification systems, anammox relies on autotrophic anaerobic bacteria capable of converting ammonium (NH_4^+) directly into nitrogen gas (N_2), using nitrite (NO_2^-) as an electron acceptor—without the need for external organic carbon. This significantly reduces operational costs and the carbon footprint of biological nitrogen removal. A recent study demonstrated the effectiveness of fixed-bed biofilm reactors enriched with anammox consortia under moderate temperatures (20–25 °C), confirming their suitability for warm and humid climates. Furthermore, strategies to suppress carbon oxidation during the nitritation phase improved overall nitrogen removal efficiency by enhancing partial nitrification and preserving carbon sources for downstream microbial processes [108].

Despite the promising advances in the use of anammox technology for nitrogen removal in wastewater treatment systems, its application in decentralized contexts still faces significant challenges. One of the main obstacles is the extremely slow growth of anammox microorganisms, with doubling times exceeding ten days. This makes the startup phase of reactors particularly difficult, especially in small-scale or intermittently operated units, such as those used in households or rural communities. Additionally, the anammox process is sensitive to environmental fluctuations, requiring relatively stable conditions of temperature, pH, and salinity — which are not always guaranteed in tropical environments or in systems exposed to the elements [108].

Another critical issue is the need for controlled nitrite (NO_2^-) concentrations, as this compound must be available at suitable levels for the direct conversion of ammonium (NH_4^+) into nitrogen gas (N_2). This necessitates a prior partial nitritation step without progressing to nitrate (NO_3^-) formation, demanding continuous monitoring and, in some cases, automation — factors that increase operational costs and limit applicability in areas with poor infrastructure or low technical capacity. Furthermore, the high cost and limited commercial availability of anammox biomass restrict its diffusion outside urban or research centers [108].

In addition to technical issues, institutional barriers also exist. In many countries, the technology is not yet widely regulated or recognized as a viable solution for public sanitation policies in decentralized areas. However, recent studies have proposed viable alternatives, such as the use of fixed-bed biofilm reactors, natural carriers, and even combinations with nature-based systems like constructed wetlands, which offer greater environmental resilience and reduced costs [108].

In this context, although the decentralized application of the anammox pathway still faces operational and structural challenges, ongoing innovations demonstrate considerable potential for its adaptation to tropical and low-income settings. This contributes to more sustainable wastewater treatment, with lower carbon emissions and higher nitrogen removal efficiency.

3.4. Microbial treatment of hydrogen sulfide in aquatic systems

Sulfur plays a vital ecological role due to its dynamic transformation within aquatic environments. Under anaerobic conditions, organic sulfur compounds are converted into sulfides, which are subsequently oxidized into sulfates by specialized microbes. These sulfates are highly soluble and tend to dissipate from sediments over time. Interestingly, in oxygen-depleted zones, sulfate can serve as an alternative electron acceptor for anaerobic microbial respiration, resulting in the generation of hydrogen sulfide (H_2S), a process driven by a complex network of microbial reductions [109]. The introduction of organic substances into water bodies enhances the production of H_2S, a gas that dissolves readily in water and is known to harm aquatic life by damaging respiratory structures, especially in bottom-dwelling organisms [110]. Even at low concentrations, the non-ionized form of hydrogen sulfide is extremely harmful to fish and may be present in both pristine and polluted waters [111].

To mitigate these toxic effects, photosynthetic sulfur bacteria have been employed in aquatic remediation strategies, particularly in sediment-rich zones of rivers. These bacteria utilize bacteriochlorophylls to capture light and carry out photosynthesis under anoxic conditions [112]. Belonging to groups commonly referred to as purple and green sulfur bacteria, these organisms oxidize hydrogen sulfide and similar compounds like nitrite, playing a vital role in organic matter degradation. They require significantly less light energy than traditional photoautotrophs, allowing them to thrive in low-light, anaerobic niches [90].

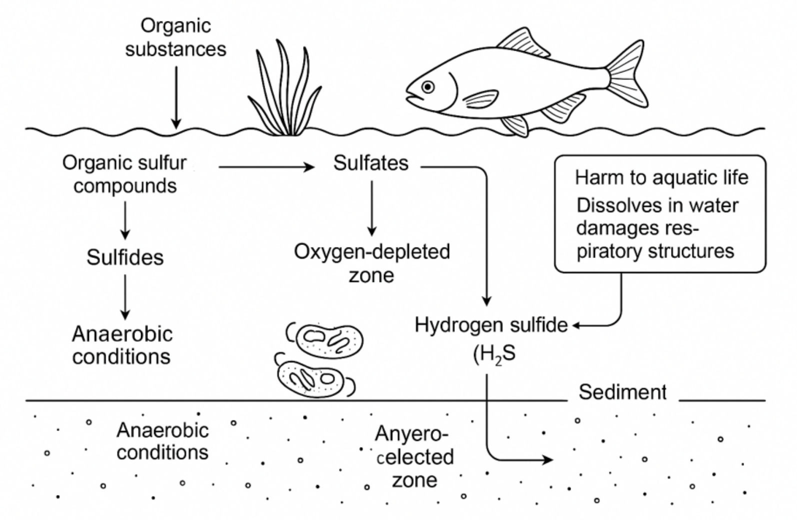

Figure 3. Sulfur biogeochemical cycle driven by microrganisms

Members of the Rhodospirillaceae family are particularly useful in bioremediation due to their metabolic flexibility. They are capable of functioning under both aerobic and anaerobic conditions, similar to heterotrophic microbes, and can break down organic waste efficiently even in the absence of light [113]. A wide variety of photosynthetic bacteria have been identified for use in environmental remediation, including, but not limited to, *Amoebobacter, Chlorobium, Chloropseudomonas, Chromatium, Clathrochloris, Ectothiorhodospira, Pelodictyon, Rhodomicrobium, Lamprocystis, Prosthecochloris, Rhodopseudomonas, Rhodospirillum, Thiocapsa, Thiocystis, Thiodictyon, Thiopedia, Thiosarcina*, and *Thiospirillum* [114].

Recent studies have highlighted significant advancements in microbiological methods for sulfur removal from water. Researchers have identified novel sulfur-oxidizing bacteria (SOB) strains, such as *Pseudomonas aeruginosa* GHWS3 and *Sphingobacterium sp.* GHWS5, which effectively remove sulfide under a range of conditions, including temperatures between 20 and 40°C and salinity up to 50‰. These strains also exhibit inhibitory effects on common aquaculture pathogens, suggesting potential applications in treating industrial and aquaculture wastewater [115].

Additionally, bioaugmentation with phototrophic green sulfur bacteria (PGB) has shown promise in anaerobic digestion systems. A study demonstrated that introducing PGB into systems treating piggery wastewater under controlled lighting conditions enhanced sulfide removal and sulfur recovery. Optimal light intensities of 400-500 lx promoted PGB growth and activity, improving treatment performance (116).

Another breakthrough is the development of the ERATO process, which uses a moving-bed biofilm reactor to efficiently convert sulfide into thiosulfate. This process supports energy- and space-efficient secondary wastewater treatment, providing an effective electron donor for denitrification processes (117).

The use of sulfur-doped biochar has also emerged as a promising method for contaminant removal, particularly in removing antibiotics like tetracycline and resistant bacteria from water. The biochar adsorbs these contaminants while activating peroxydisulfate to enhance degradation, offering a sustainable solution for wastewater treatment (118).

Furthermore, enriching sulfur-oxidizing bacterial consortia in treated wastewater has led to improved thiosulfate oxidation rates. Dominated by genera like *Thioalkalivibrio*, these consortia exhibit higher sulfate production, indicating their potential for biotechnological applications in treating reduced sulfur compounds (119).

These advancements underscore the growing potential of microbiological approaches in improving sulfur removal from various wastewater sources, contributing to more sustainable and efficient water treatment solutions, especially in decentralized water treatment processes.

3.5. Microbial strategies for controlling nutrient overload in aquatic ecosystems

The process of eutrophication—characterized by excessive algal proliferation and bloom formation—is predominantly fueled by an overabundance of essential nutrients such as carbon, nitrogen, and phosphorus within stagnant water bodies. This condition often arises in rivers or lakes where water flow is significantly hindered due to pollutant accumulation or physical obstructions [120]. Among these nutrients, phosphorus is frequently cited as the key limiting factor in the onset of eutrophication. Research suggests that concentrations exceeding 0.086 mg/L in still water can initiate eutrophic conditions, especially considering that algae typically contain proportionally more nitrogen than phosphorus [121].

To combat this phenomenon, several remediation technologies have been developed, including nutrient extraction systems and mechanical sediment removal. Traditional approaches like dredging or artificial flushing are occasionally employed, but biological methods—particularly microbial bioremediation—have emerged as efficient alternatives [122].

Microbial remediation of eutrophic waters primarily involves the use of specific organisms capable of assimilating or transforming nitrogenous and phosphatic compounds. For instance, the bacterium *Klebsiella oxytoca* has demonstrated notable potential in reducing nitrogen loads in aquatic environments [123]. Additionally, the photoautotroph *Phormidium bohneri* has been observed to simultaneously remove both nitrogen and phosphorus when exposed to appropriate light conditions, utilizing solar energy for its metabolic processes [124].

Nitrogen removal is typically achieved through sequential microbial pathways involving nitrification (oxidation of ammonia to nitrate) followed by denitrification (reduction of nitrate to nitrogen gas). In contrast, phosphorus uptake occurs via microbial assimilation, which can proceed under both oxygen-rich and oxygen-depleted environments [125].

Compared to conventional chemical or mechanical methods, microbial-based treatments are generally more cost-effective, environmentally benign, and operationally simpler. These advantages have led to their widespread adoption in the management of nutrient pollution and mitigation of eutrophication symptoms in freshwater systems.

3.6. Introduction to the use of microbial consortia in wastewater treatment

The direct use of microbial consortia within sewage networks has emerged as a promising and sustainable solution for treating wastewater, particularly in low-resource settings where centralized infrastructure is often absent. These microbial communities, either naturally occurring or specially formulated, enhance the degradation of organic matter, lower nutrient concentrations, and help restore water quality without the need for energy-intensive technologies.

One compelling study documented the application of a microbial consortium in open drainage systems carrying domestic wastewater, resulting in substantial reductions in biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), while also improving water clarity [126]. In another study, researchers implemented a biofilter-wetland hybrid system designed around microbial processes to treat domestic sewage. This decentralized setup achieved effective pollutant removal without relying on complex mechanical infrastructure, highlighting its suitability for rural or peri-urban areas [127]. For instance, a 2024 study published in Chemical Engineering Transactions describes a decentralized system combining an Anaerobic Baffled Reactor (ABR), solar-powered disinfection, and constructed wetlands. This setup achieved significant reductions in biochemical oxygen demand (85%), total suspended solids (90%), and pathogens (99.9%). The system was cost-effective, utilized renewable energy and local materials, and was easy to maintain, highlighting its suitability for rural communities [128].

Another study conducted in rural South Korea evaluated a natural and ecological wastewater treatment system (NEWS) comprising an anaerobic septic tank, absorbent-biofilter system, and constructed wetlands. The system demonstrated high removal efficiencies for chemical oxygen demand (up to 98.47%) and was noted for its low maintenance and cost-effectiveness, making it a feasible alternative for sewage treatment in decentralized communities [129].

Additionally, a study in Brazil assessed decentralized sewage treatment systems using septic tanks and anaerobic filters. The systems achieved average annual removal efficiencies of 93% for biochemical oxygen demand and 89% for chemical oxygen demand, complying with environmental standards. The study emphasized that factors like regular maintenance and proper design significantly influence system performance. [130]. In Brazil, the use of microbial inoculants in decentralized treatment systems within informal settlements has proven successful in significantly reducing organic loads, making the treated water safer for the environment [131]. These results demonstrate how microbial interventions can be tailored to different social and environmental contexts, offering an adaptable and low-impact solution for improving sanitation where conventional systems fall short. By aligning microbial activity with the biochemical characteristics of wastewater, in-situ bioremediation presents a viable and scalable method to address global sanitation challenges in a sustainable and cost-effective manner. These examples underscore the global potential of microbial consortia to address wastewater management challenges, particularly in areas with limited access to centralized treatment facilities. By tailoring microbial formulations to the specific characteristics of sewage and environmental conditions, this approach offers a flexible and scalable solution for sustainable sanitation. So, these studies collectively demonstrate that decentralized wastewater treatment systems can effectively remove pollutants without complex mechanical infrastructure, making them well-suited for rural or peri-urban areas.

4. Effectiveness of bioremediation in tropical environments

Bioremediation has shown remarkable efficiency in tropical regions, where environmental conditions such as high temperatures and elevated humidity naturally enhance microbial activity and accelerate the degradation of organic and inorganic pollutants. These favorable conditions make tropical countries uniquely suited for the application of low-cost, biologically based remediation strategies.

In Venezuela, for example, research on tropical soils contaminated by hydrocarbons demonstrated that both bioremediation and phytoremediation were effective in restoring polluted environments. The study emphasized the role of native microbial communities and local vegetation in accelerating contaminant breakdown under tropical conditions [132]. Similarly, in Brazil, laboratory-scale experiments on petroleum-contaminated coastal soils revealed that the addition of nitrogen- and phosphorus-based fertilizers significantly improved microbial degradation rates, highlighting the effectiveness of nutrient-augmented bioremediation in warm, humid environments [133].

In Nigeria, a comparative study explored various bioremediation strategies, including monitored natural attenuation, bioaugmentation, and biostimulation, in petroleum-contaminated tropical soils. The research found that a microbial consortium of actinobacteria significantly outperformed other methods, confirming the viability of microbial approaches in tropical climates [134].

Further supporting these findings, a recent review by Salama et al. (2022) [135] noted that tropical environments inherently offer ideal conditions for the biotransformation of pollutants, given the high metabolic activity of indigenous microbial communities. The review underscores the growing relevance of sustainable bioremediation technologies in addressing pollution in the Global South.

Together, these studies illustrate the untapped potential of bioremediation in tropical countries, where natural environmental advantages can be strategically leveraged to implement cost-effective and ecologically sound remediation solutions.

5. Microbial bioremediation and its role in reducing waterborne diseases in informal settlements

The application of microbial consortia in the treatment of contaminated water presents a promising alternative for improving public and environmental health, particularly in densely populated and underserved areas such as informal settlements. Waterborne diseases—including cholera, typhoid fever, hepatitis A, giardiasis, and dysentery—continue to affect millions worldwide, especially in regions lacking access to safe sanitation and clean water. Microbial bioremediation offers a sustainable, low-cost, and ecologically sound solution to mitigate these health risks [50, 56, 60].

One of the key mechanisms through which microbial bioremediation contributes to disease prevention is the reduction of organic matter and nutrient loads. Microorganisms naturally metabolize organic compounds present in wastewater and sediments, eliminating the substrates that often support the growth of pathogenic organisms. By reducing levels of nitrogen and phosphorus, and by providing competing, non-pathogenic microorganisms, bioremediation also inhibits the formation of harmful algal blooms, and the proliferation of bacteria associated with disease transmission [136].

Beneficial microorganisms also compete directly with pathogens for space and nutrients within aquatic environments. Certain strains, such as *Bacillus subtilis* and *Paenibacillus polymyxa*, are known to secrete antimicrobial substances that inhibit or kill harmful bacteria like *Escherichia coli* and *Salmonella* spp. [94]. This ecological competition not only reduces the pathogen load but also promotes the establishment of more stable, non-pathogenic microbial communities.

Microbial action can improve the physicochemical parameters of water quality, such as increasing dissolved oxygen and reducing turbidity and foul odors, conditions that are unfavorable for pathogen survival. In the case of Lake Pamvotis in Greece, the introduction of microbial consortia led to a significant decline in fecal coliforms and enhanced water transparency, demonstrating both ecological and public health benefits [137].

Beyond these indirect mechanisms, some microbial applications have shown a direct impact on pathogenic load reduction. For example, Bhatia et al. (2022) [138] documented the use of native microbial inoculants to treat domestic wastewater in India, achieving over 90% reduction in fecal coliform concentrations—an impressive outcome that highlights the potential of microbial approaches in public health interventions.

Unlike conventional sanitation methods, which often rely on centralized infrastructure, chemical disinfectants like chlorine, and high energy inputs, microbial bioremediation systems can be deployed in decentralized and low-resource environments. Their adaptability and minimal maintenance requirements make them particularly well-suited to the complex topographies and social dynamics of informal settlements in tropical regions. Moreover, these biological methods avoid the use of toxic substances, aligning with the principles of environmental justice and promoting long-term resilience [139].

In sum, microbial bioremediation not only restores the ecological function of water bodies but also serves as a preventive strategy against waterborne diseases, offering a transformative opportunity for public health improvement in marginalized communities worldwide.

6. Institutional and social barriers to the adoption of microbial bioremediation in informal settlements

Despite the growing body of evidence supporting the use of microbial consortia for the remediation of polluted water bodies, their integration into public sanitation policies—particularly in informal settlements—remains rare. One of the primary barriers is the limited technical knowledge among public officials and decision-makers, many of whom are unfamiliar with the biological mechanisms, safety, and efficacy of bioremediation approaches [140]. This gap in knowledge perpetuates the preference for traditional, infrastructure-heavy solutions. In addition, regulatory frameworks in many countries still lack legal clarity regarding the environmental release of microorganisms for remediation purposes. For instance, in Brazil [141] and India [142], two countries with extensive informal settlements, biosafety laws tend to be rigid or underdeveloped for environmental biotechnology, focusing instead on genetically modified organisms for agriculture [143]. The absence of standardized protocols or approval mechanisms for microbial bioremediation creates legal uncertainties and discourages public and private investment.

Path dependency and institutional inertia also contribute to the dominance of conventional engineering methods in public sanitation projects. Large-scale wastewater treatment plants, sewage networks, and chlorination systems are often prioritized due to existing bureaucratic procedures, engineering norms, and vested economic interests linked to civil construction firms [144]. This path dependency often marginalizes lower-cost, nature-based, or decentralized alternatives, even when such alternatives are demonstrably more feasible in specific urban contexts.

Biotechnological innovation in sanitation faces chronic underfunding, especially in marginalized or informal communities. Slums and peri-urban areas—characterized by legal informality, lack of land tenure, and political invisibility—are frequently excluded from national infrastructure budgets and research programs [145]. For example, in Kibera (Kenya) and Rocinha (Brazil), community-led sanitation initiatives struggle to scale up due to the absence of formal recognition by municipal authorities, limiting their access to public financing or technical support [146]. Sociocultural factors and community perceptions can also hinder the adoption of microbial bioremediation. In some contexts, residents may view the use of "bacteria" in sanitation as unsafe or unsanitary, underscoring the need for public education and participatory approaches that demystify the science behind bioremediation and build trust in its benefits [147].

Despite these barriers, successful examples have emerged. In Indonesia, decentralized microbial bioreactors were piloted in coastal settlements to reduce organic pollution in household wastewater, achieving promising results with minimal infrastructure [148]. In South Africa, research on microbial treatment wetlands for informal settlements demonstrated high removal rates of biochemical oxygen demand (BOD) and fecal coliforms, offering an affordable alternative to traditional systems [149].

These cases highlight the untapped potential of microbial bioremediation in underserved urban areas. However, scaling up these solutions requires a concerted effort to reform regulatory frameworks, increase investment in biotechnological research, and foster cross-sector collaboration between scientists, urban planners, and local communities.

7. Microbial invasion risks associated with the use of bioremediators in aquatic environments contaminated by domestic sewage

Bioremediation is a sustainable and widely applied technology for mitigating pollution in aquatic ecosystems contaminated with domestic sewage. It relies on the metabolic activity of microorganisms capable of degrading organic and inorganic pollutants [96, 102]. However, the deliberate introduction of exogenous microbial strains—known as bioaugmentation—raises significant ecological concerns, particularly those associated with microbial biological invasions, where introduced species compete with and displace native microbial communities [150].

In aquatic environments, non-native microorganisms may outcompete indigenous species for ecological niches and trophic resources, ultimately disrupting the structure and function of native microbial communities [151]. These impacts are particularly pronounced in eutrophic systems, where excess nutrients facilitate the rapid proliferation of opportunistic microbes. A practical example involves the application of commercial strains of *Pseudomonas putida* and *Bacillus subtilis* to urban wastewater lagoons, which demonstrated high organic matter degradation but also led to marked shifts in native microbial composition [45].

In addition to ecological competition, there is a growing concern regarding horizontal gene transfer, especially the dissemination of antibiotic resistance genes (ARGs). This process may compromise environmental and public health safety [152]. Pérez-Etayo et al. (2020) [153] showed that exogenous microorganisms introduced into organically enriched, low-oxygen aquatic environments—such as polluted urban rivers—can acquire mobile genetic elements and become vectors for antimicrobial resistance.

Another major issue is the lack of strict regulations regarding the use of microbial inoculants in tropical countries, often leading to the unregulated release of genetically modified or non-native strains into vulnerable ecosystems [154]. This contrasts with biostimulation strategies, which rely on enhancing the activity of native microbial populations and thus present a lower ecological risk.

Despite these concerns, tropical environments—characterized by higher microbial diversity—may exhibit greater ecological resistance to biological invasions. High biodiversity can promote functional redundancy and niche saturation, reducing the establishment success of foreign microbes through community-level resistance mechanisms [155]. For example, Bell et al. (2005) [156] demonstrated that bacterial communities with greater species richness were more resistant to invasion and maintained critical ecosystem functions under stress. This suggests that aquatic ecosystems in tropical regions may have a natural resilience to the unintended consequences of bioaugmentation.

To minimize the risks of microbial invasion, integrated strategies should be adopted, including:

- ecological compatibility assessments between introduced and native microbes,
- molecular monitoring of microbial diversity before and after application,
- preference for autochthonous microbial consortia already adapted to local conditions [157].

In summary, while microbial bioremediation offers well-documented benefits for treating aquatic systems contaminated by domestic sewage, its success must be balanced against the potential ecological risks of microbial invasion. In biodiversity-rich tropical ecosystems, natural microbial resistance mechanisms may offer an additional layer of protection, but rigorous risk assessments and adaptive management remain essential to ensure ecosystem stability and long-term sustainability.

8. The “favelas” of Rio de Janeiro/Brazil – A Case Study

Environmental sanitation projects are currently being implemented in the favelas of Rio de Janeiro, a major metropolitan city in southeastern Brazil. The city is home to hundreds of informal settlements, many of which have populations comparable to small cities. Among these, the Rocinha and Mangueira favelas stand out. Rocinha, located in the Southern Zone of Rio, is the largest favela in Brazil, with an estimated population of over 100,000 inhabitants [158]. Mangueira, situated near the Maracanã football Stadium, houses approximately 16,000 people.

Due to the complex geomorphological and social structures of these communities, an issue shared by informal settlements globally, the installation of conventional sanitation infrastructure has proven nearly impossible [139, 159]. In response, the local scientific community, led by the Fluminense Federal University (Universidade Federal Fluminense – UFF), in collaboration with other government and non-governmental institutions, has initiated a pioneering project to install two “ecofactories” within these neighborhoods. These ecofactories will serve microbiological processing units where native microbial strains will be isolated, cultivated, and applied directly to the open drainage channels and streams that traverse the communities. In Rocinha, untreated sewage flows into the Canal da Rocinha, which discharges into the Atlantic Ocean via São Conrado Beach, severely impacting both marine and human health [160]. In Mangueira, wastewater primarily flows into the Rio Joana and Rio Maracanã, which ultimately connect to the polluted Guanabara Bay—an estuary suffering from decades of untreated effluent discharges [161].

The deployment of microbial bioremediation in these settings aims to significantly reduce organic matter and pathogenic loads in the water, presenting a sustainable and decentralized alternative to traditional chemical or energy-intensive systems [162]. By improving the microbiological quality of water and reducing environmental contamination, the initiative is expected to mitigate the spread of waterborne diseases such as leptospirosis, gastrointestinal infections, and skin conditions, which are prevalent in flood-prone and unsanitary urban areas [163].

The chronic lack of basic sanitation in Rocinha has contributed to recurrent outbreaks of airborne infectious diseases, including tuberculosis (TB), a condition closely linked to environmental degradation and high population density. Studies have shown that tuberculosis incidence in Rocinha exceeds citywide averages, exacerbated by overcrowded living conditions, poor ventilation, and proximity to open sewage [166]. Although TB is primarily transmitted via airborne droplets, its persistence in vulnerable communities is intertwined with overall environmental and public health infrastructure. Initiatives such as bioremediation, aimed at reducing environmental contamination, may play a supportive role in integrated disease control strategies by improving general hygiene and reducing systemic vulnerabilities. The reduction in foul odors and the revitalization of local aquatic ecosystems may also contribute to improved mental well-being and a stronger sense of environmental dignity among residents [165]. In adjacent neighborhoods, the downstream effects of cleaner water bodies are also expected to benefit public health, tourism, and biodiversity. These improvements align with broader goals of climate adaptation and environmental justice, especially in cities where vulnerable populations disproportionately suffer from ecological degradation. Based on the data obtained in this first phase, the goal is to implement a national policy focused on the use of microorganisms to combat the impacts resulting from the lack of urban sanitation.

9. Conclusion

This article addresses the potential of microbial bioremediation as a viable solution for improving basic sanitation in informal settlements, particularly in tropical regions. Due to the scope of the work, the focus has been limited to domestic wastewater, emphasizing pollutants typically present in such effluents, which play central roles in eutrophication and microbial imbalance in aquatic systems.

The literature reviewed demonstrates that microbial consortia can efficiently degrade organic matter, control nutrient overload, and reduce pathogenic organisms in contaminated water. These methods are particularly suitable for decentralized applications and low-infrastructure environments, such as favelas, due to their low operational costs, adaptability, and minimal energy requirements.

In tropical climates, the efficiency of microbial activity is enhanced by favorable temperature and humidity, which accelerate biological processes and support greater microbial diversity. Case studies and ongoing initiatives, such as the “Ecofactory” projects in the Rocinha and Mangueira communities, illustrate how microbiological approaches can be locally implemented to improve water quality and reduce environmental health risks.

Despite their potential, microbial bioremediation techniques are still underrepresented in public sanitation policies. Factors such as institutional unfamiliarity, regulatory gaps, limited funding, and preference for conventional infrastructure-based approaches remain significant barriers. Addressing these challenges will require the integration of scientific knowledge into urban planning, increased interdisciplinary collaboration, and targeted pilot programs to demonstrate effectiveness at scale.

In summary, microbial bioremediation has been shown to offer a technically sound and context-appropriate alternative for treating domestic wastewater in informal settlements. Its broader adoption could contribute to improving environmental and public health outcomes, especially when aligned with strategies that consider local conditions, resources, and operational feasibility.

Acknowledgements

This research was funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). The group thanks Federal Deputy Chico Alencar for the financial support for the installation of the Ecofactory Rocinha and the Singular Institute for the installation of the Ecofactory Mangueira: Thank you, not for helping us save the world, but for helping us save a small part of it.

Authors' Contributions

Estefan M. da Fonseca and Christine C. Gaylarde: Were involved in all stages of the article’s development, from the initial conception to the final writing, review, and approval of the content. Bruno S.

Pierri, Jéssica de F. Delgado, Leonardo S. De Lima, Bismarck Alcantara, Letícia F. Garcia, José A. S. Aranha, Mariana M. M. Lopes, and Ana L. Asti: Acted as reviewers of the article and were involved in the logistics, providing suggestions and improvements to the final version.

Conflict of interest

The authors declare no conflict of interest

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