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APPLICATION OF MICROBIAL BIOTECHNOLOGY FOR THE TREATMENT OF ORGANIC POLLUTANTS AND HEAVY METALS IN WASTEWATER

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Abstract

One of the biggest environmental problems of the contemporary world is wastewater pollution caused by the fast urbanization process and the industrial growth. The traditional wastewater treatment methods are characterized by the fact that they are very costly to run and that they are not very efficient in eliminating the complex pollutants. The modern biotechnology presents viable substitutes by applying microorganisms, enzymes, and bio systems that have the capacity of degrading contaminants. This paper examines the application of microbial biotechnology in the de-contamination of wastewater of organic pollutants and heavy metals. An experimental investigation was carried out in laboratory scale incorporating microbial consortia that was conducted in controlled conditions in a treatment period of 30 days. The outcome showed that there were substantial biochemical oxygen demand (BOD) and chemical oxygen demand (COD) and heavy metal reduction. These results validate that biotechnological wastewater treatment systems are sustainable wastewater management systems which are environmentally friendly, cost-effective and efficient.

1. Introduction

One of the worst environmental problems in the world is water pollution because of the growing release of industrial effluents, domestic wastes, and agricultural effluents. Wastewater is a composite of numerous pollutants such as organic compounds, heavy metals, pathogens as well as toxic chemicals, which are harmful to aquatic life and human health (Krishna Raj et al., 2025; Sun et al., 2025; Syarifuddin et al., 2025). Other traditional methods of wastewater treatment including chemical precipitation and physical filtration are inadequate to eliminate contaminants and can generate a secondary pollution (Syarifuddin et al., 2025; Dicaldo et al., 2025; Cheliukanov et al., 2025). As such, alternative and sustainable treatment technologies are needed (Renganathan et al., 2025; Lin et al., 2024; Krishna Raj et al., 2025). Biotechnology has become an effective wastewater treatment tool. Environmental biotechnology is the application of biological processes in the removal of pollutants in contaminated environments using microorganisms, enzymes and biological systems (Bluszcz et al., 2025; Temirbekova et al., 2026; Chakraborty et al., 2026). The microbial biotechnology is specifically significant as microorganisms can break organic contaminants by metabolic routes and enzyme response (Chakraborty et al., 2026; Dornelles et al., 2025). Types of microbial consortia have been prevalent in the treatment of wastewater systems like activated sludge, biofilm reactor, and anaerobic digester (Dornelles et al., 2025; Dicaldo et al., 2025; Cheliukanov et al., 2025). Other recent developments in the field of biotechnology would be genetically engineered microorganisms, pollution monitoring biosensors, and biofilm-based treatment systems (Cheliukanov et al., 2025; Renganathan et al., 2025; Wahalathanthrige et al., 2026). Such technologies enhance the efficiency of treatment and provide the opportunity to monitor the quality of wastewater better.

This paper is going to examine the application of microbial biotechnology in the treatment of wastewater and determine its efficacy in the removal of organic and heavy metal contaminants.

2. Method

2.1. Wastewater Sample Collection

The samples of wastewater were taken in a municipal wastewater discharge point and carried to the laboratory under controlled conditions so as to preserve samples integrity (Temirbekova et al., 2026; Chakraborty et al., 2026; Dornelles et al., 2025; Dicataldo et al., 2025; Cheliukanov et al., 2025).

2.2. Preeration of Microbial Culture

The mixed microbial consortium *Bacillus* sp.; *Pseudomonas* sp.; and *Saccharomyces cerevisiae* was employed since these microorganisms have been popularly described to be effective in the degradation of organic pollutants and adsorption of heavy metals in the wastewater treatment systems (Chakraborty et al., 2026; Dornelles et al., 2025; Dicataldo et al., 2025). Before use, the microorganisms were grown in nutrient broth at 30 °C in 24 hours.

2.3. Experimental Setup

The wastewater treatment experiment was performed in a bioreactor system with a scale of lab. Conditions of the experiment: Temperature 30°C, pH 7.0, Aeration rate 1.5 L/min, and Treatment time 30 days (Dornelles et al., 2025; Dicataldo et al., 2025; Cheliukanov et al., 2025).

2.4. Analytical Methods

The parameters that were measured in the experiment included Biochemical Oxygen Demand (BOD) , Chemical Oxygen Demand (COD), Heavy metal concentration and Measurements were conducted after every 10 days.

3. Result and Discussion

Physicochemical analysis of the raw wastewater showed that the content of organic pollutants was high, as indicated by the elevated values of BOD and COD presented in Table 1. Municipal and industrial wastewater is expected to contain such features as reported in the past environmental research (Dicataldo et al., 2025; Cheliukanov et al., 2025; Syarifuddin et al., 2025).

Table 1. Physicochemical Characteristics of Raw Wastewater

| Parameter | Value | Unit |
|------------------------|-------|------|
| pH | 7.8 | - |
| Temperature | 28 | °C |
| BOD | 350 | mg/L |
| COD | 600 | mg/L |
| Total Suspended Solids | 420 | mg/L |
| Dissolved Oxygen | 1.5 | mg/L |

These properties are common to municipal wastewater that has large proportions of biodegradable organic matter.

Figure 1 depicts the conceptual framework of the biotechnological wastewater treatment process and it shows the important role played by microorganisms in the degradation of the organic contaminations and elimination of heavy metals by use of biological process.

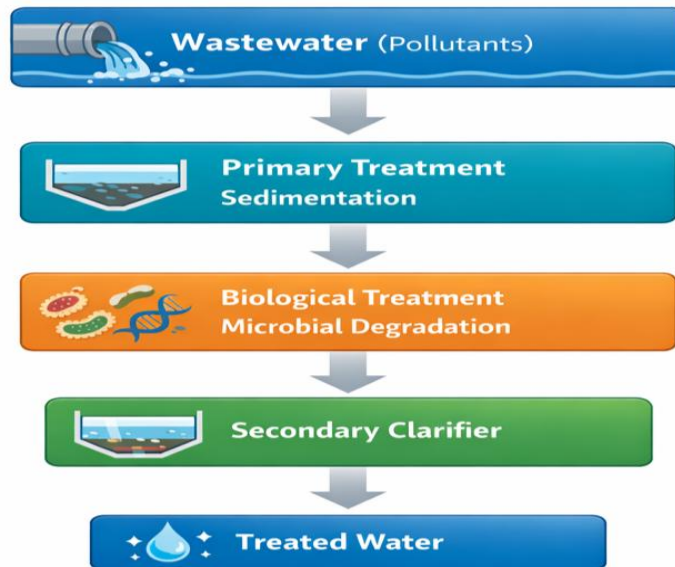


Figure 1. Conceptual framework of biotechnological wastewater treatment

It was observed that the level of organic pollutants decreased gradually over the treatment period as shown in Table 2. The initial BOD concentration of 350 mg/L reduced to 110 mg/L by the end of the 30 days period which marked the end of the treatment. Likewise, the value of COD dropped to 210 mg/L, which was 600 mg/L (Cheliukanov et al., 2025; Syarifuddin et al., 2025; Renganathan et al., 2025; Wang et al., 2026).

Table 2. Reduction of Organic Pollutants during Treatment

| Time (Days) | BOD (mg/L) | COD (mg/L) | Removal Efficiency (%) |
|-------------|------------|------------|------------------------|
| 0 | 350 | 600 | 0 |
| 10 | 260 | 480 | 25 |
| 20 | 180 | 320 | 48 |
| 30 | 110 | 210 | 65 |

The microbial degradation mechanism that degrades organic pollutants is depicted in Figure 2 whereby the microorganisms further break down the complex organic compounds to simpler and less toxic products through enzymatic reaction. The findings indicate that microbial metabolism is very important in the breakdown of organic pollutants. Bacteria use organic materials as sources of carbon and energy and transform them into simpler and less toxic products by enzymatic reactions and biochemical pathways (Wang et al., 2026; Calijuri et al., 2025; Sousa et al., 2025).

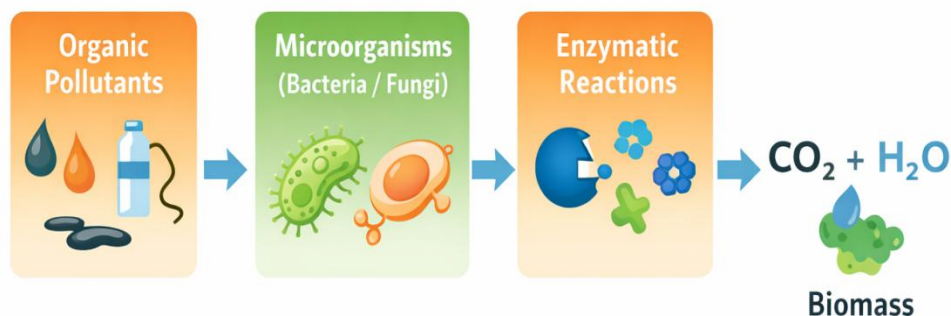


Figure 2. Microbial degradation pathway of organic pollutants

A marked decrease was recorded in the concentrations of the heavy metals following the microbial treatment process as indicated in Table 3. Lead (Pb) concentration reduced to 0.9 mg/L, and cadmium (Cd) dropped to 0.6 mg/L, whereas microbial cell wall biosorption is regarded as one of the major mechanisms of the removal process (Dicataldo et al., 2025; Cheliukanov et al., 2025; Syarifuddin et al., 2025).

Table 3. Heavy Metal Concentration Before and After Treatment

| Metal | Initial (mg/L) | Final (mg/L) | Removal % |
|-------|----------------|--------------|-----------|
| Pb | 2.5 | 0.9 | 64 |
| Cd | 1.8 | 0.6 | 67 |
| Zn | 3.2 | 1.1 | 65 |

Figures 3 and Table 4 respectively show the laboratory-scale bioreactor used in this experiment and the operational parameters of the reactor respectively. Such conditions create the best environment in which microbes thrive and interact metabolically with the pollutants in wastewater, increasing their dissolution (Wang et al., 2026; Calijuri et al., 2025; Sousa et al., 2025).

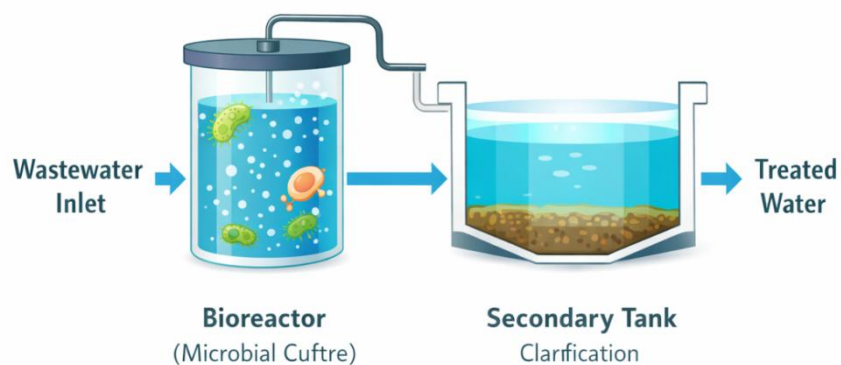


Figure 3. Laboratory-scale bioreactor used in the experiment

Table 4. Bioreactor Operating Conditions

| Parameter | Value |
|--------------------------|-----------|
| Temperature | 30 °C |
| pH | 7 |
| Aeration Rate | 1.5 L/min |
| Hydraulic Retention Time | 24 hr |
| Treatment Duration | 30 days |

The microorganisms used in this study are listed in Table 5, where each microbial species plays a specific role in pollutant removal (Sousa et al., 2025; Nasrollahpour et al., 2025; Shahid & Shafi, 2026).

Table 5. Microorganisms Used in the Study

| Microorganism | Function in Treatment |
|--------------------------|-------------------------------|
| Bacillus sp. | Organic pollutant degradation |
| Pseudomonas sp. | Heavy metal biosorption |
| Saccharomyces cerevisiae | Organic compound fermentation |

The biosorption process that involves the removal of heavy metals is described in Figure 4 whereby the metal ions are bound to the functional groups attached to the cell walls of the microbes. Besides, the overall removal of the heavy metals is illustrated in Figure 7 (Chakraborty et al., 2026; Dornelles et al., 2025; Dicataldo et al., 2025).

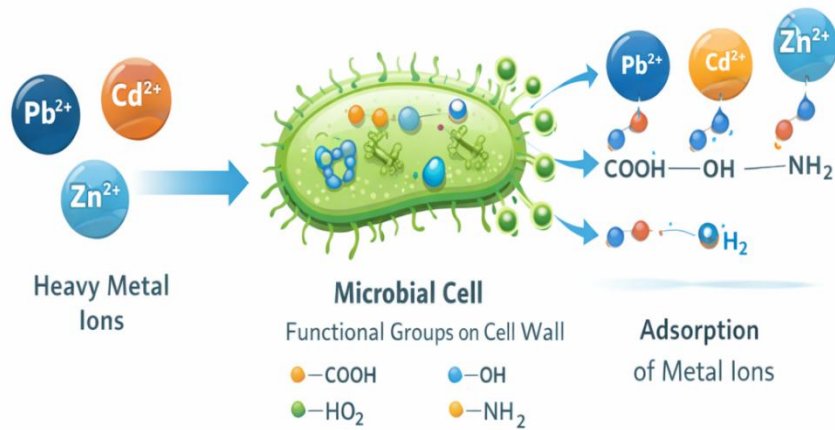


Figure 4. Biosorption mechanism of heavy metals by microbial cell walls.

The overall efficiency of the treatment system is summarized in Table 6, which shows significant reductions in both organic pollutants and heavy metals.

Table 6. Overall Treatment Efficiency

| Parameter | Initial Value | Final Value | Removal Efficiency |
|-----------|---------------|-------------|--------------------|
| BOD | 350 mg/L | 110 mg/L | 68% |
| COD | 600 mg/L | 210 mg/L | 65% |
| Pb | 2.5 mg/L | 0.9 mg/L | 64% |
| Cd | 1.8 mg/L | 0.6 mg/L | 67% |

The decreasing trend in BOD during the treatment period is clearly illustrated in Figure 5, while Figure 6 demonstrates the reduction of COD as microbial degradation progressed (Nasrollahpour et al., 2025; Shahid & Shafi, 2026; Sanjeev et al., 2025; Maurya et al., 2026).

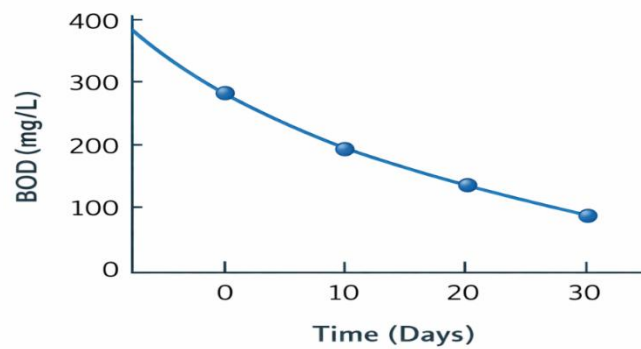


Figure 5. Reduction of BOD concentration during treatment period

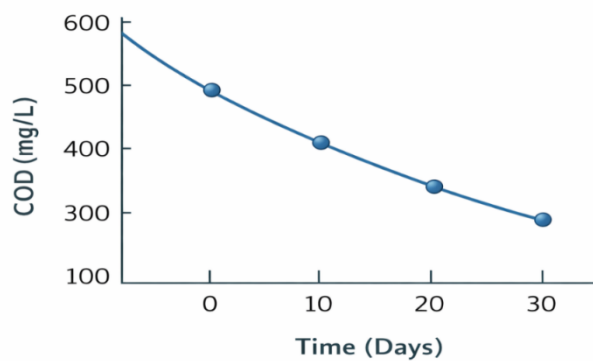


Figure 6. Reduction of COD concentration during microbial treatment

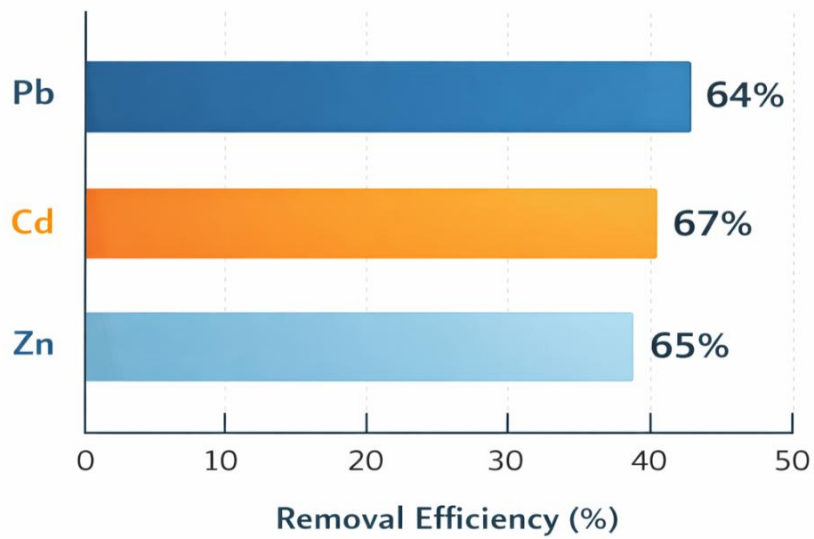


Figure 7. Removal efficiency of heavy metals using microbial biotechnology

Furthermore, biofilm formation inside the reactor, shown in Figure 8, enhances treatment efficiency by providing a stable microbial community and improving resistance to environmental fluctuations (Nasrollahpour et al., 2025; Shahid & Shafi, 2026; Sanjeev et al., 2025).

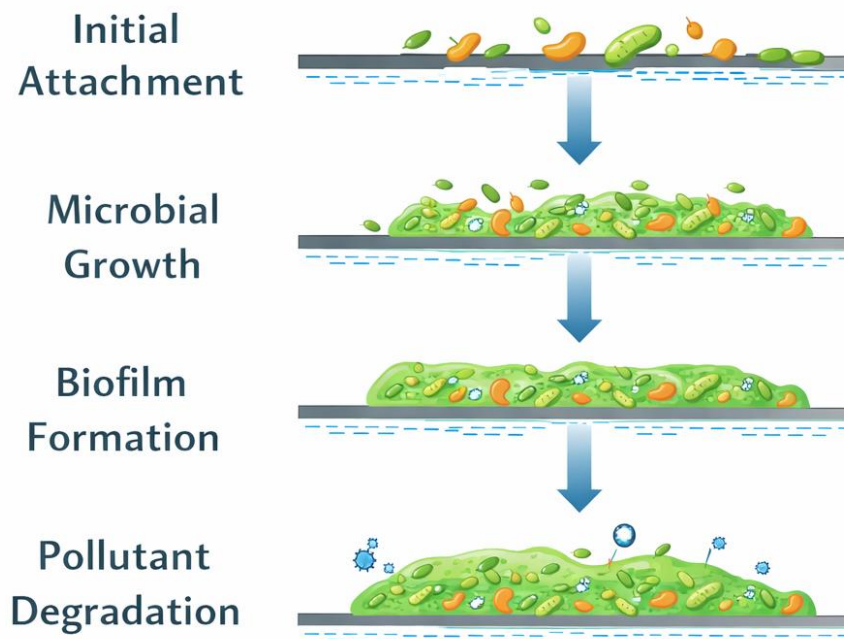


Figure 8. Biofilm formation on reactor surfaces during treatment

The metabolic pathways involved in microbial degradation are illustrated in Figure 9, showing how microorganisms transform organic pollutants into simpler compounds.

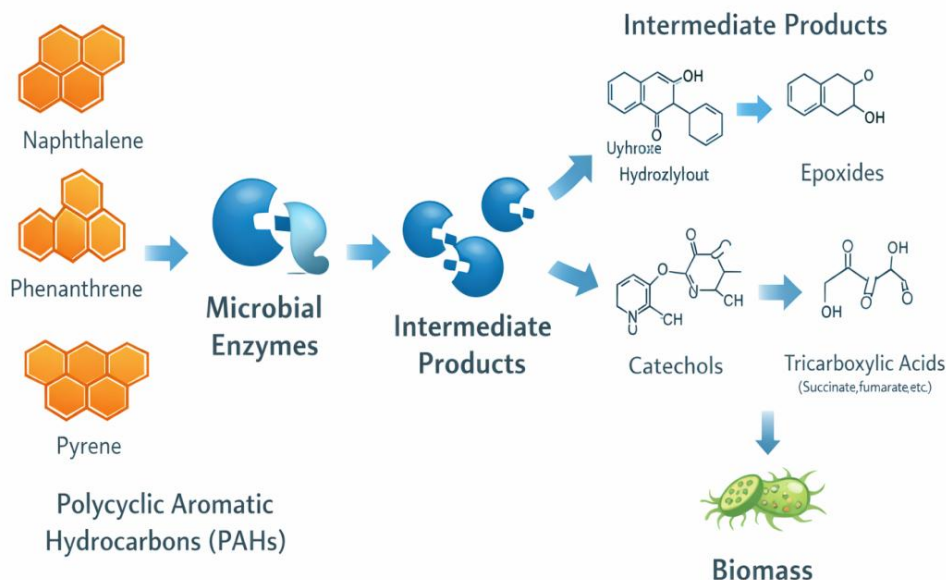


Figure 9. Microbial metabolic pathway for pollutant degradation

The integrated biotechnology system for wastewater purification is presented in Figure 10, highlighting the potential of microbial biotechnology for sustainable wastewater management.

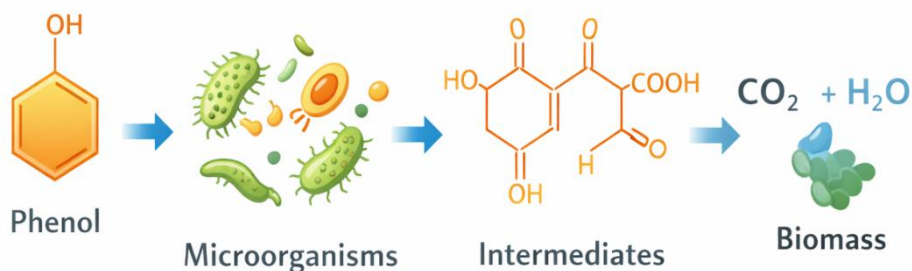


Figure 10. Integrated biotechnology system for wastewater purification

The ultimate findings of the experiment proved that the quality of wastewater was evidently improved after the treatment by the microbes. As presented in Table 2, the treatment period of 30 days showed significant decreases in the content of organic pollutants, as indicated by the reduction of BOD and COD concentrations. The decrease in the BOD 350 mg/L to 110 mg/L and COD 600 mg/L to 210 mg/L suggests that the system is well-degraded in terms of microbial degradation of organic matter which is consistent with other literature on the topic of microbial wastewater treatment systems (Calijuri et al., 2025; Sousa et al., 2025; Nasrollahpour et al., 2025; Shahid & Shafi, 2026).

Microorganisms are very crucial in the process of biodegradation. The microbial communities are able to transform complex organic compounds into simpler and less harmful substances through the enzymatic activity and metabolic pathways to carbon dioxide, water and biomass (Wang et al., 2026; Calijuri et al., 2025; Sousa et al., 2025). The use of microbial consortia also increases the level of treatment efficiency since the various microbial species are able to degrade in several types of pollutants at the same time hence augmenting the entire stability and effectiveness of the treatment process (Shahid & Shafi, 2026; Sanjeev et al., 2025; Maurya et al., 2026).

The heavy metal concentrations also significantly decreased, as shown in Table 3. The levels of Pb, Cd and Zn were reduced significantly in the course of treatment. This is mostly due to the fact that biosorption takes place on the cell walls of microorganisms (Sanjeev et al., 2025; Maurya et al., 2026; Huang et al., 2026). The presence of functional groups, including carboxyl, hydroxyl, and phosphate groups in the microbial biomass offer binding sites to metal ions, which enables their use to adsorb

and remove them effectively out of the wastewater (Nasrollahpour et al., 2025; Shahid & Shafi, 2026; Sanjeev et al., 2025).

Biofilm growth within the bioreactor also helped in better effectiveness of the treatment. Biofilms offer a consistent environment to growth of microbes and resistance to environmental changes, which improves microbial metabolic rate and pollutant degradation capacity (Sanjeev et al., 2025; Maurya et al., 2026; Huang et al., 2026).

New innovations in environmental biotechnology have also improved the efficiency of wastewater treatment by the creation of genetically modified microorganisms, biosensors to monitor the degradation of pollutants, and advanced biofilm-based reactor systems (Maurya et al., 2026; Huang et al., 2026). These technologies are potentially viable methods of long-lasting environmental and sustainable wastewater management (Sanjeev et al., 2025; Maurya et al., 2026; Huang et al., 2026).

4. Conclusion

Biotechnology has offered viable and long-term solutions to wastewater treatment. The experimental findings indicate that heavy metal levels and organic pollutants are reduced considerably when microbial consortia are used. Microbial biotechnology is associated with a number of benefits such as affordability, ecological friendliness, and high purification ability of pollutants. In further advancement of the study, future scientists ought to come up with better bioreactor and genetically modified microorganisms that can enhance better treatment of the wastewater.

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