Bioremediation Potential of Indigenous Microbial Consortia for Heavy Metal Removal in Abattoir Wastewater

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Abstract

Background: The discharge of untreated abattoir effluents in suburban areas of Nigeria poses serious environmental and public health risks due to the presence of high levels of pollutants, particularly heavy metals such as iron, copper, and zinc.

Methods: The effectiveness of indigenous microbial strains (Bacillus spp. and Pseudomonas spp.) in bioremediating heavy metals in abattoir wastewater from Gwagwalada, Abuja, Nigeria. Effluent samples were collected in pre-cleaned HDPE bottles. Microbial isolation, identification followed APHA standard procedures. A Completely Randomized Design (CRD) experiment included four treatments, incubated for 72 hours. Heavy metals were quantified using flame atomic absorption spectrophotometry (AAS), and data analyzed with two-way ANOVA.

Results: The untreated effluent contained iron (55.92 mg/L), copper (67.77 mg/L), and zinc (39.34 mg/L), exceeding the FEPA and WHO permissible limits. After 72 hours, the bacterial consortium significantly ($p < 0.001$) reduced iron, copper, and zinc by 77.3 %, 77.4%, and 58.7 %, respectively. Dissolved oxygen increased from 1.50 to 5.60 mg/L, and turbidity decreased from 28 to 4.2 NTU.

Conclusion: Indigenous Bacillus and Pseudomonas spp., in consortia, offer effective approach to bioremediate heavy metals.

Keywords: Bioremediation, indigenous microbes, microbial consortium, heavy metals, environmental pollution

Introduction

In countries like Nigeria, Africa's most populous nation, rapid urbanization and industrial growth have led to a substantial rise in waste production across various sectors. With a population exceeding 220 million and an annual growth rate of over 2.5%, there is mounting pressure on infrastructure, waste management, and water resources (World Bank, 2022). One significant consequence is the widespread discharge of untreated industrial and municipal waste, including abattoir effluents, into open drains and water bodies, especially in semi-urban and rural areas lacking centralized treatment (Adeniyi et al., 2025). Abattoir effluents are particularly problematic as they often contain blood, fats, pathogens, and heavy

metals such as iron (Fe), copper (Cu), and zinc (Zn), which are non-biodegradable and toxic to humans. (Abo-Alkasem *et al.,*2023). These metals pose serious ecological and health risks due to their bioaccumulation and transfer through the food chain (Chen et al., 2015; WHO, 2017). In the Federal Capital Territory (FCT) and other regions, abattoir effluents are discharged directly into natural water bodies, violating environmental safety regulations (FEPA, 1991; WHO, 2017). The absence of affordable and efficient water treatment technologies has led to persistent unsafe disposal practices, contaminating water sources, and harming nearby communities. Conventional treatment options are costly and generate secondary waste (Rajasulochana & Preethy, 2016; Zhao et al., 2023).

Problem Statement

Heavy metals in abattoir wastewater are particularly challenging to remove because they are non-biodegradable and persist in the environment. (Kenechukwu *et al.,*2023; Karishma *et al.,*2024) Bioremediation offers a promising, low-cost, and eco-friendly alternative that utilizes microorganisms to degrade or remove pollutants through metabolic and enzymatic processes. Indigenous bacteria, such as *Bacillus* spp. and *Pseudomonas* spp., are effective at removing heavy metals via bioadsorption and other mechanisms (Gadd, 2009; Xu *et al.,* 2023; Tayang & Songachan, 2021; Pande *et al.,* 2022). These microbes are abundant and resilient in Nigeria under tropical conditions. While their individual effectiveness has been documented, research on their combined (consortium) use under real effluent conditions is limited. (Tang *et al., 2023; Singh et al., 2023,* Rajpal *et al*., 2022) Therefore, there is a need to evaluate how indigenous microbial consortia can improve the removal of heavy metals, such as Fe, Cu, and Zn, while also improving overall effluent quality.

Research Questions

1. How effective are indigenous Bacillus sp. and Pseudomonas sp., individually and in consortium, in removing heavy metals (Fe, Cu, Zn) from abattoir wastewater?
2. What influence do treatment type and exposure duration (up to 72 hours) have on the physicochemical quality and heavy metal concentrations in abattoir effluents?

Scope of the Study

This study investigated the bioremediation efficiency of *Bacillus* sp., *Pseudomonas* sp., and their consortium in removing Fe, Cu, and Zn from abattoir wastewater in Gwagwalada and a neighboring Area Council in Abuja, Nigeria. It compares microbial treatments over a 72-hour period and analyzes physicochemical parameters and metal concentrations to assess the influence of treatment type and duration.

Methodology

Experimental Setup

The experiment was carried out in a controlled microbiology and

environmental biotechnology laboratory within a government-affiliated scientific research facility in the Federal Capital Territory (FCT), Nigeria. The laboratory is equipped with standard facilities for microbial culture, aseptic handling, incubation, and environmental sample analysis, including physicochemical and heavy metal testing. All experimental procedures were performed under sterile conditions to prevent contamination. Effluent samples were collected from two selected abattoir sites within the FCT and transported on ice to the laboratory for immediate processing. Experimental treatments were established using 250 mL Erlenmeyer flasks serving as bioreactors and incubated at room temperature (28 ± 2 °C) under static conditions for 72 hours. Sampling was conducted at 0, 24, 48, and 72 hours, with 10 mL aliquots aseptically withdrawn from each flask to analyze selected physicochemical parameters pH, temperature, turbidity, total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO) as well as heavy metals (Fe, Zn, and Cu).

Analytical methods followed the Standard Methods for the Examination of Water and Wastewater (APHA., 2012). A Completely Randomized Design (CRD) was adopted to evaluate the bioremediation efficiency of Bacillus subtilis, Pseudomonas aeruginosa, and their consortium on untreated abattoir effluent. This design was selected for its suitability in homogeneous laboratory experiments, ensuring unbiased treatment allocation and effective control of random error. Four treatment groups were established: (i) Control (effluent without bacterial inoculation), (ii) Effluent + Bacillus subtilis, (iii) Effluent + Pseudomonas aeruginosa, (iv) Effluent + Consortium (B. subtilis + P. aeruginosa). Bacterial inocular were cultured on nutrient agar and standardized using a 0.5 McFarland turbidity standard, which corresponds to approximately 1×10^8 CFU/mL. Serial dilution was then performed to obtain a working concentration of 5×10^5 CFU/mL, ensuring uniform inoculum density across all treatments. All experimental procedures adhered to established laboratory biosafety and quality assurance protocols to maintain reproducibility and reliability of results.

Data Collection

This study was conducted on raw abattoir effluent generated from the Gwagwalada abattoir, located in Gwagwalada Area Council, Federal Capital Territory (FCT), Nigeria. Gwagwalada, one of the six administrative councils in the FCT, has a population of approximately 157,770 and a land area of 1,043 km² (National Population Commission, 2006). The abattoir, situated at latitude 8.9508° N and longitude 7.0767° E, was purposively selected due to its high daily slaughter volume and continuous discharge of untreated wastewater into open drainage channels. Effluent samples were collected directly from the main discharge outlet using a composite sampling technique to ensure representative characteristics of the waste stream. Sampling was conducted in triplicate during active slaughter periods. Parameters that

exhibit rapid environmental fluctuation namely temperature, pH, and dissolved oxygen (DO) were measured in situ using portable calibrated field meters (Hanna Instruments, USA). For extended analyses, additional effluent aliquots were collected in sterile high-density polyethylene (HDPE) bottles.

These bottles were pre-cleaned with 10% sodium hypochlorite, rinsed with 70% ethanol, and finally washed with sterile distilled water to ensure sample integrity. Each bottle was filled completely to eliminate headspace, tightly sealed, and preserved at 4 ± 1 °C in insulated coolers during transport to maintain sample stability. All samples were delivered to the microbiology and environmental biotechnology laboratory within 6 hours of collection for detailed physicochemical and heavy metal analyses, following the procedures outlined by the American Public Health Association (APHA, 2012). This method minimized the risk of compositional alteration during handling, ensuring that laboratory data closely represented field conditions.

Bacterial Isolation and Identification

Bacterial isolation and characterization followed standard microbiological procedures outlined by the American Public Health Association (APHA, 2012). Effluent samples were serially diluted (10^{-1}–10^{-5}) and plated on nutrient and selective media (MacConkey, EMB, MSA) using the pour plate method. Plates were incubated at 37°C for 48 h, and distinct colonies were sub-cultured for morphological, Gram, and biochemical characterization. Heavy metal analysis (Fe, Cu, Zn) was conducted following APHA Method 3111B using Atomic Absorption Spectrophotometry (AAS) after acid digestion.

Determination of Physicochemical Parameters

Physicochemical parameters of wastewater samples were measured following **APHA (2012)** standard methods. On-site measurements included pH (Jenway 3310) and temperature (mercury thermometer). Dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5) were determined using the azide-modified Winkler method. Electrical conductivity (EC), total dissolved solids (TDS), and turbidity (NTU) were measured with a multiparameter (Model 4200) and nephelometer, respectively. Nutrientsnitrate, nitrite, phosphate, and sulfate were analyzed by UV–Visible spectrophotometry. Cation exchange capacity (CEC) was assessed via ammonium acetate extraction. Color and odour were recorded by physical observation. All analyses were conducted in duplicate with appropriate quality control measures.

Determination of Heavy Metals in Wastewater Samples

Quantifications of iron Fe, Zn, and Cu from wastewater samples were performed using flame atomic absorption spectrophotometry (FAAS). Sample preparation involved sequential filtration

through Whatman No. 1 and 0.45 µm membrane filters to eliminate suspended solids, followed by acidification to pH 3.0 with concentrated nitric acid to ensure metal ion preservation. The analysis, compliant with APHA Standard Methods (2012, Section 3111B), was conducted using a Thermo Scientific AAS instrument, which was equipped with appropriate metal-specific hollow cathode lamps and calibrated according to established methodologies. The percentage reduction of each heavy metal was calculated using the formula:

$$RE\ (\%) = \frac{C_o - C_t}{C_o} x\ 100 \ldots\ldots\ldots\ldots \text{Eqn(1)}$$

Where:

C_O= initial concentration of metal

C_t= concentration at time t, or final concentration

Preparation of Bacterial Inoculum

Nutrient broth (1.95 g in 150 mL distilled water) was sterilized at 121°C for 15 minutes. After cooling, 10 mL sterile broth and 5 mL sterile saline were aseptically transferred into bijou bottles, then inoculated separately with pure Bacillus subtilis and Pseudomonas aeruginosa strains. Cultures were incubated at 30°C and 150 rpm for 7 days to reach exponential growth and sufficient biomass for bioremediation treatments.

Data Analysis

Data were analyzed using IBM SPSS Statistics (v23) and presented as mean ± SD from triplicates. Two-way ANOVA assessed the effects of microbial treatment, exposure time, and their interaction on heavy metal (Fe, Zn, and Cu) removal. Significance was set at $p < 0.05$, with $p < 0.001$ deemed highly significant. Significant results were followed by Tukey's HSD post hoc tests to identify differences between treatments and time points. Effect sizes were calculated to measure treatment and time impacts.

Results

Effectiveness of Indigenous Microbial Treatments in Heavy Metal Removal

The untreated abattoir effluent contained elevated levels of heavy metals iron (Fe), copper (Cu), and zinc (Zn), which exceeded the permissible limits set by the FEPA and WHO. After 72 hours of bioremediation using *Bacillus sp.*, *Pseudomonas sp.*, and their consortium, a substantial reduction in heavy metal concentrations was observed (Tables 1a–c). The consortium treatment (T4) demonstrated the highest remediation efficiency for all three metals: Fe decreased from 55.92 mg/L to 12.69 mg/L (77.3%), Cu from 67.77 mg/L to 15.29 mg/L (77.4%), and Zn from 39.34 mg/L to 16.25 mg/L (58.7%).

Table 1

Heavy Metals Bioremediation Efficiency and residual concentrations of Heavy Metals over time

Table 1(a):

Iron-(Fe): *Residual Concentration and Remediation Efficiency of Iron (Fe) Over Time*

Treatment	Residual Concentration (Mg/L)				Remediation Efficiency (%)		
	Initial (Mg/L) 0 hr	Final 24 hr	Final 48 hr	Final 72hr	24 hr	48 hr	72 hr
T1 Control (Fe)	55.92	55.92	55.92	55.92	0.00	0.00	0.00
T2 Bacillus sp. (Fe)	55.92	32.25	34.60	27.95	42.32	57.16	75.37
T3 Pseudomonas sp. (Fe)	55.92	23.96	25.28	22.56	38.92	54.79	77.15
T4 Bacillus + Pseudomonas (Fe)	55.92	13.27	12.78	12.69	50.02	59.67	77.32

Note: Residual concentrations are mean values based on four replicates (n = 4).

- Remediation Efficiency (%) = ((Initial–Residual)/Initial ×100
- The control group (T1) showed no changes in zinc concentration.
- The Bacillus + Pseudomonas consortium (T4) achieved the highest Zn removal efficiency after 72 hours.

Table 1(b)

Copper-(Cu): Remediation Efficiency (%) and Residual Concentrations by Bacillus, Pseudomonas, and Their Consortium Over 72 Hours

Treatment	Residual Concentration (mg/L)					Remediation Efficiency (%)	
	Initial (mg/L) 0-hr	**Final 24-hr**	**Final 48-hr**	**Final 72-hr**	**24 h**	**48 h**	**72 h**
T1 Control (Cu)	67.77	67.77	67.77	67.77	0.00	0.00	0.00
T2 *Bacillus* sp. (Cu)	67.77	40.24	46.07	49.17	40.65	58.38	71.93
T3 *Pseudomonas* sp. (Cu)	67.77	28.18	27.93	29.17	31.30	59.50	75.29
T4 *Bacillus* + *Pseudomonas* (Cu)	67.77	19.53	16.73	15.79	26.63	56.23	77.44

Note: Residual concentrations are reported as mean values (mg/L) for n = 4.

- Remediation Efficiency (%) = ((Initial−Residual)/Initial) ×100
- No reduction in the Cu concentration was observed in the control.
- The consortium treatment (T4) achieved the highest overall efficiency by 72 hours

Table 1(c)

Zinc (Zn) Concentration and Remediation Efficiency (%) by Bacillus sp., Pseudomonas sp., and Their Consortium Over 72 Hours.

Treatment	Residual Concentration (mg/L)				Remediation Efficiency (%)		
	Initial 0 h	**Final 24 h**	**Final 48 h**	**Final 72h**	**24 h**	**48 h**	**72 h**
T1 Control (Zn)	39.34	39.34	39.34	39.34	0.00	0.00	0.00
T2 *Bacillus* sp. (Zn)	39.34	31.49	31.32	30.27	18.68	43.31	57.95
T3 *Pseudomonas* sp. (Zn)	39.34	22.78	24.77	19.49	19.11	38.29	54.32
T4 *Bacillus* + *Pseudomonas* (Zn)	39.34	16.52	18.97	16.25	23.07	51.72	58.68

Note: *Residual concentrations are mean values based on four replicates (n = 4).*

- Remediation Efficiency (%) = ((Initial–Residual)/Initial ×100
- The control group (T1) showed no change in zinc concentration.
- The Bacillus + Pseudomonas consortium (T4) achieved the highest Zn removal efficiency by 72 hours.

Table 2

Two-Way ANOVA Results Showing the Effects of Treatment and Time on Metal Concentration

Source	Sum of Squares	Df	Mean Square	F	Sig.
Treatment	27302.061	11	2482.006	242.077	.000
Time (hr)	22498.905	3	7499.635	731.461	.000
Treatment * Time (hr)	10836.025	33	328.364	32.026	.000
Error	1476.425	144	10.253		

Note: *p < .001 (highly significant)*. The significant interaction between Treatment × Time indicates that the effect of microbial treatment on heavy metal concentration varied significantly over time.

Table 3

Effect Size (Partial Eta Squared)

Source	Partial Eta Squared
Treatment	.949
Time (hr)	.938
Treatment * Time (hr)	.880

Note: Partial Eta Squared values above 0.14 is considered large effect sizes.
These results indicate that both microbial treatments and exposure duration had a strong influence on the reduction of heavy metals.

These results clearly show that the combination of *Bacillus sp.* and *Pseudomonas sp.* enhanced heavy metal removal more effectively than single-strain treatments. Two-way ANOVA results (Table 2) confirmed that the treatment type and duration significantly influenced heavy metal concentrations ($p < 0.001$). Large effect sizes were recorded for treatment ($\eta^2 = 0.949$) and time ($\eta^2 = 0.938$), as shown in Table 3, indicating that microbial activity had a strong influence on metal removal. The observed synergy in the microbial consortium suggests cooperative bioadsorption and bioaccumulation processes that improved the efficiency of metal uptake from effluent.

Influence of Treatment Type and Exposure Duration on Effluent Quality

The physicochemical properties of the abattoir effluent improved progressively throughout the 72-hour remediation period (Table 4). Dissolved oxygen (DO) increased markedly from 1.50 mg/L to 5.60 mg/L in the consortium treatment (T4), whereas turbidity decreased from 28.0 to 4.2 NTU. The pH increased from slightly acidic (6.1) to near-neutral (7.10), and both electrical conductivity (EC) and total dissolved solids (TDS) declined significantly, indicating the effective removal of suspended and ionic pollutants. These improvements demonstrate that microbial metabolism not only facilitates heavy metal reduction but also enhances overall water quality.

Table 4

Mean concentration of the Physicochemical Changes during Bioremediation from the Effluent Water

Parameter	Time	T1 Control	T2 Bacillus	T3 Pseudomonas	T4 Consortium	FEPA Limit	WHO Limit
DO (mg/L)	0 hr	1.50 ± 0.10	1.50 ± 0.10	1.50 ± 0.10	1.50 ± 0.10	≥ 4.00	≥ 5.00
	24 hr	1.52 ± 0.08	2.95 ± 0.20	2.85 ± 0.18	3.40 ± 0.16		
	48 hr	1.55 ± 0.07	4.10 ± 0.24	3.95 ± 0.22	4.70 ± 0.21		
	72 hr	1.56 ± 0.08	5.10 ± 0.28	4.95 ± 0.26	5.60 ± 0.25		
pH	0 hr	6.42 ± 0.15	6.42 ± 0.15	6.42 ± 0.15	6.42 ± 0.15	6.0–9.0	6.5–8.5
	24 hr	6.43 ± 0.10	6.50 ± 0.12	6.45 ± 0.13	6.55 ± 0.10		
	48 hr	6.45 ± 0.11	6.85 ± 0.11	6.78 ± 0.12	6.92 ± 0.11		
	72 hr	6.47 ± 0.12	7.00 ± 0.10	6.95 ± 0.10	7.10 ± 0.12		

Parameter	Time	T1 Control	T2 Bacillus	T3 Pseudomonas	T4 Consortium	FEPA Limit	WHO Limit
EC (µS/cm)	0 hr	473.1 ± 30.0	473.1 ± 30.0	473.1 ± 30.0	473.1 ± 30.0	1000	1500
	24 hr	470.0 ± 28.0	390.0 ± 23.0	405.0 ± 25.0	360.0 ± 20.0		
	48 hr	465.0 ± 25.0	270.0 ± 20.0	285.0 ± 22.0	240.0 ± 18.0		
	72 hr	460.0 ± 23.0	230.0 ± 17.0	250.0 ± 18.0	210.0 ± 15.0		
TDS (mg/L)	0 hr	211.8 ± 15.0	211.8 ± 15.0	211.8 ± 15.0	211.8 ± 15.0	2000	1000
	24 hr	210.0 ± 14.0	170.0 ± 10.0	175.0 ± 11.0	155.0 ± 9.0		
	48 hr	208.0 ± 13.0	145.0 ± 9.0	150.0 ± 9.5	125.0 ± 8.0		
	72 hr	205.0 ± 12.0	120.0 ± 7.5	125.0 ± 8.0	105.0 ± 6.5		
Turbidity (NTU)	0 hr	28.0 ± 3.0	28.0 ± 3.0	28.0 ± 3.0	28.0 ± 3.0	5.0	5.0
	24 hr	27.5 ± 2.8	21.0 ± 2.1	20.0 ± 2.0	18.0 ± 1.8		
	48 hr	26.8 ± 2.5	10.5 ± 1.0	11.0 ± 1.1	9.0 ± 0.9		
	72 hr	26.0 ± 2.3	5.0 ± 0.6	5.5 ± 0.7	4.2 ± 0.5		
Iron (Fe) (mg/L)	0 hr	55.92 ± 0.00	55.92 ± 0.00	55.92 ± 0.00	55.92 ± 0.00	1.00	0.30
	24 hr	55.92 ± 0.00	32.25 ± 1.71	34.15 ± 3.67	27.95 ± 2.04		
	48 hr	55.92 ± 0.00	23.96 ± 2.38	25.28 ± 3.00	22.56 ± 1.93		
	72 hr	55.92 ± 0.00	13.77 ± 2.95	12.78 ± 2.33	12.69 ± 4.38		
Zinc (Zn) (mg/L)	0 hr	39.34 ± 0.00	39.34 ± 0.00	39.34 ± 0.00	39.34 ± 0.00	5.00	3.00
	24 hr	39.34 ± 0.00	31.99 ± 4.40	31.82 ± 6.61	30.27 ± 1.67		
	48 hr	39.34 ± 0.00	22.30 ± 4.83	24.27 ± 6.44	18.99 ± 2.90		
	72 hr	39.34 ± 0.00	16.54 ± 0.30	17.97 ± 1.37	16.25 ± 0.96		
Copper (Cu) (mg/L)	0 hr	67.77 ± 0.00	67.77 ± 0.00	67.77 ± 0.00	67.77 ± 0.00	1.00	2.00
	24 hr	67.77 ± 0.00	40.24 ± 5.61	46.57 ± 7.97	49.72 ± 7.73		
	48 hr	67.77 ± 0.00	28.20 ± 3.85	27.43 ± 4.10	29.67 ± 5.51		
	72 hr	67.77 ± 0.00	19.03 ± 3.76	16.75 ± 5.16	15.29 ± 4.53		

Note: The data show the mean concentrations of the measured parameters at specified time intervals during the microbial bioremediation of abattoir effluent. T1: Control (no treatment); T2: Bacillus-treated effluent; T3: Pseudomonas-treated effluent; T4: Bacillus + Pseudomonas Consortium, FEPA: Nigerian discharge standards; WHO: Guidelines for drinking water quality.

Discussion

This study demonstrated that indigenous microbial consortia, specifically *Bacillus subtilis* and *Pseudomonas aeruginosa*, effectively remediated abattoir effluent contaminated with heavy metals. Initial analysis of the Gwagwalada abattoir effluent revealed elevated levels of iron (55.92 mg/L), copper (67.77 mg/L), and zinc (39.34 mg/L), all exceeding the FEPA and WHO permissible limits. The effluent also showed low dissolved oxygen and high turbidity, which are indicators of significant pollution, consistent with prior reports on untreated slaughterhouse effluents (Adeyemo et al., 2019).

Treatment with the bacterial consortium led to marked improvements in water quality over 72 hours. Dissolved oxygen increased to 5.60 mg/L, whereas turbidity, total dissolved solids, and electrical conductivity decreased significantly. These changes suggest that active microbial metabolism contributes to pollutant removal, which is in agreement with the documented mechanisms of biosorption and flocculation (Benalia *et al.,* 2021; Wu *et al.,* 2023, Wang *et al.,* 2009, Zhao *et al.,* 2023). The consortium also achieved the highest removal efficiencies for Fe (77.3%), Cu (77.4%), and Zn (58.7%), reflecting synergistic microbial interactions that enhanced bioremediation performance compared to that of single strains.

The influence of treatment type and exposure duration was further supported by ANOVA (Tables 2 and 3), which showed highly significant differences ($p < 0.001$) across treatments and time points. The strong interaction between treatment and exposure duration ($\eta^2 = 0.880$) indicates that water quality improvement depended on both the type of microorganism used and the duration of bioremediation. Time-dependent improvements were most pronounced between 48 and 72 hours, highlighting the progressive effectiveness of microbial activity during prolonged exposure.

Two-way ANOVA confirmed that both treatment type and exposure duration had significant effects on heavy metal reduction, emphasizing the importance of optimizing microbial combinations and treatment duration for maximum efficacy. These findings align with recent studies highlighting cooperative metabolism in microbial consortia (Khidr et al., 2025; Semwal et al., 2025; Nnaji *et al.*, 2023; Mishra *et al.,*2021).

Overall, the results demonstrate that indigenous microbial consortia of *Bacillus sp.* and *Pseudomonas sp.* can achieve superior heavy metal removal and improve the physicochemical quality of abattoir effluents, providing a sustainable and cost-effective strategy for wastewater treatment in resource-limited settings.

Conclusion

This study confirmed that indigenous *Bacillus* spp. and *Pseudomonas* spp., particularly as a microbial consortium, effectively bioremediated abattoir effluent contaminated with heavy metals. Initially, high concentrations of iron (55.92 mg/L), copper (67.77 mg/L), and zinc (39.34 mg/L) exceeded the safety limits, alongside poor water quality

indicators such as low dissolved oxygen and high turbidity. After 72 hours, the consortium treatment significantly improved water quality by increasing the dissolved oxygen to 5.60 mg/L, reducing turbidity to 4.2 NTU, and lowering metal concentrations by over 58%. The pH, electrical conductivity, and total dissolved solids also improved. Statistical analysis confirmed that the treatment type and exposure duration significantly influenced the remediation efficiency, with the consortium outperforming the individual strains. These findings highlight the potential of microbial consortia as a promising and low-cost strategy for decentralized wastewater treatment.

However, residual heavy metal levels remained above regulatory limits, indicating the need for longer treatment periods or further process optimization studies. Future research should focus on pilot- or full-scale applications, optimization of operational parameters and environmental safety assessments. Integrating microbial bioremediation within existing wastewater management frameworks, supported by policies, is crucial for sustainable adoption, especially in resource-limited settings.

Limitations of the Study

Despite these promising outcomes, there are some limitations. Although the 72-hour treatment duration was effective, it did not reduce all metal concentrations below regulatory standards, implying that longer or sequential treatments may be required. Controlled laboratory conditions may not fully replicate field variability in effluent composition or environmental factors, limiting direct scalability. Further research should target extended treatment periods, pilot- and field-scale validations, and optimization of operational parameters, including pH, temperature, and nutrient availability. Comprehensive ecotoxicological assessments are also vital to ensure the environmental safety of treated effluents prior to their large-scale application.

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Disclosure of AI Usage

During the preparation of this work, the authors used ChatGPT and Grammarly to draft and refine the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published work.

Conflict of Interest

None

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