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Constructed Wetland-Based Wastewater Management Model for Slum Settlements in 9-10 Ulu Urban Village, Jakabaring District, Palembang City

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Abstract: This study aimed to assess water quality based on physicochemical and microbiological parameters, identify the dominant social factors influencing pollution, and evaluate the performance of a Constructed Wetlands (CW) model as a domestic wastewater treatment solution. Water sampling was conducted at three stations along the Aur River in accordance with Indonesian National Standards (SNI). Dominant factor analysis was performed using linear and logistic regression with SPSS version 24, while CW performance was evaluated using independent t-tests in horizontal and vertical flow systems planted with three types of vegetation: water spinach, water hyacinth, and water lily. The results showed that the highest total coliform concentration was recorded at the downstream station, reaching 9×10^6 MPN/100 mL. Septic tank ownership was identified as the most dominant variable associated with total coliform concentration (OR = 9.470). All water quality parameters decreased significantly after CW intervention (p = 0.000), with removal efficiencies of 91.43% for BOD, 86.41% for COD, 94.24% for ammonia, and up to 96.05% for total coliform. No significant difference in treatment performance was observed between the horizontal and vertical configurations, indicating that CW design selection may be guided by cost considerations and site-specific field conditions.
Keywords: Water pollution; wastewater; domestic wastewater; constructed wetlands; Aur River

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INTRODUCTION

Access to clean water is one of the most pressing global challenges of the twenty-first century. Rapid population growth, accelerated urbanization, and industrial expansion have placed severe pressure on both the quantity and quality of freshwater resources worldwide. Ahuja (2015) reported that more than 80 countries face urban water scarcity, while approximately 1.9 billion people had already been living in areas at risk of water deficit since 2010—a figure projected to increase to 2.7–3.2 billion by 2050 (Burek et al., 2016). In addition to quantitative scarcity, water quality degradation has become an equally critical concern. In the Middle East alone, industrial and municipal wastewater production reaches 23 billion m³ per year, yet less than 7% is recycled (Elmeligy et al., 2023). Surface water contamination by pathogenic microorganisms has emerged as a direct public health threat (Amirat et al., 2012; Khan, 2020). Globally, at least two billion people consume drinking water contaminated with human fecal matter, a condition that contributes substantially to the incidence of diarrhea, typhoid fever, cholera, and dysentery (Troeger et al., 2018; WHO & UNICEF, 2017). In this context, *Escherichia coli* is widely used as a primary indicator of fecal pollution because it naturally inhabits the intestinal tracts of humans and animals; therefore, its presence in water bodies provides clear evidence of fecal contamination (Anggara et al., 2020; Rock et al., 2018).

In Indonesia, domestic wastewater management remains in a critical condition, with its most visible impacts occurring in densely populated riverbank settlements. Nationally, only 72.04% of households had access to improved drinking water sources, while only 67.89% had adequate sanitation facilities in 2017 (BPS, 2017). The direct discharge of household wastewater into drainage channels and water bodies without treatment has substantially reduced the natural self-purification capacity of aquatic ecosystems (Ostroumov, 2017). This problem is particularly acute in Palembang City, where the long-standing tradition of constructing houses along riverbanks has resulted in the direct disposal of domestic wastewater, including human excreta, into rivers without any treatment process (Oktriyedi et al., 2022). Jakabaring District, which has been designated as a slum area under Mayor Decree No. 325/KPTS/DPRKP/2020, has a population density of 9,871 people per square kilometer. In Kelurahan 9–10 Ulu, most residents live in stilt houses with poor sanitation conditions, while the Aur River, which flows through the area, receives untreated domestic wastewater directly from the surrounding settlement. The public health consequences are evident: diarrhea cases in this area reached 2,927 in 2019 (Sunardi et al., 2021). These cases are collectively driven by inadequate sanitation infrastructure, high population density, and the continued practice of open defecation into the river (Sunardi et al., 2021; Widiyanto et al., 2015).

Various approaches to domestic wastewater treatment have been developed and tested worldwide; however, a substantial gap remains between available technologies and the practical needs of slum settlements along Indonesian riverbanks. In Portugal, wastewater has been applied to maize fields by utilizing soil nitrification processes, but this approach faces unresolved nitrate accumulation at the end of the crop growth cycle (Hassan et al., 2021). In Bangladesh, sanitation interventions in slum areas have focused more on livelihood improvement than on technical effluent treatment, leaving water quality problems insufficiently addressed. In several other countries, ultraviolet-based photocatalytic systems have been developed to degrade textile industrial wastewater; however, these systems require costly infrastructure and controlled operating conditions (Hassan et al., 2021). Constructed Wetlands (CW), as nature-based treatment systems that rely on interactions among microorganisms, vegetation, and substrates to remove organic matter, nutrients, and pathogens, have demonstrated strong performance in reducing BOD, COD, TSS, nitrogen, and phosphorus under various environmental conditions (Bakhshoodeh et al., 2020; Bedu-Addo et al., 2023).

Mustapha et al. (2018) compared vertical subsurface-flow (VSSF) and horizontal subsurface-flow (HSSF) systems using *Typha latifolia* for petroleum refinery wastewater treatment under tropical conditions in Nigeria. Their study reported VSSF removal efficiencies of 76% for BOD, 73% for COD, and 68% for NH_4^+-N, while the hybrid VSSF+HSSF system achieved removal efficiencies of 94% for BOD and 88% for COD. However, that study focused on industrial wastewater rather than domestic wastewater and did not evaluate coliform pathogen removal. In Indonesia, a VSSF-CW system using *Typha angustifolia* and *Ipomoea aquatica* has been studied for tofu industrial wastewater treatment with BOD and COD loads of 5,000–14,000 mg/L (Rachmansyah et al., 2023). Nevertheless, that study assessed only BOD and COD removal, did not include coliform removal, and did not compare HSSF performance in parallel. Furthermore, in many countries, particularly in tropical and subtropical regions, the use of local plants, including ornamental species, has gained attention in horizontal subsurface-flow CW systems, although mixed vegetation generally outperforms monocultures in pollutant removal efficiency.

This study conducts a direct head-to-head comparison between HSSF-CW and VSSF-CW configurations planted with Indonesian local macrophytes under identical urban domestic wastewater conditions. This comparative design, involving flow configuration and local vegetation type/composition as treatment variables, has not been widely reported in the existing literature, particularly in the context of densely populated riverbank settlements in Indonesia.

Based on this research gap, the present study establishes three interrelated objectives. First, it assesses the physical, chemical, and biological quality of Aur River water in Kelurahan 9–10 Ulu, Jakabaring District, Palembang City. Second, it identifies the dominant factors influencing water pollution caused by domestic wastewater discharge in the riverbank slum settlement. Third, it designs, constructs, and evaluates a Constructed Wetlands model comprising horizontal subsurface-flow and vertical subsurface-flow configurations planted with local macrophytes as an affordable, easy-to-operate, and sustainable domestic wastewater treatment solution for urban riverbank communities in Indonesia.

METHOD

Study Area and Research Period

This study was conducted in Kelurahan 9–10 Ulu, Jakabaring District, Palembang City, Indonesia. The initial field investigation was carried out from October to December 2022. The study area is a densely populated residential settlement located along the Aur River. The location of the research area is presented in Figure 1.

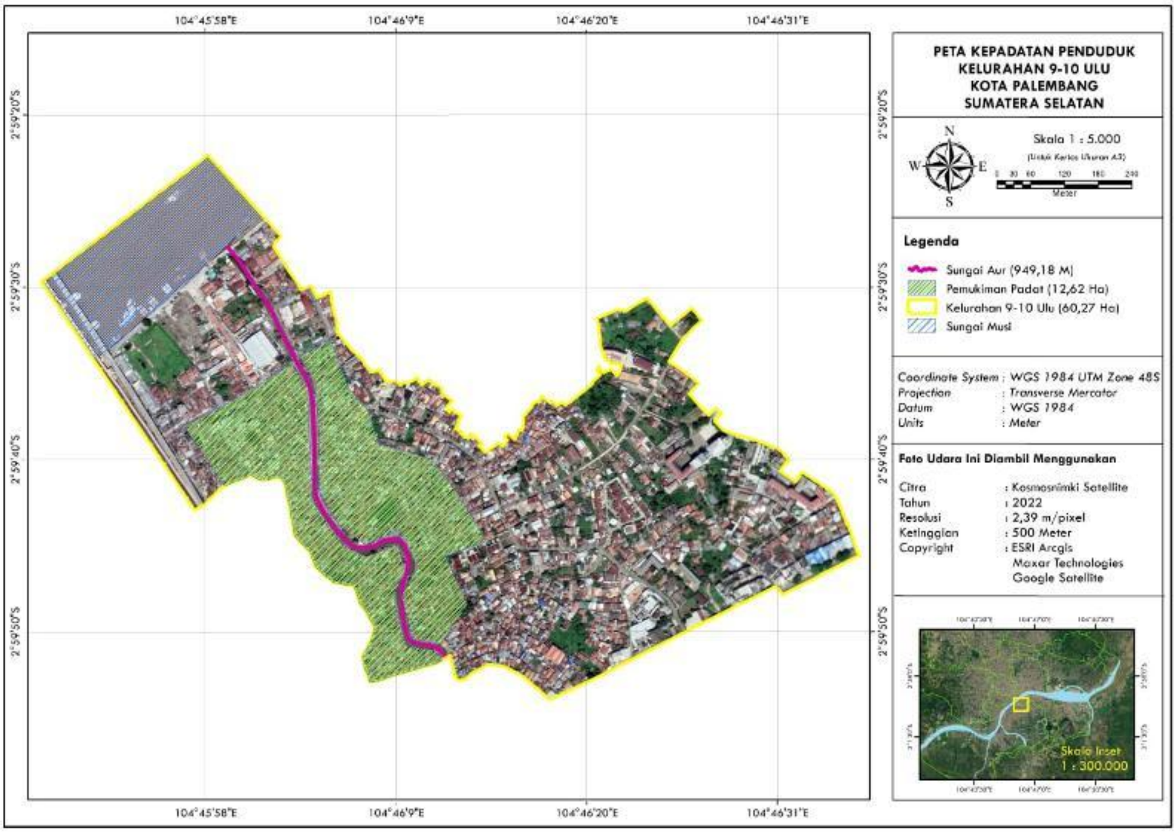

Figure 1. Map of the densely populated settlement in the study area

Water Quality Assessment

This study focused on the assessment of surface water quality in the Aur River. The investigation began with a field survey and GIS-based mapping to identify areas with potential pollution sources associated with residential activities. Water sampling was conducted at three stations representing the upstream segment (coordinates: -2.998377, 104.771467), middle segment (coordinates: -2.995815, 104.768369), and downstream segment (coordinates: -2.991283, 104.766674) of the river. Each station consisted of five sampling points, resulting in a total of 15 observation points.

Water samples were collected using the grab sampling method in accordance with SNI 6989.59:2008. Samples were placed in contaminant-free glass or polyethylene containers and subsequently analyzed in a KAN-accredited laboratory. The analyzed parameters referred to the water quality standards stipulated in South Sumatra Governor Regulation No. 16 of 2005 concerning River Water Designation and Water Quality Standards. The equipment used in this study included a GPS device, electrodes, a spectrophotometer, a BOD reader, and gravimetric apparatus. Quantitative data were processed using the Statistical Program for Social Science (SPSS).

Social Survey and Analysis of Dominant Pollution Factors

To identify the dominant factors contributing to river pollution, a cross-sectional approach was employed, in which data on explanatory and outcome variables were collected simultaneously from February to March 2023. The study population comprised all residents living along the Aur River. A total of 100 respondents were selected using cluster sampling, and data were collected through a structured questionnaire.

The independent variables examined included demographic characteristics, namely age, sex, education level, occupation, and income; housing conditions, including length of residence, number of household members, land ownership status, building type and condition, and building area; availability of sanitation facilities, including access to clean water, wastewater facilities, and solid waste management; as well as community knowledge and perceptions. River pollution was treated as the dependent variable. The analysis was also supported by the results of the first-stage water pollution assessment and was performed using SPSS.

Constructed Wetlands Performance Test

The third stage of the study was conducted in Kelurahan Kalidoni, Palembang City, from May to September 2023. This stage focused on evaluating the performance of constructed wetlands as a domestic wastewater treatment system. Both vertical-flow and horizontal-flow constructed wetland configurations were tested to assess their effectiveness in improving wastewater quality.

RESULTS AND DISCUSSION

Analysis of Water Pollution

The results of the biological pollution analysis of the Aur River are presented in Table 1.

Table 1. Biological quality of surface water in the Aur River

Station	Parameter	Unit	Water quality standard	T1	T2	T3	T4	T5	Mean
1	Total coliform	100 mL	5×10^3/100 mL	$5.4 \times 10^{6*}$	$5.1 \times 10^{6*}$	$5.2 \times 10^{6*}$	$5.3 \times 10^{6*}$	$5.2 \times 10^{6*}$	5×10^6
2	Total coliform	100 mL	5×10^3/100 mL	$1.1 \times 10^{4*}$	$1.1 \times 10^{4*}$	$1.2 \times 10^{4*}$	$1.1 \times 10^{4*}$	$1.2 \times 10^{4*}$	1×10^4
3	Total coliform	100 mL	5×10^3/100 mL	$9.2 \times 10^{6*}$	$9.1 \times 10^{6*}$	$9.2 \times 10^{6*}$	$9.4 \times 10^{6*}$	$9.3 \times 10^{6*}$	9×10^6

River water pollution caused by the direct discharge of domestic wastewater into water bodies poses serious public health risks, particularly through exposure to pathogenic microorganisms that can survive and proliferate in aquatic systems (Khan, 2020; Andriani & Ariesyady, 2013). *Escherichia coli* is widely recognized as a primary indicator of fecal contamination because of its consistent presence in the feces of warm-blooded animals, with its distribution extending across surface waters, sediments, agricultural land, and groundwater (Amirat et al., 2012; Li et al., 2021). In developing countries, the direct discharge of untreated wastewater into surface water bodies further exacerbates this problem because pollutant ion concentrations often far exceed safe thresholds and may compromise the suitability of groundwater for consumption and irrigation (Abd-Elhamid et al., 2021; Kuroda et al., 2012).

The high total coliform concentrations in the Aur River were influenced by distinct pollution characteristics in each river segment. In the upstream section, direct bathing, washing, and defecation activities in the river, together with the absence of septic tanks in many households, constituted the dominant sources of fecal contamination (Anggara et al., 2020; Cho et al., 2018). In the middle section, poorly maintained septic tanks may overflow during the rainy season, allowing fecal pollutants to enter the river (Li et al., 2021; Paruch et al., 2019). In the downstream section, activities associated with traditional markets, including the direct disposal of meat, fish, and vegetable waste into the river, as well as the use of public toilets without septic tanks, contributed substantially to the coliform load. These conditions were further aggravated by inadequate hygiene practices in the market environment, increasing the risk of cross-contamination (Fernández et al., 2022; Michaels et al., 2004).

Analysis of Dominant Factors Contributing to Aur River Pollution

The dominant parameters contributing to water pollution in the Aur River were BOD, COD, DO, oil and grease, detergent, ammonia, and *Escherichia coli*. Measurements taken at 15 sampling points across three stations showed that several parameters exceeded the applicable water quality standards. Therefore, multiple linear regression analysis was conducted to identify the dominant factors influencing the water quality of the Aur River.

Table 2. Concentrations of dominant pollutant parameters in the Aur River

Station	Parameter	T1	T2	T3	T4	T5
1	BOD	36*	34*	36*	35*	34*
1	COD	145*	141*	143*	159*	160*
1	DO	0.75*	0.83*	0.75*	0.74*	0.70*
1	Oil and grease	0.7*	0.7*	0.6*	0.7*	0.7*
1	Detergent	0.220*	0.198*	0.222*	0.221*	0.223*
1	Ammonia	7.950*	8.012*	7.962*	7.990*	7.948*
1	Total coliform	5.4×10^{6}*	5.1×10^{6}*	5.2×10^{6}*	5.3×10^{6}*	5.2×10^{6}*
2	BOD	18*	17*	17*	19*	18*
2	COD	167*	165*	168*	160*	158*
2	DO	0.84*	0.89*	0.78*	0.91*	0.82*
2	Oil and grease	0.6*	0.6*	0.5*	0.5*	0.6*
2	Detergent	0.272*	0.269*	0.271*	0.252*	0.268*
2	Ammonia	6.987*	7.231*	7.002*	7.052*	7.128*
2	Total coliform	1.1×10^{4}*	1.1×10^{4}*	1.2×10^{4}*	1.1×10^{4}*	1.2×10^{4}*
3	BOD	37*	34*	35*	36*	37*
3	COD	151*	147*	153*	163*	163*
3	DO	0.76*	0.75*	0.76*	0.76*	0.79*
3	Oil and grease	0.6*	0.7*	0.6*	0.7*	0.7*
3	Detergent	0.229*	0.227*	0.229*	0.226*	0.225*

Station	Parameter	T1	T2	T3	T4	T5
3	Ammonia	7.894*	7.648*	7.362*	7.889*	7.836*
3	Total coliform	$9.2 \times 10^{6*}$	$9.1 \times 10^{6*}$	$9.2 \times 10^{6*}$	$9.4 \times 10^{6*}$	$9.3 \times 10^{6*}$

Oil and Grease Concentration

Multiple linear regression analysis

Multiple linear regression analysis was performed to determine the effects of length of residence, number of family members, volume, number of occupants, building type, building condition, bathroom ownership, septic tank ownership, knowledge, participation, and community perception on oil and grease concentrations. The results of the multiple linear regression analysis are presented in Table 3.

Table 3. Multiple linear regression analysis of oil and grease concentration

Step	Variable	B	SE	Standardized Coefficient (Beta)	t	P value
1	Constant	0.743	0.062	—	11.958	0.000
1	Length of residence	-0.006	0.000	-0.947	-18.429	0.000
1	Number of family members	0.002	0.006	0.021	0.329	0.743
1	Volume	-3.918E-5	0.000	-0.019	-0.343	0.732
1	Number of occupants	0.000	0.004	-0.007	-0.096	0.923
1	Building type	0.119	0.011	0.579	11.047	0.000
1	Building condition	0.007	0.009	0.036	0.774	0.441
1	Bathroom ownership	-0.185	0.024	-0.455	-7.582	0.000
1	Septic tank ownership	0.028	0.019	0.070	1.540	0.127
1	Knowledge	0.003	0.010	0.012	0.257	0.798
1	Participation	0.002	0.009	0.010	0.217	0.829
1	Community perception	-0.015	0.010	-0.076	-1.544	0.126
2	Constant	0.740	0.049	—	15.223	0.000
2	Length of residence	-0.006	0.000	-0.948	-18.615	0.000
2	Number of family members	0.002	0.005	0.018	0.329	0.743
2	Volume	-4.019E-5	0.000	-0.020	-0.356	0.723
2	Building type	0.119	0.011	0.579	11.134	0.000
2	Building condition	0.007	0.009	0.036	0.789	0.432
2	Bathroom ownership	-0.183	0.019	-0.451	-9.618	0.000
2	Septic tank ownership	0.029	0.018	0.070	1.555	0.123
2	Knowledge	0.003	0.010	0.012	0.266	0.791
2	Participation	0.002	0.009	0.010	0.225	0.822
2	Community perception	-0.015	0.010	-0.075	-1.554	0.124
3	Constant	0.742	0.047	—	15.864	0.000
3	Length of residence	-0.006	0.000	-0.948	-18.740	0.000
3	Number of family members	0.001	0.005	0.015	0.288	0.774
3	Volume	-3.465E-5	0.000	-0.017	-0.316	0.753
3	Building type	0.119	0.011	0.579	11.207	0.000
3	Building condition	0.007	0.009	0.036	0.786	0.434
3	Bathroom ownership	-0.184	0.019	-0.452	-9.733	0.000
3	Septic tank ownership	0.029	0.018	0.071	1.574	0.119
3	Knowledge	0.003	0.010	0.013	0.275	0.784
3	Community perception	-0.014	0.009	-0.073	-1.547	0.125

Step	Variable	B	SE	Standardized Coefficient (Beta)	t	P value
4	Constant	0.745	0.046	—	16.289	0.000
4	Length of residence	-0.006	0.000	-0.949	-18.839	0.000
4	Number of family members	0.001	0.005	0.016	0.293	0.770
4	Volume	-3.351E-5	0.000	-0.016	-0.307	0.759
4	Building type	0.119	0.011	0.579	11.264	0.000
4	Building condition	0.007	0.009	0.036	0.792	0.430
4	Bathroom ownership	-0.183	0.019	-0.451	-9.788	0.000
4	Septic tank ownership	0.028	0.018	0.068	1.558	0.123
4	Community perception	-0.014	0.009	-0.069	-1.543	0.126
5	Constant	0.748	0.044	—	16.817	0.000
5	Length of residence	-0.006	0.000	-0.948	-18.953	0.000
5	Volume	-1.776E-5	0.000	-0.009	-0.188	0.851
5	Building type	0.119	0.010	0.583	11.682	0.000
5	Building condition	0.007	0.009	0.033	0.751	0.454
5	Bathroom ownership	-0.183	0.019	-0.452	-9.851	0.000
5	Septic tank ownership	0.028	0.018	0.068	1.559	0.122
5	Community perception	-0.014	0.009	-0.071	-1.595	0.114
6	Constant	0.745	0.042	—	17.812	0.000
6	Length of residence	-0.006	0.000	-0.948	-19.112	0.000
6	Building type	0.120	0.010	0.583	11.781	0.000
6	Building condition	0.007	0.009	0.034	0.775	0.440
6	Bathroom ownership	-0.184	0.018	-0.454	-10.424	0.000
6	Septic tank ownership	0.028	0.018	0.069	1.587	0.116
6	Community perception	-0.014	0.009	-0.069	-1.594	0.114
7	Constant	0.753	0.040	—	18.635	0.000
7	Length of residence	-0.006	0.000	-0.953	-19.409	0.000
7	Building type	0.121	0.010	0.589	12.044	0.000
7	Bathroom ownership	-0.184	0.018	-0.454	-10.441	0.000
7	Septic tank ownership	0.029	0.018	0.070	1.633	0.106
7	Community perception	-0.014	0.009	-0.071	-1.648	0.103
8	Constant	0.777	0.038	—	20.507	0.000
8	Length of residence	-0.006	0.000	-0.953	-19.229	0.000
8	Building type	0.122	0.010	0.595	12.088	0.000
8	Bathroom ownership	-0.183	0.018	-0.450	-10.268	0.000
8	Community perception	-0.014	0.009	-0.068	-1.566	0.121
9	Constant	0.763	0.037	—	20.575	0.000
9	Length of residence	-0.006	0.000	-0.957	-19.194	0.000
9	Building type	0.120	0.010	0.587	11.903	0.000
9	Bathroom ownership	-0.184	0.018	-0.452	-10.258	0.000

Based on the multiple linear regression analysis, the final regression equation was: $Y = 0.763 - 0.006$ (length of residence) $+ 0.120$ (building type) $- 0.184$ (bathroom ownership) $+ \varepsilon$. This equation indicates that, among the social variables retained in the final model, building type was the dominant factor influencing oil and grease concentrations in the Aur River, as shown by its positive coefficient. The constant value of 0.763 suggests that when all independent variables remain constant, the predicted oil and grease concentration in the water body is 0.763. The positive coefficient for building type indicates that higher building-type categories, which in the context of Kelurahan 9–10 Ulu are associated with stilt houses along the riverbank without structured wastewater disposal systems, contributed to increased oil and grease concentrations in the river. Conversely, length of residence and bathroom ownership showed negative coefficients, suggesting that longer residence duration and the availability of private bathroom facilities were associated with lower oil and grease concentrations in the Aur River.

F-test

The F-test was used to determine whether the independent variables simultaneously affected the dependent variable. The results are shown in Table 4.

Table 4. F-test results for oil and grease concentration

Model	Sum of Squares	df	Mean Square	F	P value
Regression	0.761	3	0.254	144.004	0.000
Residual	0.169	96	0.002		
Total	0.930	99			

The F-test results showed a significance value of 0.000, or $p < 0.05$, indicating that the independent variables—length of residence, building type, and bathroom ownership—simultaneously had a significant effect on oil and grease concentration.

t-test

The t-test was conducted to examine the partial effects of each independent variable on oil and grease concentration.

Table 5. t-test results for oil and grease concentration

Variable	t	P value	Conclusion
Constant	11.958	0.000	-
Length of residence	-18.429	0.000	Significant effect
Number of family members	0.329	0.743	No significant effect
Volume	-0.343	0.732	No significant effect
Number of occupants	-0.096	0.923	No significant effect
Building type	11.047	0.000	Significant effect
Building condition	0.774	0.441	No significant effect
Bathroom ownership	-7.582	0.000	Significant effect
Septic tank ownership	1.540	0.127	No significant effect
Knowledge	0.257	0.798	No significant effect
Participation	0.217	0.829	No significant effect
Community perception	-1.544	0.126	No significant effect

The results indicate that length of residence, building type, and bathroom ownership significantly influenced oil and grease concentration. In contrast, number of family members, volume, number of occupants, building condition, septic tank ownership, knowledge, participation, and community perception did not show significant effects.

Coefficient of Determination

The coefficient of determination is presented in Table 6.

Table 6. Coefficient of determination for oil and grease concentration

R	R Square	Adjusted R Square	SE
0.905	0.818	0.813	0.21236

The coefficient of determination showed an R^2 value of 0.818, indicating that the independent variables—length of residence, building type, and bathroom ownership—explained 81.8% of the variation in oil and grease concentration. The remaining 18.2% was explained by other variables not included in this study.

Detergent Concentration

F-test

The F-test was used to determine whether the independent variables simultaneously affected detergent concentration. The results are presented in Table 7.

Table 7. F-test results for detergent concentration

Model	Sum of Squares	df	Mean Square	F	P value
Regression	0.044	6	0.007	116.044	0.000
Residual	0.006	93	0.000		
Total	0.050	99			

The F-test yielded a significance value of 0.000, or $p < 0.05$, indicating that the independent variables—length of residence, number of family members, volume, number of occupants, building type, and knowledge—simultaneously had a significant effect on detergent concentration.

t-test

The t-test was conducted to examine the partial effects of the independent variables on detergent concentration.

Table 8. t-test results for detergent concentration

Variable	t	P value	Conclusion
Constant	24.201	0.000	-
Length of residence	11.124	0.000	Significant effect
Number of family members	15.837	0.000	Significant effect
Volume	-11.476	0.000	Significant effect
Number of occupants	-10.922	0.000	Significant effect
Building type	-9.447	0.000	Significant effect
Building condition	0.748	0.456	No significant effect
Bathroom ownership	-0.569	0.571	No significant effect
Septic tank ownership	-0.506	0.614	No significant effect
Knowledge	-14.838	0.000	Significant effect
Participation	-0.581	0.563	No significant effect
Community perception	0.828	0.410	No significant effect

The results show that length of residence, number of family members, volume, number of occupants, building type, and knowledge significantly influenced detergent concentration. In contrast, building condition, bathroom ownership, septic tank ownership, participation, and community perception did not have significant effects.

Coefficient of Determination

The coefficient of determination is shown in Table 9.

Table 9. Coefficient of determination for detergent concentration

R	R Square	Adjusted R Square	SE
0.939	0.882	0.875	0.00797

The R^2 value of 0.882 indicates that the independent variables—length of residence, number of family members, volume, number of occupants, building type, and knowledge—explained 88.2% of the variation in detergent concentration. The remaining 11.8% was explained by other variables not examined in this study.

Ammonia Concentration

F-test

The F-test was used to determine whether the independent variables simultaneously affected ammonia concentration. The results are shown in Table 10.

Table 10. F-test results for ammonia concentration

Model	Sum of Squares	df	Mean Square	F	P value
Regression	3.173	6	0.529	85.174	0.000
Residual	0.577	93	0.006		
Total	3.750	93			

The F-test showed a significance value of 0.000, or $p < 0.05$, indicating that length of residence, number of family members, number of occupants, bathroom ownership, septic tank ownership, and knowledge simultaneously affected ammonia concentration.

t-test

The t-test was used to examine the partial effects of each independent variable on ammonia concentration.

Table 11. t-test results for ammonia concentration

Variable	t	P value	Conclusion
Constant	53.426	0.000	—
Length of residence	-10.059	0.000	Significant effect
Number of family members	-7.356	0.000	Significant effect
Volume	-0.426	0.671	No significant effect
Number of occupants	8.432	0.000	Significant effect
Building type	0.031	0.976	No significant effect
Building condition	0.250	0.803	No significant effect
Bathroom ownership	8.009	0.000	Significant effect
Septic tank ownership	11.549	0.000	Significant effect
Knowledge	13.589	0.000	Significant effect

Variable	t	P value	Conclusion
Participation	-1.265	0.209	No significant effect
Community perception	-0.244	0.808	No significant effect

The results indicate that length of residence, number of family members, number of occupants, bathroom ownership, septic tank ownership, and knowledge significantly influenced ammonia concentration. By contrast, volume, building type, building condition, participation, and community perception did not show significant effects.

Coefficient of Determination
The coefficient of determination is presented in Table 12.

Table 12. Coefficient of determination for ammonia concentration

R	R Square	Adjusted R Square	SE
0.920	0.846	0.836	0.07879

The R^2 value of 0.846 indicates that length of residence, number of family members, number of occupants, bathroom ownership, septic tank ownership, and knowledge explained 84.6% of the variation in ammonia concentration. The remaining 15.4% was explained by other variables not included in this study.

Total Coliform Concentration
F-test

The F-test was used to determine whether the independent variables simultaneously affected total coliform concentration. The results are presented in Table 13.

Table 13. F-test results for total coliform concentration

Model	Sum of Squares	df	Mean Square	F	P value
Regression	76,906,783.889	4	19,226,695.972	101.041	0.000
Residual	18,077,152.644	95	190,285.817		
Total	94,983,936.534	99			

The F-test showed a significance value of 0.000, or $p < 0.05$, indicating that the independent variables—number of occupants, bathroom ownership, septic tank ownership, and community perception—simultaneously had a significant effect on total coliform concentration.

t-test

The t-test was conducted to examine the partial effects of each independent variable on total coliform concentration.

Table 14. t-test results for total coliform concentration

Variable	t	P value	Conclusion
Constant	19.775	0.000	-
Length of residence	-1.177	0.242	No significant effect
Number of family members	0.267	0.790	No significant effect
Volume	-0.498	0.620	No significant effect
Number of occupants	-9.889	0.000	Significant effect

Variable	t	P value	Conclusion
Building type	0.322	0.748	No significant effect
Building condition	0.748	0.457	No significant effect
Bathroom ownership	-10.465	0.000	Significant effect
Septic tank ownership	10.559	0.000	Significant effect
Knowledge	1.492	0.139	No significant effect
Participation	1.002	0.319	No significant effect
Community perception	-9.117	0.000	Significant effect

The results indicate that number of occupants, bathroom ownership, septic tank ownership, and community perception significantly influenced total coliform concentration. In contrast, length of residence, number of family members, volume, building type, building condition, knowledge, and participation did not have significant effects.

Coefficient of Determination

The coefficient of determination is shown in Table 15.

Table 15. Coefficient of determination for total coliform concentration

R	R Square	Adjusted R Square	SE
0.900	0.810	0.802	436.21763

The R^2 value of 0.810 indicates that number of occupants, bathroom ownership, septic tank ownership, and community perception explained 81.0% of the variation in total coliform concentration. The remaining 19.0% was explained by other variables not examined in this study.

Constructed Wetland Performance Model

Daily observations were conducted for seven days, beginning on the first day after wastewater application. The results are presented in Table 16.

Table 16. Leaf diameter and stem/petiole diameter during horizontal CW operation

Vegetation type	Parameter	Day	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Mean
Water spinach	Leaf diameter	Day 1	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Water spinach	Leaf diameter	Day 2	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Water spinach	Leaf diameter	Day 3	0.4	0.4	0.4	0.4	0.3	0.3	0.4
Water spinach	Leaf diameter	Day 4	0.4	0.5	0.4	0.6	0.4	0.5	0.5
Water spinach	Leaf diameter	Day 5	0.8	0.7	0.7	0.8	0.6	0.7	0.7
Water spinach	Leaf diameter	Day 6	0.9	0.9	1.0	1.0	0.8	0.9	0.9
Water spinach	Leaf diameter	Day 7	1.1	1.1	1.2	1.2	1.0	1.0	1.1
Water spinach	Stem diameter	Day 1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Water spinach	Stem diameter	Day 2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Water spinach	Stem diameter	Day 3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Water spinach	Stem diameter	Day 4	0.2	0.3	0.2	0.2	0.2	0.3	0.2
Water spinach	Stem diameter	Day 5	0.4	0.4	0.3	0.3	0.3	0.3	0.3
Water spinach	Stem diameter	Day 6	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Water spinach	Stem diameter	Day 7	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Water hyacinth	Leaf diameter	Day 1	4.0	3.0	3.0	3.0	3.0	3.0	3.2

Vegetation type	Parameter	Day	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Mean
Water hyacinth	Leaf diameter	Day 2	4.0	4.0	4.0	4.0	3.0	3.0	3.7
Water hyacinth	Leaf diameter	Day 3	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Water hyacinth	Leaf diameter	Day 4	5.0	4.5	5.0	5.0	4.0	4.0	4.6
Water hyacinth	Leaf diameter	Day 5	5.2	5.0	5.5	5.7	5.0	5.0	5.2
Water hyacinth	Leaf diameter	Day 6	5.4	5.5	5.9	6.0	5.4	5.6	5.6
Water hyacinth	Leaf diameter	Day 7	6.2	6.0	6.5	6.6	6.0	6.0	6.2
Water hyacinth	Petiole diameter	Day 1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water hyacinth	Petiole diameter	Day 2	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water hyacinth	Petiole diameter	Day 3	1.1	1.1	1.1	1.1	1.0	1.0	1.1
Water hyacinth	Petiole diameter	Day 4	1.3	1.3	1.2	1.2	1.1	1.2	1.2
Water hyacinth	Petiole diameter	Day 5	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Water hyacinth	Petiole diameter	Day 6	1.4	1.4	1.3	1.4	1.3	1.4	1.4
Water hyacinth	Petiole diameter	Day 7	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Water lily	Leaf diameter	Day 1	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Water lily	Leaf diameter	Day 2	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Water lily	Leaf diameter	Day 3	2.2	2.1	2.0	2.2	2.0	2.1	2.1
Water lily	Leaf diameter	Day 4	2.5	2.4	2.6	2.6	2.4	2.4	2.5
Water lily	Leaf diameter	Day 5	3.1	3.2	3.5	3.5	3.0	3.0	3.2
Water lily	Leaf diameter	Day 6	3.5	3.6	3.9	4.0	3.6	3.5	3.7
Water lily	Leaf diameter	Day 7	4.0	4.0	4.2	4.5	4.1	4.0	4.1
Water lily	Petiole diameter	Day 1	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Water lily	Petiole diameter	Day 2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Water lily	Petiole diameter	Day 3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Water lily	Petiole diameter	Day 4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Water lily	Petiole diameter	Day 5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Water lily	Petiole diameter	Day 6	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Water lily	Petiole diameter	Day 7	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Daily observations were conducted for seven days, beginning on the first day after wastewater application. The observed variables included leaf diameter, stem diameter, and petiole diameter in the three plant species.

Effect of CW Intervention on Wastewater Quality

The independent t-test results showed $p = 0.000$, or $p < 0.05$, for all water quality parameters, including BOD, COD, DO, oil and grease, detergent, ammonia, and total coliform, across all combinations of CW type, namely horizontal and vertical systems, and all three plant species, namely water spinach, water hyacinth, and water lily. These findings indicate that the constructed wetland system consistently functioned as an effective nature-based wastewater treatment solution for riverbank slum settlements, regardless of flow configuration or vegetation type. The practical implication of this consistent response is important: the absence of meaningful differences in treatment effectiveness between horizontal and vertical systems suggests that configuration selection may be based primarily on site-specific technical considerations, such as land availability, construction feasibility, and cost, rather than on differences in treatment performance. This design-related information has not been explicitly addressed in previous CW studies, which have generally examined only one configuration without comparing both systems under identical field conditions (Hassan et al., 2021; Bakhshoodeh et al., 2020).

The substantial reductions in BOD and COD—BOD from 35.17 mg/L to 3.00 mg/L and COD from 148.83 mg/L to 20.33 mg/L in the water spinach treatment, with BOD reaching 2.00 mg/L and COD reaching 6.00 mg/L in the water hyacinth and water lily treatments—reflect the effectiveness of organic matter degradation through microbial activity in the rhizosphere. Aquatic plants play a crucial role in transferring oxygen to the root zone, thereby supporting simultaneous aerobic and anaerobic degradation processes (Vymazal, 2014). The superior performance of water hyacinth and water lily compared with water spinach may be related to their larger root biomass and greater oxygen transfer capacity, which create broader redox gradients within the media. Such conditions have been shown to support the more efficient degradation of complex organic matter (Zhu et al., 2018). Consistent with the reductions in BOD and COD, DO concentrations increased significantly from an average of 0.75 mg/L to 5.33–6.67 mg/L, with the highest increases observed in the water hyacinth and water lily treatments. This increase in DO was not merely an indicator of improved water quality, but also evidence that the CW system restored the aeration capacity of water that had previously been in an anoxic condition due to high organic loading. The decrease in ammonia concentration from 7.97 mg/L to 0.43–0.47 mg/L further supports this finding, as nitrification by *Nitrosomonas* and *Nitrobacter* in the root zone can occur optimally only under sufficient DO conditions (Kadlec & Wallace, 2009). The reductions in oil and grease and detergent concentrations across all treatment groups indicate that physical filtration by the media and adsorption by the root system, combined with surfactant biodegradation by microbial communities within the CW, were effective even for pollutants that are often difficult to remove using simple treatment systems.

Total coliform also decreased significantly, from an average of 526.67 MPN/100 mL to 20.80–21.80 MPN/100 mL ($p = 0.000$). However, the non-uniform weekly reduction pattern should be interpreted critically. The final coliform concentrations, which remained above the required wastewater quality standard, indicate that CW systems without an additional disinfection stage have structural limitations in completely eliminating pathogens. Several mechanisms may explain this limitation. First, an insufficient hydraulic retention time (HRT) may have allowed some microorganisms to pass through the system before natural die-off occurred through nutrient competition and predation (Vymazal, 2014). Second, the very high initial microbial load reflected the actual condition of direct fecal discharge into the Aur River, which may have exceeded the biological removal capacity of the tested CW system. Third, hydraulic disturbances may have caused the resuspension of microorganisms previously adsorbed onto the media (Kadlec & Wallace, 2009). This finding is important because it differs from several previous CW studies conducted under lower initial coliform loads and more controlled laboratory conditions (Vymazal, 2014; Bedu-Addo et al., 2023). Practically, these results indicate that, in riverbank slum settlements with extreme fecal contamination such as Kelurahan 9–10 Ulu, CW systems should be complemented with post-treatment disinfection units, such as low-dose chlorination or ultraviolet irradiation, to ensure that the effluent meets microbiological safety standards before being discharged into receiving water bodies.

CONCLUSION

The water quality of the Aur River exceeded the Class II water quality standards across all assessed parameters, with BOD, COD, DO, oil and grease, detergent, ammonia, *Escherichia coli*, and total coliform identified as the dominant pollutants exceeding the established threshold limits. Regression analyses, which satisfied the classical assumption tests with no indication of multicollinearity, heteroscedasticity, or deviation from normality, showed that socio-environmental variables—including length of residence, number of occupants, building type and ownership status, septic tank ownership, and community knowledge and perception—significantly influenced pollutant concentrations. These variables explained 81.0–88.2% of the variation in oil and grease, detergent, ammonia, and total coliform concentrations. In addition, the incidence of diarrhea among communities living near the river was significantly associated with building type and building condition. However, community perception emerged as the most dominant predictor (OR = 9.470), indicating that behavior-change interventions and improved environmental awareness should be prioritized in pollution control efforts and public health protection strategies.

RECOMMENDATION

Based on the findings of this study, domestic wastewater management and water quality monitoring in the Aur River should be improved through the provision of adequate sanitation facilities, community education, and the implementation of Constructed Wetlands technology as an environmentally friendly alternative for wastewater treatment. Future studies are recommended to examine additional factors influencing river pollution and diarrhea incidence, such as industrial activities, hydrological conditions, and community socioeconomic characteristics, using broader spatial coverage and longer observation periods.

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