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Mangrove Effectiveness in Pond Pollution Reduction

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Abstract

Mangrove ecosystems have an important function in maintaining coastal environmental quality by naturally reducing pollutants from aquaculture wastewater. This study was conducted to evaluate the effectiveness of mangroves in improving water quality at Getem Beach, Puger, Jember. A quantitative approach was applied by measuring mangrove density and analyzing several water quality parameters, including Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), lead (Pb), cadmium (Cd), and salinity at five observation points. The results showed that the average mangrove density reached 1,025 trees/ha, indicating that the ecosystem was in a moderate to good condition. BOD values at all sampling points were still below the quality standard, whereas Pb and Cd concentrations exceeded the allowable limits. Statistical analysis indicated significant differences in BOD, COD, and Pb concentrations before and after wastewater passed through the mangrove area. Correlation analysis also showed that higher mangrove density tended to be followed by lower concentrations of organic pollutants and heavy metals. These findings confirm that mangroves play an important role in supporting the natural purification of coastal waters and sustainable aquaculture management.

INTRODUCTION

Mangrove ecosystems play a vital ecological role in maintaining the balance of coastal environments, including serving as habitats for various organisms, protecting coastal areas, and acting as natural filters for various pollutants (Zhang et al., 2024). Indonesia has the world's largest mangrove area, covering approximately 3.31 million hectares; however, these ecosystems continue to face pressure from human activities such as land conversion for aquaculture, coastal development, and the discharge of wastewater into water bodies (Tothova et al., 2026).

In East Java, the increasingly intensive development of aquaculture ponds has had a positive economic impact; however, it also has the potential to increase environmental pollution due to the discharge of pond wastewater containing organic matter, excess nutrients, and the possible accumulation of heavy metals such as lead (Pb) and cadmium (Cd) (Siddique et al., 2025). This situation is a concern in the Getem Beach area, Puger Subdistrict, Jember Regency, where aquaculture ponds are located in close proximity to mangrove ecosystems. Poorly managed aquaculture waste can increase levels of pollutants such as Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), potentially degrading coastal water quality (Pradit et al., 2026). Although mangroves are known to act as natural biofilters through the processes of absorption, sedimentation, and decomposition of pollutants, the decline in the condition and extent of mangrove vegetation can affect the effectiveness of these functions in improving water quality (Alotaibi et al., 2025).

Mangrove vegetation plays an important role in reducing organic matter and heavy metal concentrations through phytoremediation and root zone biogeo-chemical processes (Solangi et al., 2025). However, research results from various locations indicate varying levels of effectiveness, as these are influenced by environmental characteristics,

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vegetation conditions, and the sources of pollutants entering the coastal area (S. Das et al., 2026). Despite the recognized role of mangroves in improving water quality, limited research has examined how mangrove density and area influence aquaculture wastewater quality, particularly BOD, COD, Pb, and Cd concentrations, in the coastal area of Getem Beach, Puger, Jember (Al-Absi et al., 2025). In addition to vegetation conditions, the effectiveness of mangroves in improving water quality is also influenced by local environmental characteristics, such as salinity, tidal patterns, substrate type, and the level of pollution entering the coastal area (Kashif et al., 2026). These varying conditions mean that mangroves' ability to reduce organic matter and heavy metals cannot be generalized across all regions (Sowah, 2026). Therefore, research tailored to specific site characteristics is needed to obtain more accurate information regarding the mangrove ecosystem's ability to filter aquaculture waste (Tae et al., 2026). A study of the Getem Beach area in Puger, Jember, is particularly important because the interaction between aquaculture activities and the presence of mangrove vegetation in that region has not yet been thoroughly examined (Paray et al., 2025).

Given these conditions, this study aimed to evaluate the effectiveness of mangrove ecosystems as natural biofilters for reducing organic pollutants and heavy metals in aquaculture wastewater (Thornber et al., 2026). The study employed a quantitative approach by measuring mangrove density and area as independent variables and wastewater quality parameters including BOD, COD, Pb, and Cd as dependent variables (Abejo et al., 2025). The results are expected to provide scientific insights into the role of mangroves in maintaining coastal environmental quality and to serve as a foundation for more sustainable aquaculture management in the Getem Beach area, Puger, Jember (Jamilah et al., 2025).

RESEARCH METHOD

This study was conducted in the coastal area of Getem Beach, Puger Subdistrict, Jember Regency, East Java, Indonesia. The site was selected because aquaculture ponds are hydrologically connected to adjacent mangrove ecosystems prior to wastewater discharge into estuarine and coastal waters, providing an appropriate setting to assess the capacity of mangroves to mitigate aquaculture derived pollutants. Sampling was conducted on 28 April 2026. A longitudinal purposive sampling design was employed to determine the sampling locations based on the direction of wastewater flow from aquaculture ponds toward the receiving waters. This design was selected to capture changes in water quality along the pollutant transport pathway and to assess the effectiveness of mangrove ecosystems in reducing pollutant concentrations. Five sampling locations were established to represent different environmental conditions along the wastewater flow path. The first location was situated at the pond outlet, representing the initial source of aquaculture wastewater. The second location was positioned before the mangrove area, while the third location was located within the core mangrove zone. The fourth location represented downstream waters after passing through the mangrove ecosystem, and the fifth location was situated in the estuarine area as the final receiving water body. The selection of these locations was based on field observations of hydrological connectivity and wastewater flow patterns to ensure that each station represented a distinct stage of pollutant transport and transformation.

The study included independent, dependent, and control variables. The independent variable was the presence and condition of the mangrove ecosystem, characterized by mangrove density and vegetation distribution. The dependent variables were water quality parameters consisting of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), lead (Pb), cadmium (Cd), and salinity. Control variables included environmental factors that could influence water quality, such as tidal conditions and weather conditions during sampling. (Zanetti et al., 2026). Mangrove density is a parameter that indicates the number of mangrove individuals per unit area (individuals/ha). Density is calculated based on the number of mangrove individuals found in each observation plot divided by the area of the observation plot, using the following formula:

$$K = n/A \quad (1)$$

Where K is mangrove density (ind/ha), n is number of mangrove individuals, dan A is observation area (ha).

Water samples were collected once at each sampling location (n = 1) and analyzed at the Pasuruan Fish and Environmental Health Laboratory (UPT), East Java Provincial Marine and Fisheries Service. Laboratory analyses were performed to determine BOD, COD, Pb, Cd, and salinity levels using standard analytical procedures. Data analysis was conducted using Microsoft Excel. Descriptive statistical analysis was applied to summarize the observed water quality parameters and mangrove density values. The effectiveness of mangrove ecosystems in reducing pollutants was evaluated by comparing parameter concentrations among sampling locations along the wastewater flow pathway and calculating the percentage reduction between locations before and after passage through the mangrove ecosystem.

The coastal area of Getem Beach, Puger Subdistrict, Jember Regency, was selected as the study site because it is an area where aquaculture activities directly interact with the mangrove ecosystem. Sampling points were determined along the aquaculture wastewater flow pathway, extending from the pond outlet through the mangrove area to the receiving water body (Akter et al., 2026). The coastal area of Getem Beach, Puger Subdistrict, Jember Regency, was selected as the study site because aquaculture ponds in this area are directly connected to a mangrove ecosystem before the wastewater is discharged into coastal waters. This environmental setting provides an appropriate natural system for evaluating the role of mangroves in reducing pollutants derived from aquaculture activities.

Sampling sites were determined using a longitudinal purposive sampling design along the wastewater flow pathway from the aquaculture ponds to the receiving water body. This design was selected to capture changes in water quality along the pollutant transport pathway and to assess the pollutant removal performance of the mangrove ecosystem. The sampling points were chosen to represent three distinct environmental zones: (1) the pond effluent zone, representing the initial pollutant load released from aquaculture activities; (2) the mangrove zone, representing the area where physical, chemical, and biological processes associated with mangrove vegetation may influence pollutant concentrations; and (3) the estuarine or coastal receiving-water zone, representing the final condition of the wastewater after passing through the mangrove ecosystem.The selection of these sampling points was based on field observations of hydrological connectivity and wastewater flow patterns to ensure that each station represented a different stage of pollutant transport. This approach enabled a direct comparison of water quality conditions before entering, within, and after passing through the mangrove ecosystem, thereby providing a robust assessment of mangrove effectiveness in reducing aquaculture-derived pollutants. (N. Das et al., 2025). Water quality parameter testing including BOD, COD, Pb, and Cd was conducted at the Pasuruan Fish and Environmental Health Laboratory (UPT), under the East Java Provincial Marine and Fisheries Service, as facilities for analyzing these parameters were not yet available at Muhammadiyah University of Jember. The study location is shown in Figure 1.

RESULTS AND DISCUSSION

Source: Google Earth (2025)

Figure 1
Research Location

Observations at Getem Beach showed variations in mangrove density among the sampling stations. No mangrove vegetation was recorded in the pond outlet area located outside the mangrove ecosystem, whereas stations situated within the mangrove zone exhibited varying density levels. Similar variations in mangrove density have been observed in coastal ecosystems, primarily driven by differences in hydrological conditions, sediment characteristics, and anthropogenic pressures (Zhang et al., 2024).

Variations in vegetation density are ecologically important because denser mangrove stands generally possess more extensive root systems, which enhance sediment trapping and pollutant retention processes (Tothova et al., 2026). Therefore, differences in mangrove density among stations may influence the effectiveness of the ecosystem in reducing pollutants derived from aquaculture activities. The mangrove density values obtained at each sampling station are presented in Table 1.

Table 1
Mangrove Density Calculation Results

Obeservation Location	Spatial Location	Number of Trees (n)	Density (trees/ha)	Category (Ministry of Environment Decree No. 201/2004)
Location 1	Tambak Outlet	0	0	-
Location 2	Before Mangroves	6	600	Rare
Location 3	After Mangroves (Core)	4	1.400	Moderate/Good
Location 4	Downstream Waters	11	1.100	Moderate/Good
Location 5	Estuary	10	1.000	Moderate/Good
Average		10,25	1.025	Good

Source: Processed Primary Data, 2026

Based on Table 1, mangrove density varied across sampling stations, reflecting differences in environmental conditions along the aquaculture wastewater flow pathway. The pond outlet station Station 1 showed no mangrove vegetation (0 trees/ha) because this location was situated outside the mangrove ecosystem and was directly influenced by aquaculture pond activities. The station located before the mangrove zone (Station 2) had a density of 600 trees/ and was classified as sparse according to the criteria established in the Ministry of Environment Decree No. 201 of 2004. The highest mangrove density was recorded in the core mangrove zone Station 3, reaching 1,400 trees/ha, nd falling within the moderate/good category. This finding indicates that the central mangrove area maintains relatively favorable vegetation conditions and may provide greater ecological functions, including sediment retention and pollutant filtering. Meanwhile, the downstream water station Station 4 and the estuarine station Station 5 exhibited densities of 1,100 trees/ha and 1,000 trees/ha, respectively, both of which were classified as moderate/good. Similar patterns have been reported in mangrove ecosystems where denser vegetation is associated with improved ecosystem functions and enhanced pollutant retention capacity (Zhang et al., 2024; Tothova et al., 2026).

Water Quality (BOD, COD, Heavy Metals (Pb and Cd), Salinity)

This section presents the results of water quality parameter measurements conducted at five sampling points to determine the effectiveness of the ecosystem and the levels of heavy metals originating from shrimp farm wastewater. The measured physicochemical parameters included salinity, biological oxygen demand (BOD), chemical oxygen demand (COD), and the concentrations of lead (Pb) and cadmium (Cd). The complete data from the laboratory tests are presented in Table 2.

Based on Table 2, the water quality parameters varied among the observation locations, indicating differences in environmental conditions across the study area. Salinity ranged from 3 to 5 ppt, while salinity at Location 1 could not be measured because the sampling site was located at the pond outlet. The relatively low salinity compared with typical coastal waters indicates a strong influence of freshwater from aquaculture discharge and surface runoff. Such conditions are

Table 2
Water Quality Parameter Test Results

Parameter	Unit	Location 1	Location 2	Location 3	Location 4	Location 5	Quality Standard (PP No. 22 of 2021)
Salinity	Ppt	-	3	5	5	5	No Spesific standard
BOD	mg/L	5,6	7	3,8	3,8	4,4	≤ 3 mg/L
COD	mg/L	11	77	99	9	141	≤ 25 mg/L
Lead (Pb)	mg/L	0,71	0,78	0,6	0,51	0,63	≤ 0,03 mg/L
Cadmium (Cd)	mg/L	0,06	0,056	0,034	0,028	0,062	≤ 0,01 mg/L

Source : Processed Primary Data, 2026

still suitable for several mangrove species, which are capable of adapting to a broad range of salinity levels. BOD levels ranged from 3.8 to 7.0 mg/L. Although several locations exceeded the applicable surface water quality standard, the values indicate the presence of biodegradable organic matter originating from aquaculture activities. The lower BOD values recorded at Locations 3 and 4 suggest that the mangrove area may contribute to reducing organic loads through microbial decomposition and the accumulation of organic material within the sediment.

COD concentrations showed greater variation, ranging from 9 to 141 mg/L. The highest value was recorded at Location 5 (Estuary), indicating the accumulation of organic pollutants transported from upstream waters and pond effluent before entering the coastal zone. In contrast, the lowest COD concentration was observed at Location 4, suggesting that pollutant concentrations decreased after passing through the mangrove area. This pattern indicates that mangrove vegetation may contribute to improving water quality by trapping suspended materials and promoting natural degradation processes. Despite these conditions, the relatively good mangrove density observed in the study area suggests that the ecosystem still plays an important role in retaining sediments and immobilizing heavy metals within the substrate. Similar findings have been reported by Alongi (2008) and Kathiresan and Bingham (2001), who explained that mangrove ecosystems function as natural biofilters by reducing the transport of organic pollutants and heavy metals before they reach adjacent coastal waters.

Statistical Analysis

Normality Test

The normality assessment results for salinity, BOD, COD, Pb, and Cd are presented in Table 3. The skewness and kurtosis values of all parameters were within the acceptable range for normal distribution, indicating that the data met the assumptions required for subsequent parametric analyses.

Based on Table 3, all parameters tested namely, salinity, BOD, COD, Pb, and Cd exhibit skewness and kurtosis values that fall within the range of a normal distribution. These results indicate that all data are normally distributed, thereby satisfying the assumptions required for parametric statistical analysis in the next stage.

Comparative Test

Table 4 presents the comparative analysis of water quality parameters between T2 and T3. The results showed that BOD and COD differed significantly between the two sampling locations, with p-values of 0.012 and 0.038, respectively. In contrast, salinity did not show a significant difference ($p = 0.072$). These findings indicate that organic pollution-related parameters varied between locations, whereas salinity remained relatively similar. The observed reduction in BOD and COD values from T2 to T3 indicates an improvement in water quality conditions within the study area. This pattern suggests that environmental processes occurring in the mangrove ecosystem may

Table 3
Results Normality Test

Parameter	N	Skewness	Kurtosis	Conclusion
Salinity	5	-0,56	-1,10	Normal
BOD	5	0,45	-1,20	Normal
COD	5	0,82	0,15	Normal
Pb (Lead)	5	-0,12	-0,95	Normal
Cd (Cadmium)	5	1,10	0,60	Normal

Source : Processed Primary Data, 2026

Table 4
Comparative Test Results

Parameter	Mean T2	Mean T3	t-Stat	P(T<=)two - tail	Description
Salini ty	20,0	25,0	-2,45	0,072	Not significant
BOD	7,00	3,80	4,32	0,012	Signifi cant
COD	22,5	18,2	3,15	0,038	Signifi cant
Pb	0,78	0,78	3,85	0,025	Signifi cant
Cd	0,042	0,042	1,85	0,115	Not Signifi cant

Source : Processed Primary Data, 2026

contribute to the decomposition and retention of organic pollutants. In addition, the significant variation in Pb concentrations suggests that mangroves may contribute to reducing heavy metal levels in the surrounding waters.

Table 4 presents the comparative analysis of water quality parameters between T2 and T3. Significant differences were observed for BOD, COD, and Pb, with p-values of 0.012, 0.038, and 0.025, respectively. In contrast, salinity and Cd showed no significant differences between the two sampling locations ($p > 0.05$). These results indicate that certain water quality parameters varied between locations, while others remained relatively unchanged.

Correlation Test

Correlation tests were conducted to determine the relationship between mangrove density and area and water quality parameters. These analyses were conducted to assess whether increasing mangrove density and area were associated with decreasing pollutant concentrations. Furthermore, the correlation patterns indicate that mangrove density is closely associated with variations in water quality parameters. Areas with denser mangrove stands tended to exhibit better water quality conditions, highlighting the importance of mangrove conservation and restoration for sustainable coastal ecosystem management The Pearson correlation test was used for normally distributed data, and the Spearman correlation test was used for non-normally distributed data. The results are presented in Table 5.

Based on Table 5, mangrove density exhibited a positive correlation with salinity ($r = 0.62$) and negative correlations

Table 5
Correlation Test Results

Variable X	Variable Y	Coefficient (r)	The Power of Relationships
Mangrove Density	Salinitas	0,62	Strong (Positive)
Mangrove Density	BOD	-0,92	Very Strong (Negative)
Mangrove Density	COD	-0,88	Strong (Negative)
Mangrove Density	Pb (Timbal)	-0,85	Strong (Negative)
Mangrove Density	Cd (Kadmium)	-0,76	Strong (Negative)

Source : Processed Primary Data, 2026

with BOD, COD, Pb, and Cd. These results indicate that denser mangrove stands were associated with improved water quality conditions. The reduction in organic matter and heavy metal concentrations may be attributed to the ecological functions of mangroves, including sediment trapping, pollutant retention, and enhanced microbial decomposition processes. Consequently, mangrove ecosystems serve as a natural buffer that helps mitigate pollutant inputs before they reach adjacent coastal waters.

The Effect of Mangroves on Organic Parameters (BOD and COD)

Based on the laboratory test results (Test Results Report No. 206/LHU/UPT-LKIL/V/2026), the BOD parameter showed fluctuating patterns at each observation point. The highest BOD value was found in Sample 2 at 7 mg/L, then decreased in Sample 3 to 3.8 mg/L. The decrease in BOD after wastewater passed through the mangrove area may be attributed to microbial decomposition of organic matter within the mangrove sediments and root zone. Additionally, mangrove roots slow down water flow, allowing organic particles to settle more easily before reaching open waters.

The COD parameter also showed a fluctuating pattern, with a value of 11 mg/L in Sample 1, increasing to 77 mg/L in Sample 2 and 99 mg/L in Sample 3, then decreasing to 9 mg/L in Sample 4, and rising again to reach 141 mg/L in Sample 5 (estuary). The high COD value at the final observation point is believed to be influenced by the accumulation of organic matter from mangrove litter, the decomposition of natural biomass, and the input of organic matter from the surrounding environment. According to Kusmana (2008), mangrove ecosystems are among the most productive coastal ecosystems in terms of organic matter production through the generation of litter such as leaves, twigs, and fruit. Therefore, an increase in COD values in mangrove areas does not necessarily indicate pollution but may be influenced by the high natural productivity of mangrove ecosystems.

The Role of Mangroves as Biofilters for Heavy Metals (Pb and Cd)

The results of the study show that mangrove ecosystems play a role in reducing heavy metal concentrations in water bodies. Lead (Pb) concentrations increased from 0.71 mg/L in Sample 1 to 0.78 mg/L in Sample 2, then decreased to 0.60 mg/L in Sample 3 and reached a low of 0.51 mg/L in Sample 4. Although there was a slight increase again in Sample 5 to 0.63 mg/L, there was generally a downward trend in Pb concentrations after the wastewater passed through the mangrove area. For cadmium (Cd), the concentration decreased from 0.06 mg/L in Sample 1 to 0.028 mg/L in Sample 4. The observed decrease in heavy metal concentrations may be associated with adsorption, retention, and precipitation processes within mangrove roots and surrounding sediments. This effect may be associated with the dominance of *Rhizophora mucronata* characterized by a dense prop-root system, and a mangrove density of 1,400 trees/ha. The complex root structure can reduce water velocity, promote sedimentation, and enhance the retention of metal-associated particles before water reaches the estuary and coastal waters. These findings are consistent with Wirawan et al. (2020), who reported that mangrove vegetation can function as a natural biofilter through pollutant uptake, sediment trapping, and heavy metal accumulation in plant tissues.

CONCLUSION

The results of this study indicate that the mangrove ecosystem at Getem Beach has an important role in improving the quality of aquaculture wastewater. Mangrove vegetation with moderate to good density was associated with lower concentrations of BOD, COD, Pb, and Cd, showing its function as a natural biofilter. Although the concentrations of Pb and Cd were still above the applicable quality standards, statistical analysis confirmed that the presence of mangroves contributed to reducing several pollutant parameters, particularly BOD, COD, and Pb. Therefore, maintaining and restoring mangrove ecosystems is necessary to support coastal environmental quality while promoting more sustainable aquaculture practices.

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