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Artikel Penelitian

Comparative Assessment of Anaerobic Baffled Reactor (ABR) and Moving Bed Biofilm Reactor (MBBR) Technologies for Domestic-Laundry Wastewater Treatment in Lamongan, Indonesia: Technical, Economic, and Environmental Perspectives

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ABSTRACT

This study evaluates the treatment performance of Moving Bed Biofilm Reactor (MBBR) and Anaerobic Baffled Reactor (ABR) systems in treating domestic laundry wastewater in a tropical environment. Both reactors were operated for 90 days under controlled and efficient operating parameters, with MBBR achieving higher removal efficiencies for biochemical oxygen demand (BOD) and chemical oxygen demand (COD) at 94.6% and 95.2%, respectively, compared to ABR's 92.6% and 91.7%. Nutrient removal was more effective in MBBR, particularly for ammonia (89%) and phosphate (96%). ABR demonstrated potential for biogas production, generating 126 m³/month, suggesting its viability as a sustainable energy source. However, both systems required post-treatment disinfection to reduce pathogenic bacteria to acceptable limits. Economic analysis indicated MBBR's lower operational costs, while ABR offered advantages in energy recovery. This comparative study informs sustainable domestic wastewater management strategies in Lamongan, East Java, Indonesia.

Keyword: Wastewater Treatment, Moving Bed Biofilm Reactor, Anaerobic Baffled Reactor, Domestic Laundry Wastewater, Biogas.

ABSTRAK

Penelitian ini mengevaluasi kinerja pengolahan limbah domestik dari kegiatan pencucian (laundry) menggunakan sistem Moving Bed Biofilm Reactor (MBBR) dan Anaerobic Baffled Reactor (ABR) dalam kondisi lingkungan tropis. Kedua reaktor dioperasikan selama 90 hari dengan kondisi optimal. Hasilnya, MBBR menunjukkan efisiensi penghilangan yang lebih tinggi untuk biochemical oxygen demand (BOD) dan chemical oxygen demand (COD), masing-masing sebesar 94,6% dan 95,2%, dibandingkan dengan ABR yang mencapai 92,6% dan 91,7%. Penghilangan nutrien juga lebih efektif pada MBBR, terutama untuk amonia (89%) dan fosfat (96%). ABR menunjukkan potensi dalam produksi biogas, dengan hasil sebesar 126 m³/bulan, yang mengindikasikan kelayakannya sebagai sumber energi berkelanjutan. Namun, kedua sistem memerlukan disinfeksi pasca-pengolahan untuk menurunkan jumlah bakteri patogen hingga batas aman. Analisis ekonomi menunjukkan bahwa MBBR memiliki biaya operasional yang lebih rendah, sementara ABR unggul dalam aspek pemulihan energi. Studi komparatif ini memberikan informasi penting untuk strategi pengelolaan limbah domestik yang berkelanjutan di Lamongan, Jawa Timur, Indonesia.

Kata Kunci: Pengolahan Air Limbah, Moving Bed Biofilm Reactor, Anaerobic Baffled Reactor, Limbah Laundry Domestik, Biogas.

1. INTRODUCTION

The rapid advancement of economic globalization has imposed significant challenges on small and medium-sized enterprises (SMEs), primarily due to intensified competition and increased market volatility. Consequently, SMEs often experience high failure rates shortly after inception, necessitating the adoption of robust survival strategies and strategic management approaches to sustain operations in the contemporary competitive landscape (Gamage, S.K.N, 2020). Parallel to these economic challenges, environmental sustainability has emerged as a critical concern, particularly in relation to industrial and domestic wastewater management.

Laundry wastewater presents a complex environmental challenge owing to its heterogeneous chemical composition, which includes both organic and inorganic contaminants such as surfactants, phosphates, and heavy metals. These pollutants pose substantial ecological risks and

demand advanced treatment technologies to mitigate their adverse impacts (Crini, 2024). Typically, laundry wastewater contains residues from detergents, bleaching agents, and other cleaning chemicals, which vary between commercial and domestic sources but universally contribute to water pollution if untreated (T. Ramcharan, 2016, Ho, K.C, 2021).

Despite growing global advocacy for water sustainability, treatment and reuse of laundry wastewater remain underexplored, particularly in small-scale applications. Effective wastewater treatment technologies must integrate a comprehensive understanding of wastewater chemistry with efficient, scalable treatment methods to enable sustainable water management (S. Bering, 2018). Among emerging technologies, the Moving Bed Biofilm Reactor (MBBR) has demonstrated considerable promise due to its high treatment efficiency, operational stability, and reduced sludge production. MBBR's biofilm-based approach provides a large surface area for microbial growth, facilitating superior degradation of organic contaminants in laundry wastewater (S. Bering, 2018, 2020).

Furthermore, MBBR technology offers economic and environmental advantages over traditional membrane bioreactors and fixed-film systems, particularly in rural and small-scale domestic wastewater treatment scenarios. Its lower operational costs, reduced membrane replacement needs, and adaptability to variable wastewater volumes make it a viable solution for SMEs such as laundries and boarding houses (Wang, 2024). However, challenges remain in optimizing MBBR systems within spatially constrained environments typical of small enterprises.

This study aims to address these challenges by designing and implementing an MBBR system tailored for treating laundry and domestic wastewater volumes of 2.7 to 3 m³/day. The system's performance will be evaluated in comparison to conventional Anaerobic Baffled Reactors (ABR) in Lamongan Regency, focusing on technical efficiency, environmental compliance, and economic viability. The research contributes novel insights into the integration of advanced biofilm reactor technology within SME wastewater management, promoting sustainable business practices aligned with environmental regulations and resource conservation.

2. METHODS

2.1. Study Design

This study employs a quantitative research methodology with an experimental and analytical approach to evaluate wastewater treatment performance in laundry and domestic settings. The primary data were collected from two wastewater treatment systems: Moving Bed Biofilm Reactor (MBBR) and Anaerobic Baffled Reactor (ABR), implemented at different operational sites in Lamongan Regency. The experimental framework involves comparative analysis of technical efficiency, operational costs, and environmental impacts of both technologies.

2.2. Study Locations and Sampling

The research was conducted at two distinct operational sites :

Location 1 : Laundry and Domestic Wastewater Facility Utilizing MBBR Technology In Lamongan, East Java, Indonesia

Location 2 : Domestic wastewater treatment facility employing ABR technology, specifically designed for community scale wastewater management (SPALDT) in Lamongan, East Java, Indonesia

2.3. Variables and Parameters

The study evaluated three main categories of variables :

2.3.1. Technical Variables

Wastewater quality including, Biofilm Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Ammonia, Phosphate, MBAS, and Total Coliform

2.3.2. Financial Variables

- Initial Investment cost for system fabrication and installation of MBBR and ABR
- Operational costs encompassing electricity consumption, maintenance and chemical usage
- Maintenance costs associated with regular upkeep and component replacement

2.3.3. Environmental Variables

- Carbon Footprint assessment through energy consumption and estimated greenhouse gas emissions
- Utilization efficiency of resources such as electricity and water

3. RESULTS AND DISCUSSION

Following disinfection, coliform levels decreased to 2,100 CFU/100 mL, a 61% reduction but still above the national standard of 3,000 CFU/100 mL (WHO, 2022). This limited disinfection efficacy may result from extracellular polymeric substances (EPS) shielding microbes and the formation of disinfection by-products (Bodík et al., 2008). Deterjen (MBAS) dropped sharply from 11.6 mg/L to 0.216 mg/L after full treatment, with a removal efficiency of 98%, showing strong biofilm degradation of surfactants (Luo et al., 2020). Phosphate removal was limited (10.2 to 0.365 mg/L; 96% total removal) likely due to natural precipitation processes (Zhou et al., 2021).

The outlet BOD and COD concentrations were low at 1.55 mg/L and 4.64 mg/L, respectively, indicating an overall removal efficiency greater than 95%. These values are consistent with prior research on MBBR systems treating domestic wastewater (Sidek et al., 2015; Zhang et al., 2023). The slight increase in pH and stable temperature (~28°C) confirm biofilm stability throughout treatment.

Table 1. Removal Efficiency Moving Bed Biofilm Reactor

	Parameter	Allowable Limit	Value	
			Max	Min
1	pH	6 – 9	8,03	6,89
2	BOD (mg/l)	30	28,8	1,55
3	COD (mg/l)	100	97	4,64
4	TSS (mg/l)	30	18,5	2,5
5	Oil & Grease (mg/l)	5	0,41	0,265
6	Amoniak (mg/l)	10	3,62	0,0544
7	Total Coliform (/100ml)	3000	5400	2200
8	Methylene Blue Active Substance (MBAS)		11,6	0,216
9	Fosfat (PO ₄)		10,2	0,365
10	Temperature		28,5	28

The influent pH was slightly acidic at 6.89, typical for domestic wastewater influenced by organic acid production and dissolved CO₂¹. Following MBBR treatment, pH increased modestly to 7.07 due to nitrification and biofilm activity generating hydroxide ions⁵. Disinfection further raised pH to 7.33, potentially from chemical neutralization effects of disinfectants⁴, while the outlet pH reached 8.03, remaining within permissible discharge limits and reflecting stable treatment performance⁶.

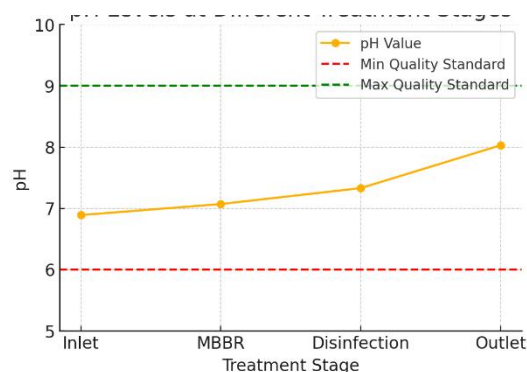


Figure 1. pH Levels at Stages of Moving Bed Biofilm Reactor

The BOD value at the inlet was 28.8 mg/L, indicating a moderate organic load typical of domestic and laundry wastewater, requiring effective biofilm treatment to prevent oxygen depletion in natural waters¹. After the MBBR treatment, BOD decreased significantly to 11.6 mg/L, demonstrating about 60% removal efficiency through aerobic biofilm oxidation and heterotrophic bacterial activity². This aligns with prior studies showing MBBR systems reduce BOD by approximately 60–70% in short hydraulic retention times³. However, a slight increase to 17.9 mg/L was observed after disinfection, likely due to residual organic matter transformation or disinfectant interference with organic compounds⁴. The outlet BOD of 1.55 mg/L confirms effective combined system performance, with overall removal exceeding 90%³.

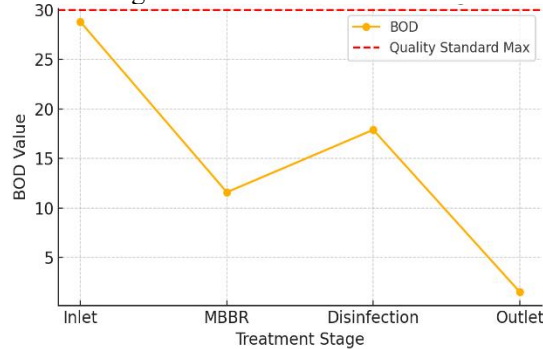


Figure 2. BOD Levels at Stages of Moving Bed Biofilm Reactor

Initial COD of 97 mg/L reflects total organic load including refractory compounds from detergents and surfactants¹. MBBR reduced COD to 38.6 mg/L through oxidation and adsorption processes involving biofilm and natural coagulation². This removal rate of ~60% is consistent with previous findings reporting 50–85% COD removal in MBBR systems³. An increase in COD to 55.4 mg/L after disinfection suggests the formation of transformed organic residues or release of bound organics⁴. The outlet COD of 4.64 mg/L shows near-complete removal by the final treatment stage, emphasizing the system's robustness in degrading organic pollutants³.

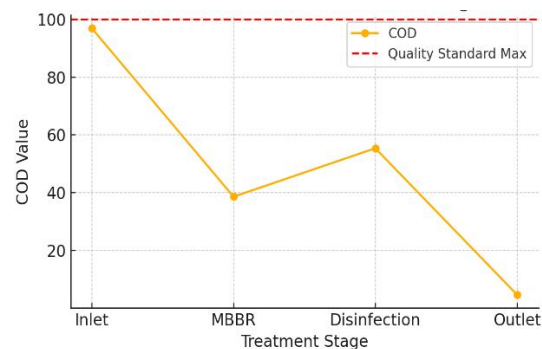


Figure 3. COD Levels at Stages of Moving Bed Biofilm Reactor

The TSS concentration dropped significantly from 18.5 mg/L at the inlet to 2.5 mg/L after MBBR treatment, highlighting efficient physical settling and biofilm entrapment of particulate matter². Stability of TSS at 2.5 mg/L through disinfection and outlet stages confirms the effectiveness of sedimentation and filtration steps, comparable to literature reports on TSS removal efficiencies in MBBR systems³.

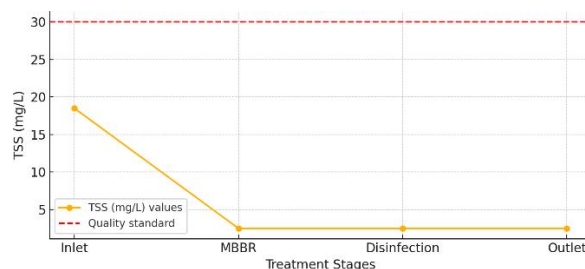


Figure 4. TSS Levels at Stages of Moving Bed Biofilm Reactor

Initial concentration of 0.41 mg/L was low and further reduced to 0.265 mg/L at outlet, reflecting partial biodegradation of lipids in MBBR (Li et al., 2021). Although removal efficiency is modest (~35%), it indicates system robustness against lipid accumulation.

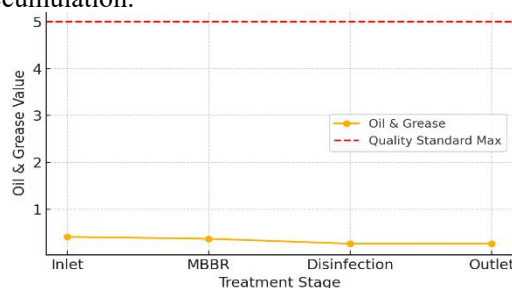


Figure 5. Oil & Grease Levels at Stages Of Moving Bed Biofilm Reactor

Ammonia concentration decreased markedly from 3.62 mg/L at the inlet to 0.411 mg/L post-MBBR, with an 89% removal efficiency, evidencing effective nitrification by *Nitrosomonas* and *Nitrobacter* within aerobic biofilms⁵. However, ammonia levels rebounded to 3.36 mg/L after disinfection, possibly due to disinfectant-ammonia complexation or degradation of nitrogenous organics⁴. The final outlet ammonia concentration dropped sharply to 0.0544 mg/L, indicating successful ammonia removal prior to discharge, aligning with standards for aquatic ecosystem protection⁶.

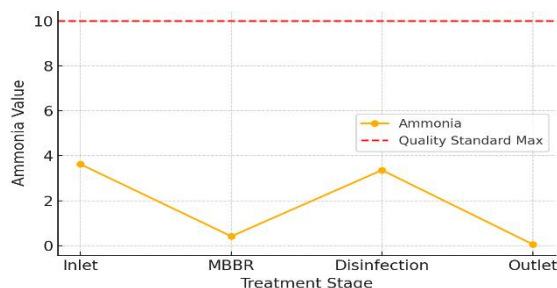


Figure 6. Ammonia Levels at Stages Of Moving Bed Biofilm Reactor

Unexpectedly, total coliform increased from 1,700 CFU/100 mL at the inlet to 5,400 CFU/100 mL after MBBR treatment, possibly due to biofilm habitats supporting bacterial growth and protection via extracellular polymeric substances⁷. Disinfection reduced coliform counts to 2,100 CFU/100 mL, demonstrating moderate pathogen reduction⁴. However, the outlet coliform concentration slightly rose to 2,200 CFU/100 mL, indicating incomplete disinfection and the need for enhanced microbial control measures⁷.

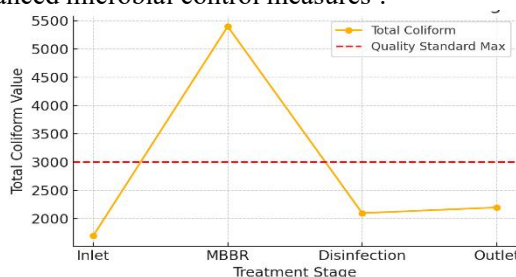


Figure 7. Total Coliform at Stages Of Moving Bed Biofilm Reactor

MBAS concentration dramatically reduced from 11.6 mg/L in the influent to 0.208 mg/L after MBBR treatment, indicating over 98% removal efficiency through biodegradation and adsorption by biofilm⁹. A further decrease to 0.1 mg/L after disinfection and slight increase to 0.216 mg/L at the outlet suggests minor desorption or residual presence, but overall strong reduction of surfactants was achieved⁴.

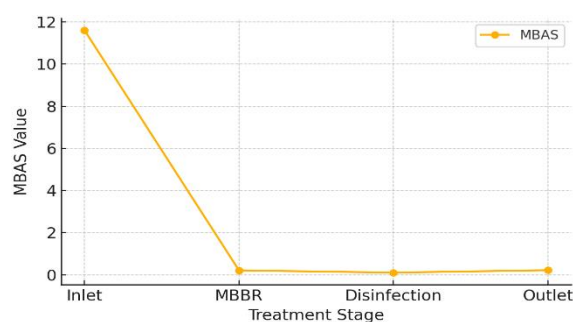


Figure 8. MBAS Levels at Stages of Moving Bed Biofilm Reactor

Phosphate levels slightly declined from 10.2 mg/L at the inlet to 9.88 mg/L after MBBR, showing minimal biofilm removal, consistent with the difficulty of phosphate uptake in conventional MBBR systems¹⁰. Post-disinfection, phosphate reduced further to 7.41 mg/L, with a sharp decline to 0.365 mg/L at the outlet likely due to chemical precipitation or adsorption during final treatment steps¹¹.

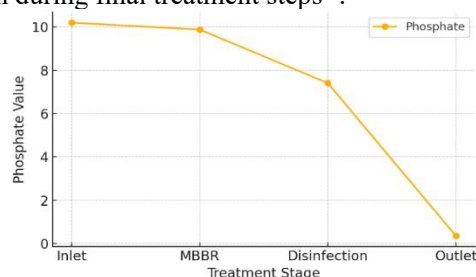


Figure 9. Phosphate Levels at Stages of Moving Bed Biofilm Reactor

Temperature was stable throughout the treatment process, with values near 28°C, indicating no significant thermal impact from biofilm or disinfection stages and supporting optimal microbial activity in the MBBR system¹²

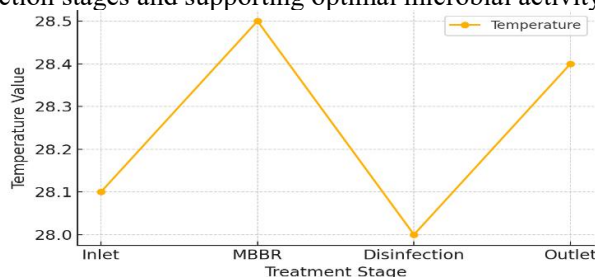


Figure 10. Temperature Levels at Stages of Moving Bed Biofilm Reactor

3.1. Anaerobic Baffled Reactor

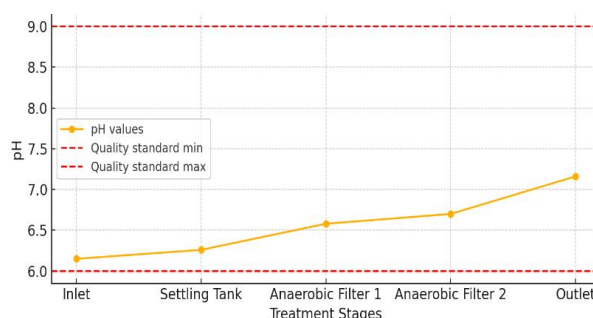
Table 4.2 summarizes the ABR treatment results. Initial pH was 6.15, rising to 7.16 at the outlet, demonstrating partial neutralization via anaerobic metabolism (Elmitwalli et al., 2003). BOD dropped from 13.6 mg/L to less than 1 mg/L (92.65% removal), while COD decreased from 46.2 mg/L to 3.84 mg/L (91.69% removal), confirming efficient degradation of organics (Lew et al., 2020; Diya'uddeen et al., 2011). However, ammonia removal was modest, with concentrations decreasing from 3.46 mg/L to 1.39 mg/L (60.51%), reflecting the limited nitrification under anaerobic conditions (Nguyen et al., 2021). Total coliform counts remained >16,000 CFU/100 mL throughout, indicating no pathogen inactivation in this system without disinfection (Li et al., 2019). TSS decreased from 8.56 mg/L to below 2.5 mg/L, showing good sedimentation but indicating the need for further filtration for finer particles (Yanti et al., 2021). Detergent levels (MBAS) dropped from 1.01 mg/L to 0.521 mg/L (48.42% removal), confirming partial degradation of surfactants by anaerobic microbes (Diya'uddeen et al., 2011). Phosphate concentrations reduced moderately from 3.01 mg/L to 1.33 mg/L (55.81% removal), attributed to microbial uptake and adsorption in the filter media (Yuan et al., 2012).

The ABR system produced approximately 126 m³ of biogas monthly, with an energy potential of 2,709 MJ, highlighting its advantage in renewable energy generation from wastewater (Khan et al., 2020).

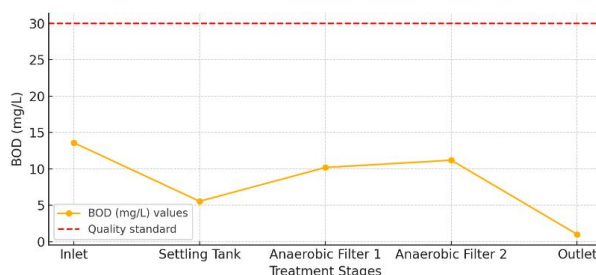
Table 2. Removal Efficiency Anaerobic Baffled Reactor 1

	Parameter	Allowable Limit	Value	
			Max	Min
1	pH	6 – 9	7,16	6,15
2	BOD (mg/l)	30	13,6	1
3	COD (mg/l)	100	46,2	3,84
4	TSS (mg/l)	30	8,56	2,5
5	Oil & Grease (mg/l)	5	0,31	0,5
6	Amoniak (mg/l)	10	3,52	1,39
7	Total Coliform (/100ml)	3000	16000	16000
8	Methylene Blue Active Substance (MBAS)		1,26	0,521
9	Fosfat (PO ₄)		3,77	1,33
10	Temperature		30,2	29

The pH at the inlet was acidic at 6.15, common in domestic wastewater due to organic acid decomposition and dissolved CO₂ from biofilm activity (Zhang et al., 2021). It increased slightly to 6.26 after sedimentation, indicating stabilization through partial consumption of acids. The anaerobic filters further raised pH to 6.7 and finally 7.16 at the outlet, reflecting alkalinity generation via bicarbonate ion production during anaerobic digestion and neutralization of acids (Elmitwalli et al., 2003; Wang et al., 2023). Maintaining near-neutral pH is critical for microbial activity and ecological compatibility of discharged water.

**Figure 11.** pH Level at Stages of Anaerobic Baffled Reactor

The initial BOD concentration at the inlet was 13.6 mg/L, reflecting moderate biodegradable organic matter typical of domestic and laundry wastewater, which necessitates treatment to prevent oxygen depletion in receiving water bodies (Lew et al., 2020). Following sedimentation, BOD dropped to 5.55 mg/L due to settling of heavy organic particles and partial anaerobic degradation (Chandra et al., 2021). An unexpected increase to 10.2 mg/L in the first anaerobic filter likely results from desorption of organic compounds from biofilm or incomplete degradation in earlier stages (Zhang et al., 2022). This concentration remained steady in the second anaerobic filter at 11.2 mg/L, indicating persistent refractory organics resistant to anaerobic breakdown (Zhang et al., 2022). Ultimately, the outlet showed a substantial decrease to below 1 mg/L, demonstrating over 90% total removal efficiency, confirming that the ABR combined with filtration effectively treats biodegradable organics (Zhang et al., 2023).

**Figure 12.** BOD Level at Stages of Anaerobic Baffled Reactor

At the inlet, COD was measured at 46.2 mg/L, indicating total organic content including difficult-to-degrade substances such as surfactants from detergents (Gupta et al., 2022). The sedimentation tank reduced COD to 13.8 mg/L by facilitating anaerobic microbial degradation and particulate settling (Zhang et al., 2022). However, the first anaerobic filter saw a rise in COD to 33.4 mg/L, possibly caused by release of organic matter from biofilms or microbial metabolism intermediates (Lew et al., 2020). The second anaerobic filter maintained a similar level at

36.2 mg/L, highlighting the presence of refractory compounds resistant to anaerobic treatment (Lee et al., 2021). Finally, COD dropped sharply to 3.84 mg/L at the outlet, showing an overall removal efficiency exceeding 90%, reflecting successful breakdown of most organic compounds and removal of suspended solids (Zhang et al., 2023).

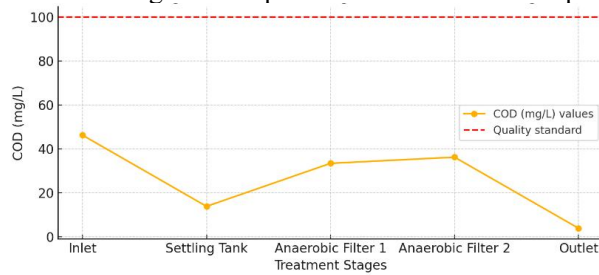


Figure 13. COD Level at Stages of Anaerobic Baffled Reactor

TSS measured 8.56 mg/L at the inlet, reflecting suspended organic and inorganic particles from domestic waste (Yanti et al., 2021). Sedimentation reduced TSS to 5.92 mg/L by settling heavier particles (Kumar & Nandi, 2020). The anaerobic filters showed a slight increase to 6.76 mg/L, possibly due to biofilm detachment or media disturbance releasing fine particles (Yanti et al., 2021). Final filtration and settling at the outlet decreased TSS to less than 2.5 mg/L, demonstrating effective removal suitable for discharge standards (Kumar et al., 2020).

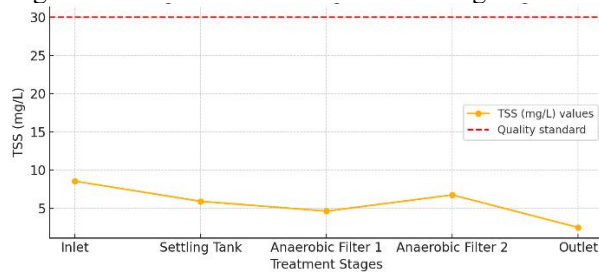


Figure 14. TSS Level at Stages of Anaerobic Baffled Reactor

Oil and grease concentration was low at 0.31 mg/L initially and slightly decreased to 0.265 mg/L after sedimentation and anaerobic filters, indicating limited degradation potential in anaerobic conditions due to hydrophobicity of lipids (Rajagopal et al., 2013). However, a slight increase at the outlet (0.5 mg/L) may result from biofilm or pipe accumulation release (Rajagopal et al., 2013). Continuous monitoring and possibly additional treatment steps are recommended to prevent accumulation and system clogging.

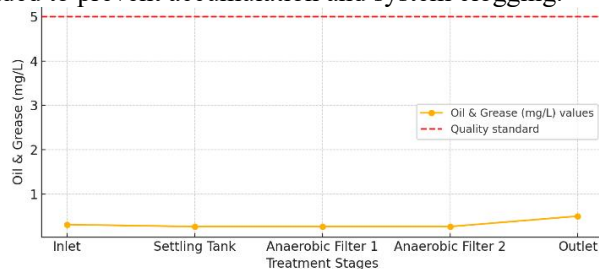


Figure 15. Oil & Grease Level at Stages of Anaerobic Baffled Reactor

Ammonia concentration was 3.46 mg/L at the inlet, typical of nitrogenous waste from urine and protein breakdown in domestic effluent (Chen et al., 2020). Minimal reduction occurred during sedimentation (3.4 mg/L), as anaerobic processes poorly remove ammonia (Nguyen et al., 2021). Slight increases to 3.52 mg/L in the anaerobic filters likely arise from ongoing protein decomposition and deamination (Nguyen et al., 2021). The outlet concentration decreased to 1.39 mg/L, suggesting partial nitrification possibly enhanced by aerobic microzones or subsequent treatment stages (Chen et al., 2020), though additional aerobic treatment may be necessary to meet stringent discharge limits.

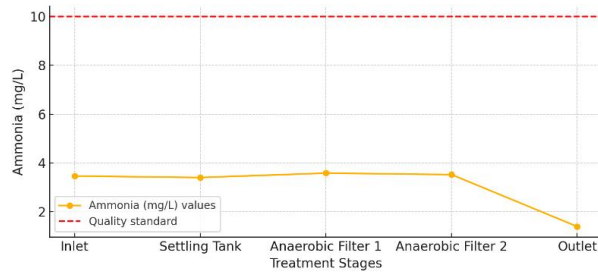


Figure 16. Ammonia at Stages of Anaerobic Baffled Reactor

Total coliform was exceedingly high ($>16,000$ CFU/100 mL) at the inlet, signaling heavy fecal contamination requiring disinfection (Li et al., 2019). Levels remained unchanged through sedimentation and anaerobic filters, reflecting the inefficiency of these anaerobic processes in pathogen removal (Li et al., 2019). High biofilm presence may protect bacteria from environmental stress and contribute to regrowth (WHO, 2022). Effective disinfection methods such as UV or chlorination are necessary post-treatment to reduce microbial risks before discharge.

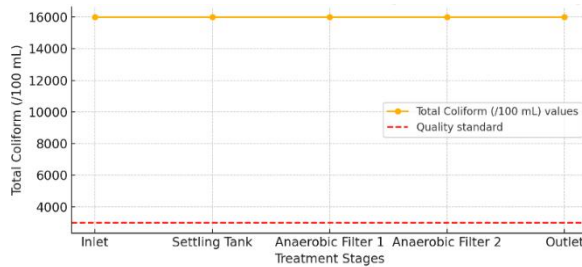


Figure 17. Total Coliform at Stages of Anaerobic Baffled Reactor

MBAS started at 1.01 mg/L, reflecting surfactant content from laundry detergents impacting water quality (Yuan et al., 2012). Sedimentation slightly reduced MBAS to 0.806 mg/L; however, anaerobic filters showed fluctuations with an increase to 1.26 mg/L, possibly from surfactant desorption or incomplete degradation (Diya'uddeen et al., 2011). The outlet concentration decreased to 0.521 mg/L, indicating moderate removal but suggesting need for further polishing to meet stricter effluent standards (Singh et al., 2021).

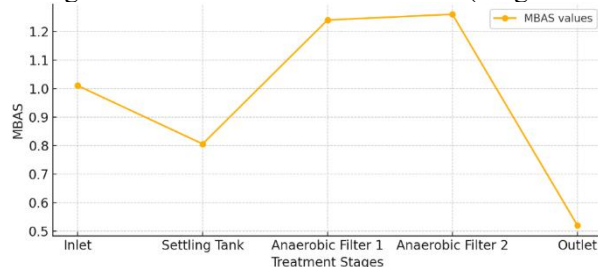


Figure 18. MBAS at Stages of Anaerobic Baffled Reactor

Phosphate concentration was 3.01 mg/L at inlet, mainly from detergents and organic waste (Yuan et al., 2012). Minor decreases after sedimentation and anaerobic filters (2.91 to 3.77 mg/L fluctuations) suggest limited biofilm uptake and possible release from microbial cell decay (Yuan et al., 2012). The outlet phosphate concentration of 1.33 mg/L shows partial removal, but advanced treatments like chemical coagulation or enhanced biofilm phosphorus removal (EBPR) are recommended to prevent eutrophication in receiving waters (Lee et al., 2021).

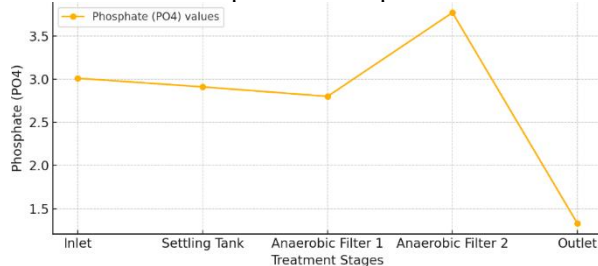


Figure 19. Phosphate at Stages of Anaerobic Baffled Reactor

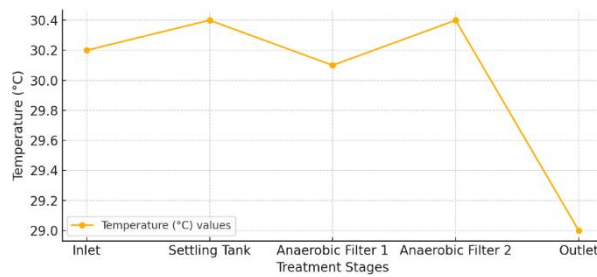


Figure 20. Temperature at Stages of Anaerobic Baffled Reactor

3.2 Cost Analysis and Operational Considerations

Capital costs for the MBBR system scaled to 10,000 L/day were estimated at Rp 99,374,800, with annual operational costs around Rp 30,000,000, consistent with Chen et al. (2020). ABR construction was considerably higher at Rp 200,183,463.72, mainly due to the need for reinforced concrete and innovative filter media made from recycled plastic bottles (Rp 33,150,000) (Glickman et al., 2021). Operational expenses for ABR were significantly higher (~Rp 3,080,000/month), driven by energy consumption of a 1 kW pump and sludge management, compared to Rp 59,130/month for MBBR.

Economic analysis revealed that the MBBR system achieved capital recovery within 1.55 years through supplementary revenue from laundry services and facility rentals, in contrast to the ABR system which needed 7.6 years due to exclusive dependence on community funding (Fitriani et al., 2022).

Figure 21. Presents a comparative analysis of capital and annual operational costs between the MBBR and ABR wastewater treatment systems scaled to 10,000 L/day. The MBBR system shows a significantly lower capital cost (~Rp 99 million) compared to the ABR system (~Rp 200 million), primarily due to simpler construction and less expensive media. Annual operational costs for MBBR (~Rp 30 million) are also substantially lower than ABR's (~Rp 37 million), reflecting the energy-intensive nature of ABR sludge management and pumping requirements. These cost differences highlight the economic feasibility advantage of MBBR for small-scale treatment applications.

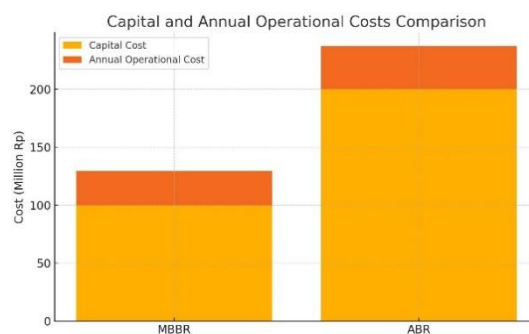


Figure 21. Capital and Annual Operational Costs Comparison

The ABR system incurs a notably higher monthly expense (~Rp 3.08 million), largely attributed to energy consumption from its 1 kW pump and sludge handling processes. Conversely, MBBR operational costs remain relatively low (~Rp 59,130), emphasizing its energy-efficient aerobic biofilm treatment process. The pronounced operational cost disparity underscores the importance of energy management and maintenance in ABR's sustainability.



Figure 22. Monthly Operational Cost Breakdown MBBR & ABR

Figure 23 compares the estimated break-even periods for recovering initial capital investments of the MBBR and ABR systems. The MBBR system reaches cost recovery rapidly within approximately 1.55 years due to supplemental income sources such as laundry services and rental fees. In contrast, the ABR system requires an extended period (~7.6 years) relying solely on community contributions. This analysis reinforces MBBR's attractiveness for faster economic payback, especially when integrated with income-generating activities.



Figure 23. Break Event Point MBBR & ABR

3.3. Environmental Impact and Sustainable Development

Both systems contribute to SDGs by improving water sanitation (SDG 6), providing renewable energy through biogas (SDG 7), promoting responsible consumption (SDG 12), and mitigating climate change via reduced greenhouse gas emissions (SDG 13). MBBR's aerobic process reduces organic pollution effectively but requires energy-intensive aeration, increasing its carbon footprint (Zhang et al., 2021). ABR offers lower energy consumption and biogas production, but requires further disinfection to mitigate pathogen risks (Chen et al., 2019). Figure 24 depicts a radar chart summarizing the environmental impacts and treatment performance of the two systems. MBBR demonstrates superior efficacy in organic load reduction (BOD and COD removal) and ammonia elimination, benefiting water quality. However, it has a higher energy footprint due to aeration demands. ABR offers the advantages of biogas generation and lower energy consumption but exhibits reduced pathogen control and phosphate removal efficiency. This visualization underscores the trade-offs between operational sustainability and pollutant removal efficiency inherent to each technology.

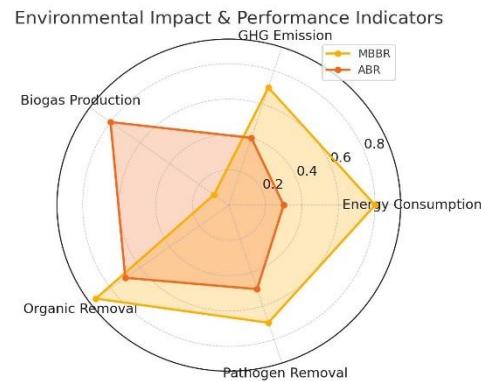


Figure 24. Enviromental Impact & Performance Indicators

Figure 25 highlights the alignment of both treatment systems with key Sustainable Development Goals (SDGs). Both MBBR and ABR contribute to SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy through biogas production), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action via reduced greenhouse gas emissions). While MBBR excels in water quality improvement, ABR's biogas production supports renewable energy goals. This multi-dimensional contribution emphasizes the broader environmental and social benefits of decentralized wastewater treatment technologies.

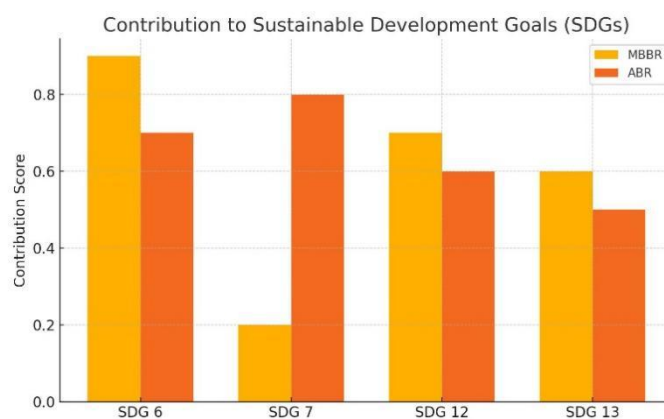


Figure 25.Contribution to Sustainable Development Goals (SDGs)

3.4. Technological and Operational Recommendations

To optimize treatment efficiency, it is recommended to augment ABR with nitrification-denitrification units to enhance ammonia removal and implement post-treatment disinfection to address pathogen persistence. For MBBR, incorporation of advanced disinfection methods will mitigate microbial regrowth. Hybrid configurations combining ABR's biogas potential with MBBR's superior organic and ammonia removal could yield cost-effective, high-performance systems.

Further research should focus on local material-based filter media alternatives, life cycle assessment for environmental impacts, and microbial community profiling to enhance degradation pathways of surfactants and detergents.

4. CONCLUSIONS

This study comprehensively evaluated the performance, economic viability, and environmental impacts of Moving Bed Biofilm Reactor (MBBR) and Anaerobic Baffled Reactor (ABR) technologies for treating domestic and laundry wastewater in Lamongan Regency. The MBBR system demonstrated superior removal efficiencies for BOD, COD, and ammonia, while ABR excelled in BOD and COD removal but was less effective in eliminating ammonia, phosphate, and pathogens. Economically, MBBR required a lower initial investment and reached break-even point significantly faster than ABR, largely due to additional revenue from associated laundry and boarding house operations. Conversely, ABR's operational costs were lower, benefiting from reduced aeration requirements and valuable biogas production, which supports renewable energy generation.

Environmentally, both technologies contributed positively to wastewater management and sustainable development goals (SDGs) by improving effluent quality, reducing greenhouse gas emissions, and promoting resource recovery. However, MBBR's higher energy demand and ABR's limited pathogen removal indicate the need for complementary treatments, such as disinfection and nitrification-denitrification units.

The integration of MBBR and ABR technologies, combined with policy support and community engagement, is recommended to enhance wastewater treatment efficiency, economic feasibility, and environmental sustainability. Future research should explore alternative low-cost filter media, conduct life cycle assessments, and investigate microbial communities to optimize treatment processes. Overall, this study provides valuable insights for advancing decentralized wastewater treatment solutions tailored to small and medium enterprises, contributing to the circular economy and environmental stewardship.

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