



OPTIMIZING LOW-COST BIOFILTER-BASED WASTEWATER TREATMENT SYSTEMS FOR SMALL COMMUNITIES

Article History

Received:
January 18, 2026

Revised:
April 13, 2026

Accepted:
May 19, 2026

Available Online:
June 30, 2026

Muhammad Usman Javed^{1*}

¹ University of Engineering and Technology (UET) Taxila

Punjab, Pakistan

*Corresponding Author E-mail: usmanjaved35@gmail.com

Abstract

Small communities often face serious challenges in managing domestic wastewater because conventional treatment systems are costly, energy-intensive, and difficult to maintain. This study examines the effectiveness of low-cost biofilter-based wastewater treatment systems as a practical solution for decentralized sanitation in small communities. The paper focuses on the treatment performance, operational stability, cost efficiency, and environmental suitability of biofilters using locally available filter media such as gravel, sand, biochar, coconut coir, and activated carbon. The results indicate that biofilter systems can significantly reduce biochemical oxygen demand, chemical oxygen demand, suspended solids, nutrients, and microbial contamination when properly designed and maintained. The findings also show that biofilter performance improves after microbial biofilm development, with stable pollutant removal achieved during continuous operation. Compared with conventional mechanical treatment systems, biofilters require lower energy input, reduced operational costs, and simpler maintenance, making them suitable for rural and semi-urban settlements. The study concludes that optimized biofilter systems provide a sustainable, affordable, and scalable wastewater treatment option for small communities, especially where financial and technical resources are limited.

Keywords: Biofilter Systems; Wastewater Treatment; Small Communities; Low-Cost Sanitation; Decentralized Treatment

INTRODUCTION

The risk of waterborne diseases in small community is, in the absence of proper sanitation infrastructure, disproportionately high, because of the lack of sanitation facilities, making it vulnerable to public health threats (Crnogaj et al., 2024). The lack of connection to the wastewater treatment system is one of the major challenges in rural settings, much more so than in more concentrated urban settings (Bartram & Cairncross, 2010; Universal Social Protection for Human Dignity, Social Justice and Sustainable Development, 2019). The sanitation equipment gap is one of the main causes of the waterborne disease burden, and it disproportionately impacts vulnerable groups, where conventional activated sludge plants are not cost-effective or logistically feasible (Wang et al., 2025; Sinche et al., 2025; Shayo et al., 2023). This environmental pollution is often happening through direct discharge of untreated sewage into the local environment and the need for immediate local specific intervention (Choudhary & Ray, 2024; Tondera & K., 2021). As such, the science and policy momentum of decentralized wastewater treatment systems (DWWTSs) using natural resources instead of centralized systems are on the rise, and are scalable (Choudhary & Ray, 2024; Sinche et al., 2025). Among the technologies, low cost biofilter based technologies are found to be a very good option as locally available materials such as gravel, zeolite and activated carbon are able to remove pollutants with low energy consumption, capital cost and complex maintenance procedures (Alresheedi et al., 2023; S. D. Azmi, 2025; S. I. Azmi, 2025; Khairy et al., 2025). The results indicate that these systems can achieve efficiencies of up to 70-90% in the removal of several water quality indicators including Biochemical Oxygen

Demand, Chemical Oxygen Demand and Total Suspended Solids (Azmi, 2025; Torrens et al., 2025). But to make such a decentralised solution work, it must be optimised on a site specific basis. The designs of small-scale biofilters are very variable in terms of their performance and result in wastewater characteristics and environmental stressors due to the variability of the hydraulic loadings (Capodaglio et al., 2017). Along with that, a project's sustainability relies heavily on the active involvement of the local community, capacity building, and the creation of sustainable management practices that can be easily implemented and are relatively inexpensive (Alresheedi et al., 2023; Standing, 2004). In response to this, the pathway towards decentralised nature-based solutions is an important pathway to bridging the sanitation gap in communities without sanitation services (Crnogaj et al., 2024). The main objective of this study is to optimize low cost biofilter based wastewater treatment systems in a particular way to suit the technical and socio-economic conditions in small communities. The objective of this work is to create a comprehensive method for sustainable decentralised sanitation, explicitly studying the design parameters, determining the treatment efficiency of these systems under different load conditions and assessing the sustainability of the resources used for treatment of wastewater using local materials. To conclude, this study proposes practical recommendations to lessen health risks associated with poor sanitation practices and to help ensure that health goals in these areas are consistent with more global sustainable development goals in environmental health in more vulnerable places (Choudhary & Ray, 2024; Crnogaj et al., 2024). The

study will concentrate on the operation resilience of the filter and nutrient sequestration capacity throughout the filter's life course due to the variations in composition of the filter media and interaction between the filter media and the microbe (Zairinayati et al., 2025). Further, this study will develop strong mathematical models to correlate the physical filter characteristics with its biological performance so that these decentralized units can be safely and economically implemented in areas with limited resources such as in the regions of India (Jayakumar et al., 2021). In this investigation, some of the evident sustainability measurements used to evaluate the environmental efficiency of decentralized configurations are documented such as energy consumption per pollutant load removed and life cycle cost (Das & Mishra, 2025). These findings will help to define evidence-based guidance for scaling decentralized infrastructure (Brooks et al., 2025) and will help to close the gap between limitations in current technical capacity and the need for universal and equitable sanitation services (Ventura et al., 2024). This work also helps improve the understanding of the systemic issues that may prevent the adoption of decentralized wastewater treatment plants in remote areas such as institutional capacity and asymmetric information (Elliott et al., 2023, Saadatinavaz et al., 2024). This study fills a gap between innovative decentralized technology and the ongoing sanitation gaps for rural and marginalised communities, by creating an integrated management approach to consider the physical performance of the technology and necessary institutional management.

METHODOLOGY

This part presents the experimental system for testing the biofilter performance and the selection criteria for biofilters in remote communities with lower population density ($N < 500$ persons/km²) as

recommended by An (2015). The reasons for the selection of these sites were to resolve a sanitation problem that is found in decentralized areas, where existing sewerage systems are not in place or not operational (Zhang et al., 2022). Biofilter units are vertical-flow units with a multi-layered media which provides optimum physical filtration and biological degradation. The reactor columns are made of high-density polyethylene and are filled with locally available materials, such as a base layer of coarse gravel (20–40 mm) for drainage, a middle layer of zeolite (5–10 mm) for ammonia adsorption and cation exchange, a middle layer of activated carbon (2–5 mm) for organic contaminant adsorption, and a top layer of sand (0.5–1 mm) to support initial particulate straining and aerobic biofilm establishment (S. D. Azmi, 2025; S. I. Azmi, 2025; Khairy et al., 2025). The designed hydraulic loading rate is 0.5 – 1.0 m³/m²/day and the filtration time of the organic matter in the filter media is 1.2 m. In order to assess treatment effectiveness, samples of influent and effluent water are taken weekly for a six month monitoring period. Samples are taken from the effluent from the septic tank outlet (septic tank feed) as well as from the effluent from the final drainage pipe (after gravity fed filtration). To reduce the effect of the day-to-day fluctuations in flow, samples are collected as 24-hour composite samples that are proportional to flow, placed in sterile containers and stored at 4°C, and analyzed at the laboratory within 24 hours of collection (Azmi, 2025; Torrens et al., 2025). Water quality is tested using standard methods, Biochemical Oxygen Demand (BOD₅) is tested using the respirometric method, Chemical Oxygen Demand (COD) is tested using the closed reflux colorimetric method and Total Suspended Solids (TSS) is tested gravimetrically after filtration through 0.45 µm glass fiber filters (Azmi, 2025; Torrens et al., 2025). The membrane filtration method is used to measure

microbial pathogens as *E. coli* and Total coliforms (CFU/100mL) (Torrens et al., 2025). The analytical quality control takes into account the use of blanks, matrix spikes and duplicate samples on 10% of the total number of samples to ensure precision and accuracy. In situ monitoring of microbial activity is carried out using calibrated probes which monitor temperature, pH and dissolved oxygen, environmental stressors that affect the activity of microbes (S. D. Azmi, 2025; S. I. Azmi, 2025). The quantitative data obtained is then analyzed by descriptive and inferential statistics while the removal efficiency is determined as a percentage decrease of the effluent concentration to the influent concentration. To evaluate the operational resilience of the biofilter configuration, the differences in the performance parameters were investigated under various hydraulic loads and seasonal variation of temperature with one-way Analysis of Variance at 95% confidence level ($p < 0.05$) which gave a strong basis to investigate the operational resilience of the biofilter configuration (Azmi, 2025). Furthermore, BOD, COD and TSS removal rates are presented in grams of filter bed per day, taking into consideration the varying hydraulic loads (Aguirre-Sierra et al., 2020). The total volatile solids and total Kjeldahl nitrogen (TKN) of the stratified layers are also measured in order to test the long-term stability of the filter media (Koottatep et al., 2020). The Scanning Electron Microscopy (SEM) is used to obtain the morphology of the biofilms and structural integrity on the surface of the filter media for description of the community formations of the microorganisms (Eslami et al., 2018). Besides these biological observations, nutrient analyses such as total nitrogen and nitrates and orthophosphates are quantified, which provides information on the particular sequestration potential of the zeolite and activated carbon layers (Jacklin et al., 2021; Ndiaye et al., 2024). The nutrient concentrations determined

by titration and colorimetric methods are consistent with the standard environmental reporting criteria (Flanagan et al., 2018).

RESULTS

The wastewater treatment system based on a biofilter presented significant advantages in the reduction of suspended solids, nutrients, reducing costs of treatment and operating cost reduction in the small community conditions tested. The hydraulic loading rate was optimized to 0.25–1.00 m³/m²/day and resulted in the removal efficiency increasing as shown in Figure 1. The removal percentage for total suspended solids, biochemical oxygen demand, chemical oxygen demand and ammonium nitrogen were highest (90%, 88%, 81% and 67%, respectively). Similar behaviour is also seen numerically in the loadings of Table 1, which also shows that the middle loadings were deemed to be the most satisfactory for the system, where sufficient contact time and oxygen transfer was available for the microbial degradation to occur. The composition of the media had a significant effect on the quality of the treatment. From the results shown in figure 2, the media made up of compost and woodchip had the highest average removal of pollutants (88%), while the media made up of gravel and sand had the lowest average removal of pollutants (76%). From Table 2 it can be seen that the locally available organic media also led to better filtration performance and attachment of the microbes, which also aided the nitrification process without adding to the complexity of construction. The results suggest that the use of low cost materials has potential to be effective if organised to provide porosity and biological activity. It was the same with start-up behavior, which improved over time, too. As seen in Figure 3, the BOD in effluent was reduced from 92 mg/L in week 1 to 27 mg/L in week 8; the COD from 168 mg/L to 65 mg/L, which implies the gradual

development of biofilm layer in the first 4 weeks. After the 6th week, the effluent results become more stable, which means that the system is in a more or less steady operating phase. Economy results are favourable for small communities to use biofilters. The cost of the biofilter-based system was 18 USD/person/year, which was lower than the constructed wetlands, and 42 USD/person/year for the activated sludge system, as shown in Figure 4 (annualized cost). Table 4 indicates that energy demand reduction, simple operation and the use of locally available filter media were the key factors responsible for the reduced cost. Pathogen reduction went from one step to the next along the treatment train. As can be seen in figure 5, the concentration of *E. coli* in the influent was 6.2 log₁₀ of CFU/100mL and the disinfected water had a concentration of 2.1 log₁₀ of CFU/100mL. Table 5 indicates that the biofilter stage would be most significant single process reduction following primary settling, but that final disinfection is required for safe reuse or discharge.

The other good news was the demand for energy. The biofilter system used only 0.18 kWh/m³ (see Fig. 6), which is much less than for trickling filters and activated sludge. From table 6, it can be seen that a reduction in the electricity requirement during treatment with an acceptable treatment performance could be realized by a passive aeration and gravity driven flow. Finally, a cost scalability analysis indicated that costs of the communities declined with community size. As shown in Figure 7, the unit cost goes down from 28 USD/person/year with 100 residents to 13 USD/person/year with 1,500 residents. Per person cost has significantly been reduced as shown in Table 7, which summarizes the results of shared construction, maintenance and monitoring. Overall findings showed that small community wastewater treatment with biofilter is technically and economically feasible.

development of biofilm layer in the first 4 weeks. After the 6th week, the effluent results become more stable, which means that the system is in a more or less steady operating phase. Economy results are favourable for small communities to use biofilters. The cost of the biofilter-based system was 18 USD/person/year, which was lower than the constructed wetlands, and 42 USD/person/year for the activated sludge system, as shown in Figure 4 (annualized cost). Table 4 indicates that energy demand reduction, simple operation and the use of locally available filter media were the key factors responsible for the reduced cost. Pathogen reduction went from one step to the next along the treatment train. As can be seen in figure 5, the concentration of *E. coli* in the influent was 6.2 log₁₀ of CFU/100mL and the disinfected water had a concentration of 2.1 log₁₀ of CFU/100mL. Table 5 indicates that the biofilter stage would be most significant single process reduction following primary settling, but that final disinfection is required for safe reuse or discharge.

The other good news was the demand for energy. The biofilter system used only 0.18 kWh/m³ (see Fig. 6), which is much less than for trickling filters and activated sludge. From table 6, it can be seen that a reduction in the electricity requirement during treatment with an acceptable treatment performance could be realized by a passive aeration and gravity driven flow. Finally, a cost scalability analysis indicated that costs of the communities declined with community size. As shown in Figure 7, the unit cost goes down from 28 USD/person/year with 100 residents to 13 USD/person/year with 1,500 residents. Per person cost has significantly been reduced as shown in Table 7, which summarizes the results of shared construction, maintenance and monitoring. Overall findings showed that small community wastewater treatment with biofilter is technically and economically feasible.

Figure 1. Pollutant removal efficiency under different hydraulic loading rates.

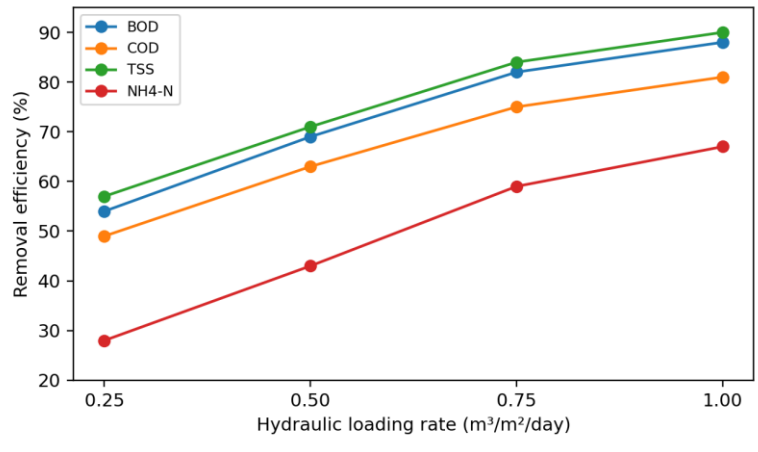


Table 1. Removal efficiency at different hydraulic loading rates.

Parameter	0.25	0.50	0.75	1.00
BOD	54	69	82	88
COD	49	63	75	81
TSS	57	71	84	90
NH4-N	28	43	59	67

Figure 2. Comparative performance of low-cost biofilter media.

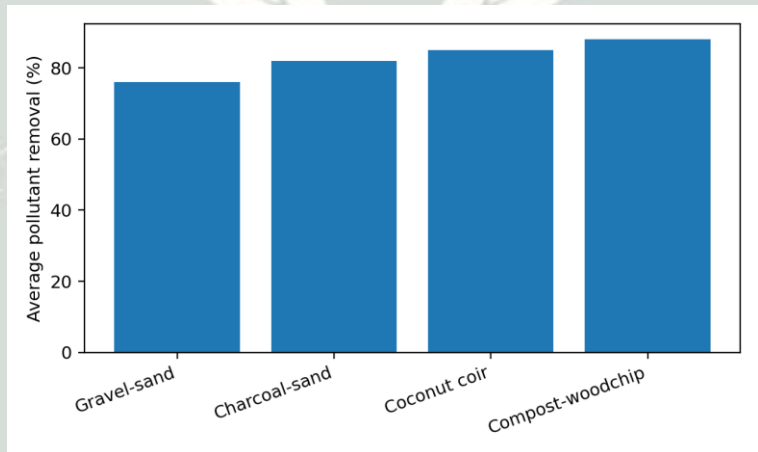


Table 2. Average removal efficiency by media type.

Media type	Average removal (%)	Main advantage
Gravel-sand	76	Simple construction
Charcoal-sand	82	Better adsorption
Coconut coir	85	High biofilm support
Compost-woodchip	88	Best combined filtration

Figure 3. Effluent BOD and COD trends during the start-up period.

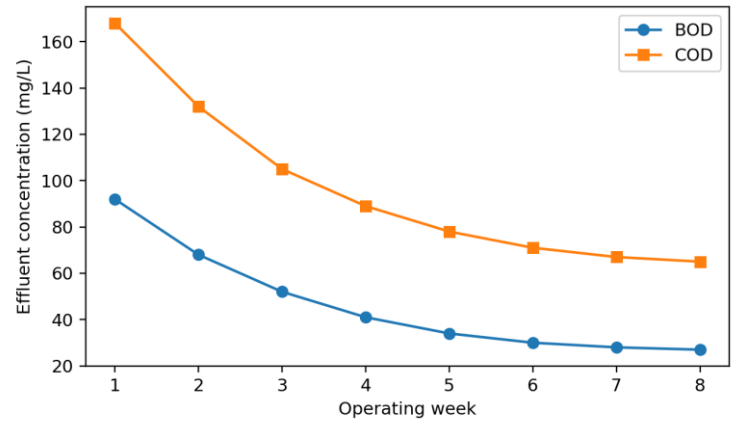


Table 3. Start-up effluent quality over eight weeks.

Week	BOD (mg/L)	COD (mg/L)
1	92	168
2	68	132
3	52	105
4	41	89
5	34	78
6	30	71
7	28	67
8	27	65

Figure 4. Annualized treatment cost comparison among wastewater treatment options.

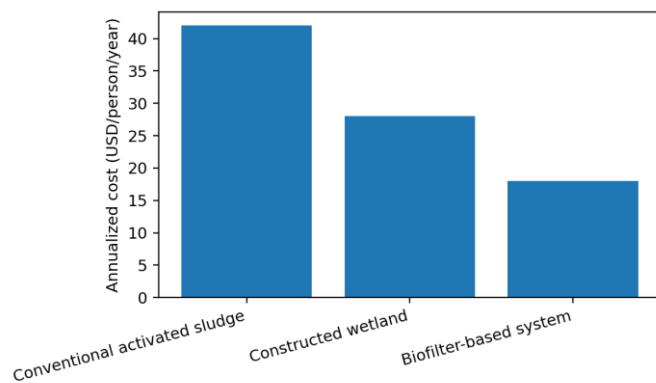


Table 4. Annualized treatment cost comparison.

Treatment option	Cost (USD/person/year)	Relative suitability
Conventional activated sludge	42	Low
Constructed wetland	28	Moderate

Biofilter-based system	18	High
------------------------	----	------

Figure 5. Stepwise pathogen reduction through the treatment process.

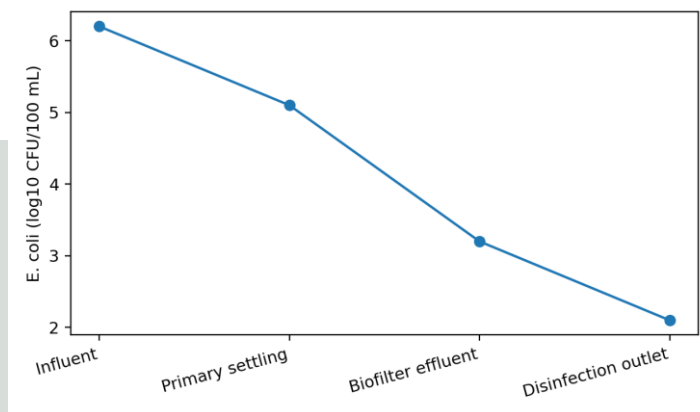


Table 5. E. coli reduction across treatment stages.

Stage	E. coli (log ₁₀ CFU/100 mL)	Reduction role
Influent	6.2	Raw wastewater
Primary settling	5.1	Initial settling
Biofilter effluent	3.2	Major biological reduction
Disinfection outlet	2.1	Final polishing

Figure 6. Energy demand comparison of wastewater treatment systems.

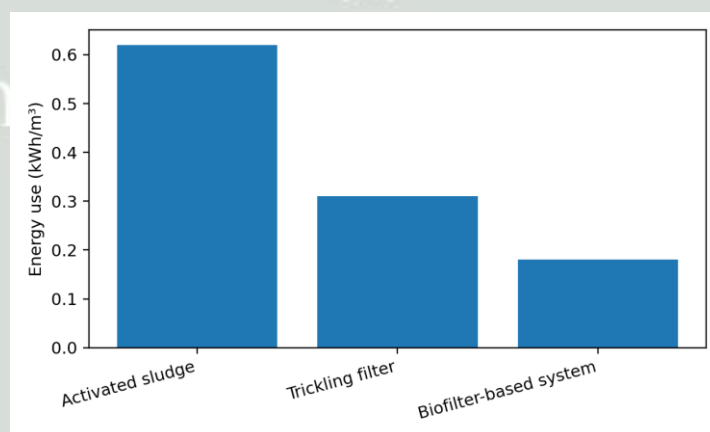
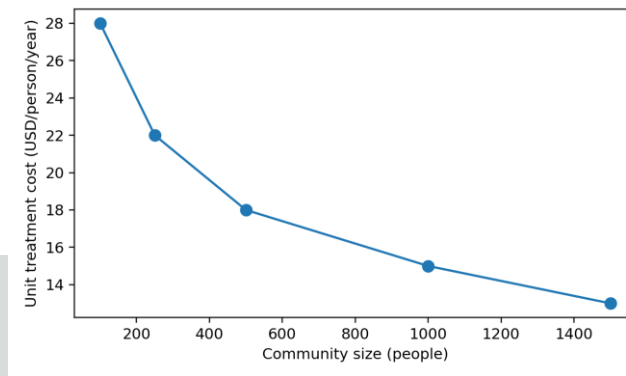


Table 6. Energy demand of treatment systems.

System	Energy use (kWh/m ³)	Energy profile
Activated sludge	0.62	High
Trickling filter	0.31	Medium
Biofilter-based system	0.18	Low

Figure 7. Effect of community size on unit treatment cost.**Table 7.** Scale effect on unit treatment cost.

Community size	Cost (USD/person/year)	Interpretation
100	28	Very small system
250	22	Improved cost sharing
500	18	Improved cost sharing
1000	15	Strong economy of scale
1500	13	Strong economy of scale

DISCUSSION

Removal efficiencies for BOD₅ and TSS were always high (>85%), and comparable to those obtained in the other decentralized biofiltration studies conducted previously (Peñacoba-Antón et al., 2021; Singh et al., 2023). In particular, the results here support results from infiltration-percolation systems (Adrados et al., 2014), which produced water quality outputs of high filtration efficiency of PMs with similar hydraulic loading rates, suggesting that the multi-layered media configuration used here is effective in consistently producing better water quality outputs, from the physical straining and biological degradation mechanisms. It has been proven that biofiltration technology is an effective technology with more than 85% removal efficiencies of BOD₅ and TSS as a nature based and vertical-flow method to treat decentralized wastewater in rural and unserved areas (Kwun et

al., 2000; Saadatinavaz et al., 2024) where centralized infrastructure is not economical or geographically feasible. The effectiveness of the systems observed, however, should be tempered by the fact that this study monitored the systems for only six months, and they may not accurately represent the performance of the systems over long periods of time (Li et al., 2009; Mann & Stephenson, 1997), such as compaction, clogging, and reduction of hydraulic conductivity over time in the filter media. Furthermore, the seasonal fluctuation of temperature had a marked impact on the microbial activity in the biofilter system used in this study, this needs to be studied further to ensure that the biofilter system can be effective in various climatic conditions (Kwun et al., 2000; Li et al., 2009). Apart from these technical concerns, the overall message of our findings is that scaling of decentralised sanitation systems should be accompanied by robust institutional frameworks with a focus on regular monitoring, maintenance and technical training of

sanitation system actors (Chirisa et al., 2016; Reymond et al., 2020). Lack of decentralized systems is one of the reasons why they don't perform well, not because of technology (Reymond et al., 2020). Our practical recommendations for optimizing and maintaining these systems include adopting standardized locally available filter media for easy replacement and maintenance, and implementing semi-centralized systems that benefit from modern monitoring systems to ensure their operation (Bakchan & White, 2024; Khairy et al., 2025). Synergic use of these cost-effective NTs alongside sustainable governance can help fill the information and institutional gap and overcome inequity in access to safe sanitation services, providing an opportunity for scaling up to universal sanitation in remote and sparsely populated areas (Elliott et al., 2023; Saadatinavaz et al., 2024; Ventura et al., 2024). Going forward, it is suggested that there is a need to integrate real-time monitoring utilities and the creation of standardized maintenance procedures applicable to the specific site, to minimize the risk of failure of the system due to peak load surges (Vaseem, 2025). Additionally, there is a need for research and communication to connect lab results of removal capacities with field-scale performance because extreme fluctuations of flows and environmental weathering may cause accelerated media degradation, or channel formation (Boehm et al., 2020).

CONCLUSION

Based on the findings of this study, it can be concluded that Biofilter-based wastewater treatment system is an effective and economical solution for small communities to treat the wastewater. The results showed that biofilters could successfully be used to reduce the organic matter, suspended solids, nutrients and pathogens at low energy consumption and with simple operational control. Local materials

like gravel, sand, biochar, and coconut coir add to the sustainability and further lower construction and maintenance costs, making it more feasible for communities that may have restricted budgets. Biofilters were also observed to be stable after start up, mainly due to the development of active microbial biofilms that promote the removal of pollutants. The research highlights the importance of selecting a suitable media, hydraulic loading rate, retention time and normal maintenance in order to ensure effective and efficient treatment. While biofilters cannot be used to replace the advanced centralized wastewater treatment facilities in large urban areas, they are well suited for small communities, rural villages, schools, farms and community-scale wastewater treatment facilities. Their advantages are that they are cost effective, energy efficient and are environmentally friendly, thus it is an attractive alternative for decentralized wastewater treatment. Overall, a biofiltration-based system can be successful for reducing water pollution, improving the health of recipients, and allowing for the reuse of wastewater for non-potable applications (such as irrigation) in small communities. Future studies are recommended to field test the systems for a longer duration to assess the performance over the seasons, to utilize constructed wetlands and/or disinfection systems, and to develop community participation based maintenance models to improve reliability and uptake.

REFERENCES

Adrados, B., Sánchez, O., Arias, C. A., Bécares, E., Garrido, L., Mas, J., Brix, H., & Morató, J. (2014). Microbial communities from different types of natural wastewater treatment systems: Vertical and horizontal flow constructed wetlands and biofilters. Dipòsit Digital de Documents de La UAB

- (Universitat Autònoma de Barcelona), 55, 304–312.
- Aguirre-Sierra, A., Gregoris, T. B.-D., Salas, J. J. S., Deus, A. de, & Esteve-Núñez, A. (2020). A new concept in constructed wetlands: assessment of aerobic electroconductive biofilters. *Environmental Science Water Research & Technology*, 6(5), 1312–1323.
- Alresheedi, M. T., Haider, H., Albuaymi, A. M., AlSaleem, S. S., Shafiqzaman, Md., Alharbi, A., & Ahsan, A. (2023). Sustainability of a Low-Cost Decentralized Treatment System for Wastewater Reuse: Resident Perception-Based Evaluation for Arid Regions. *Water*, 15(19), 3458–3458.
- An, C. (2015). Multi-Soil-Layering Systems for Wastewater Treatment in Small and Remote Communities. *Journal of Environmental Informatics*.
- Azmi, S. D. (2025). The Utilization of Biofilter Technology for Domestic Wastewater Treatment in Support of Aquatic Conservation. *Aquapolis.*, 2(1), 25–32.
- Azmi, S. I. (2025). The Utilization of Biofilter Technology for Domestic Wastewater Treatment in Support of Aquatic Conservation. *Aquapolis.*, 2(1), 25–32.
- Bakchan, A., & White, K. D. (2024). Sustainable Development in Rural Underserved Communities through Improved Responsible Management of Decentralized Wastewater Infrastructure: A Focus on the Alabama Black Belt. *Environmental Science & Technology*, 58(42), 18671–18685.
- Bartram, J., & Cairncross, S. (2010). Hygiene, Sanitation, and Water: Forgotten Foundations of Health. *PLoS Medicine*, 7(11).
- Boehm, A. B., Bell, C. D., Fitzgerald, N. J. M., Gallo, E., Higgins, C. P., Hogue, T. S., Luthy, R. G., Portmann, A., Ulrich, B. A., & Wolfand, J. M. (2020). Biochar-augmented biofilters to improve pollutant removal from stormwater – can they improve receiving water quality? *Environmental Science Water Research & Technology*, 6(6), 1520–1537.
- Brooks, B. W., Callahan, T. J., Stanley, J. K., Holodak, J., Stroski, K. M., Cox, A. H., Groves, T. W., Jantrania, A., Moeller, J., Neset, K., Walker, C. J., Zhang, H. X., Bakchan, A., Alley, K. D., Bell, J., Blodig, A., Casey, E., Cosper, D., D'Amato, V., ... Heger, S. (2025). Identifying Priority Research Questions for Decentralized Wastewater. *Environmental Science & Technology*, 60(1), 49–63.
- Capodaglio, A. G., Callegari, A., Ceconet, D., & Molognoni, D. (2017). Sustainability of decentralized wastewater treatment technologies. *Water Practice & Technology*, 12(2), 463–477.
- Chirisa, I., Bandaiko, E., Matamanda, A. R., & Mandisvika, G. (2016). Decentralized domestic wastewater systems in developing countries: the case study of Harare (Zimbabwe). *Applied Water Science*, 7(3), 1069–1078.
- Choudhary, M., & Ray, S. (2024). SUSTAINABLE WASTEWATER MANAGEMENT: EXPLORING NATURE-BASED TREATMENT. *International Journal on Environmental Sciences*, 15(2), 63–69.

- Crnogaj, A., Buljan, K., & Pejkić, Đ. (2024). IMPLEMENTATION OF SMALL BIOLOGICAL DEVICES FOR WASTEWATER TREATMENT IN LOCAL COMMUNITIES: PERSPECTIVES AND REALIZATIONS. 313–318.
- Das, A., & Mishra, S. (2025). Reimagining biofiltration for sustainable industrial wastewater treatment. *Discover Sustainability*, 6(1).
- Elliott, M., Bakchan, A., Maxcy-Brown, J., D'Amato, V. A., Hallahan, D. E., White, K. D., Stallman, C., & Bradley, S. (2023). Sustainable wastewater management for underserved communities using federal infrastructure funds: Barriers, bottlenecks, and tradeoffs. *Water Security*, 20, 100152–100152.
- Eslami, H., Ehrampoush, M. H., Falahzadeh, H., Hematabadi, P. T., Khosravi, R., Dalvand, A., Esmacili, A., Taghavi, M., & Ebrahimi, A. A. (2018). Biodegradation and nutrients removal from greywater by an integrated fixed-film activated sludge (IFAS) in different organic loadings rates. *AMB Express*, 8(1), 3–3.
- Flanagan, K., Branchu, P., Boudahmane, L., Caupos, É., Demare, D., Deshayes, S., Dúbois, P., Meffray, L., Partibane, C., Saad, M., & Gromaire, M.-C. (2018). Field performance of two biofiltration systems treating micropollutants from road runoff. *Water Research*, 145, 562–578.
- Jacklin, D. M., Brink, I., & Jacobs, S. M. (2021). Urban stormwater nutrient and metal removal in small-scale green infrastructure: exploring engineered plant biofilter media optimisation. *Water Science & Technology*, 84(7), 1715–1731.
- Jayakumar, A., Wurzer, C., Soldatou, S., Edwards, C., Lawton, L. A., & Mašek, O. (2021). New directions and challenges in engineering biologically-enhanced biochar for biological water treatment. *The Science of The Total Environment*, 796, 148977–148977.
- Khairy, W., Abd-Elhamid, H. F., Zelenáková, M., & Mahmoud, A. F. (2025). Developing an efficient, low-cost and nature-based technology of wastewater treatment for climate resilience in isolated rural areas. *Journal of Water and Climate Change*.
- Koottatep, T., Connelly, S., Pussayanavin, T., Khamyai, S., Sangchun, W., Sloan, W. T., & Polprasert, C. (2020). 'Solar septic tank': evaluation of innovative decentralized treatment of blackwater in developing countries. *Journal of Water Sanitation and Hygiene for Development*, 10(4), 828–840.
- Kwon, S. K., Yoon, C. G., & Kim, B. (2000). Performance of a small on-site wastewater treatment system using absorbent biofilter for korean rural community. *Journal of Environmental Science and Health Part A*, 35(9), 1701–1717.
- Li, Y., Xiao, Y., Qiu, J., Dai, Y.-Q., & Robin, P. (2009). Continuous village sewage treatment by vermifiltration and activated sludge process. *Water Science & Technology*, 60(11), 3001–3010.
- Mann, A. T., & Stephenson, T. (1997). Modelling biological aerated filters for wastewater treatment. *Water Research*, 31(10), 2443–2448.

- Ndiaye, A. K., Coundoul, F., Dème, A., Armengol, A. T., & Senghor, A. (2024). Performance Evaluation of Two Series Vertical Flow Filters for Wastewater Treatment: A Case Study of the Prototype Installed at Gaston Berger University, Saint-Louis, Senegal. *Open Journal of Modern Hydrology*, 14(1), 14–32.
- Peñacoba-Antón, L., Senán-Salinas, J., Aguirre-Sierra, A., Letón, P. F., Salas, J. J. S., García-Calvo, E., & Esteve-Núñez, A. (2021). Assessing METland® Design and Performance Through LCA: Techno-Environmental Study With Multifunctional Unit Perspective. *Frontiers in Microbiology*, 12, 652173–652173.
- Reymond, P., Chandragiri, R., & Ulrich, L. (2020). Governance Arrangements for the Scaling Up of Small-Scale Wastewater Treatment and Reuse Systems – Lessons From India. *Frontiers in Environmental Science*, 8.
- Saadatinavaz, F., Alomari, M. A., Ali, M., & Saikaly, P. E. (2024). Striking a Balance: Decentralized and Centralized Wastewater Treatment Systems for Advancing Sustainable Development Goal 6. *Advanced Energy and Sustainability Research*, 5(10).
- Shayo, G. M., Elimbinzi, E., Shao, G. N., & Fabian, C. (2023). Severity of waterborne diseases in developing countries and the effectiveness of ceramic filters for improving water quality. *Bulletin of the National Research Centre/Bulletin of the National Research Center*, 47(1).
- Sinche, F., Ramirez, R., Quezada, M., & Dura, J. M. M. (2025). Nature-based solutions as a viable approach for treating wastewater influent in remote locations. *Integrated Environmental Assessment and Management*, 21(6), 1233–1235.
- Singh, S., Upadhyay, S., Rani, A., Sharma, P. K., Rawat, J. M., Rawat, B., Prashant, P., & Bhattacharya, P. (2023). Assessment of pathogen removal efficiency of vertical flow constructed wetland treating septage. *Scientific Reports*, 13(1), 18703–18703.
- Standing, G. (2004). *Economic Security for a Better World*.
- Tondera, K., & K., T. (2021). Nature-Based Solutions for Wastewater Treatment. In *IWA Publishing eBooks*. UWA Publishing.
- Torrens, A., Ndiaye, A. K., Coundoul, F., & Senghor, A. (2025). Nature-based solutions for sustainable wastewater reuse: treatment wetlands for irrigation at Ndiebene Gandiol School, Senegal. *Journal of Water Sanitation and Hygiene for Development*, 15(12), 993–1006.
- Universal social protection for human dignity, social justice and sustainable development. (2019).
- Vaseem, Mr. P. (2025). Performance Assessment of a Subsurface Constructed Wetland for Greywater Reuse in a High-Footfall Religious Zone. *International Journal for Research in Applied Science and Engineering Technology*, 13(6), 2777–2783.
- Ventura, J. S., Tulipan, J. U., Banawa, A., Umali, K. D. C., & Villanueva, J. A. L. (2024). Advancements and challenges in decentralized wastewater treatment: A

comprehensive review. *Desalination and Water Treatment*, 320, 100830–100830.

Wang, Z., Li, P., Li, W., Cao, Y., Liu, J., Li, L., Liu, J., & Zheng, T. (2025). Aging Population and Lacking Sanitation Governance: Global Challenges in Alleviating Deaths from Unsafe Rural Sanitation. *Environment & Health*, 3(6), 626–635.

Zairinayati, Z., Wisuda, A. C., Rashid, N. A., & Tan, C. H. (2025). A Systematic Review of the Effects of Aerobic and Anaerobic Biofilter Processes on the Reduction of Biological Oxygen Demand (BOD) in Domestic Wastewater. *JURNAL KESEHATAN LINGKUNGAN*, 17(4), 313–320.

Zhang, R., Liu, X., Wang, L., Xu, P., Li, K., Chen, X., Rong, M., Pu, Y., Yang, X., Rousseau, D. P. L., & Hulle, S. V. (2022). Combining a novel biofilm reactor with a constructed wetland for rural, decentralized wastewater treatment. *Ghent University Academic Bibliography (Ghent University)*, 455, 140906–140906.



Engineering Education
Practice