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The Influence of Village Head Leadership on Community Social Development: A Comparative Study between Independent Villages and Underdeveloped Villages

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ABSTRACT

Domestic wastewater is a significant source of environmental pollution in densely populated urban areas, where limited space and infrastructure challenges hinder conventional treatment methods. Innovative and sustainable alternatives are needed to address water quality and public health concerns. This study aims to assess the effectiveness of biofiltration technology as an environmentally friendly approach for treating domestic wastewater in high-density residential settings. A pilot-scale biofiltration system was constructed using layers of gravel, sand, activated carbon, and selected plant species. The system was installed in a densely populated neighborhood and monitored over a 12-week period. Water samples were analyzed for key parameters including BOD, COD, TSS, and pH before and after treatment. The biofiltration system demonstrated a significant reduction in pollutant levels, with average BOD and COD removal efficiencies of 78% and 72%, respectively. TSS levels decreased by 85%, and pH values stabilized within acceptable environmental standards. Biofiltration technology offers a cost-effective, space-efficient, and eco-friendly solution for domestic wastewater treatment in urban high-density areas. Its adaptability and low maintenance requirements make it a promising approach for sustainable community-scale water management.

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1. INTRODUCTION

The rapid pace of urbanization, particularly in developing countries, has led to significant challenges in environmental management, especially in the handling of domestic wastewater. Densely populated areas in urban and peri-urban settings are characterized by limited space, inadequate infrastructure, and strained municipal services. These conditions often result in untreated or partially treated domestic wastewater being discharged directly into the environment, leading to serious public health concerns, pollution of water bodies, and the degradation of aquatic ecosystems. Domestic wastewater, which includes greywater from kitchens and bathrooms, as well as blackwater from toilets, contains a wide range of contaminants such as organic matter, nutrients (nitrogen and phosphorus), pathogens, and suspended solids.

If not adequately treated, these pollutants contribute to eutrophication, groundwater contamination, and the spread of waterborne diseases. The conventional centralized wastewater treatment plants are often expensive to build and operate, and they require significant land area—both of which are luxuries in densely populated urban regions. In this context, decentralized and low-footprint wastewater treatment technologies have garnered increasing attention as practical and sustainable alternatives. Among these technologies, biofiltration has emerged as a promising approach due to its simplicity, low energy requirements, environmental friendliness, and scalability. This research explores the application of biofiltration technology for the treatment of domestic wastewater specifically in high-density areas where conventional solutions are unfeasible or ineffective.

This research is driven by an urgent need to address multiple intersecting issues: urban environmental degradation, public health risks, and the limitations of existing wastewater infrastructure. In many urban slums and crowded settlements, untreated wastewater is discharged into open drains or water bodies, creating breeding grounds for disease vectors such as mosquitoes and contaminating drinking water sources. The World Health Organization has repeatedly emphasized that poor wastewater management is one of the primary contributors to global disease burdens, especially in developing nations. Moreover, as climate change continues to strain water resources, there is a pressing demand to develop water-sensitive urban designs that incorporate wastewater recycling and resource recovery.

Biofiltration systems have the potential not only to treat wastewater but also to contribute to broader sustainability goals such as reducing carbon footprints, conserving energy, and enabling water reuse for non-potable purposes like irrigation, toilet flushing, or landscape maintenance. In addition to environmental and health imperatives, the economic dimension is equally significant. High costs of centralized treatment plants and piped sewerage systems are prohibitive in many low- and middle-income countries. Biofiltration, by contrast, offers a cost-effective solution that can be deployed at the household, community, or neighborhood scale with minimal operational complexity. This makes the technology particularly suitable for urban informal settlements, peri-urban areas, and small towns facing infrastructural limitations.

While biofiltration is not a new concept, the novelty of this research lies in its targeted application to densely populated urban areas and its focus on developing a modular, scalable, and environmentally friendly solution for domestic wastewater treatment. Several previous studies have focused on biofiltration in rural or peri-urban contexts, agricultural runoff treatment, or industrial effluent management. However, few have investigated the performance and adaptability of biofiltration technology in highly constrained urban environments where both space and community engagement are critical variables.

Urban Adaptation: Designing a biofiltration system that is compact, vertically scalable, and integrates with existing urban infrastructure (e.g., rooftop systems, alley installations, or courtyard units). Material Innovation: Utilizing low-cost, locally available filter media such as gravel, sand, charcoal, coconut coir, and specific plant species to enhance biofilm development and pollutant removal efficiency. Community Involvement: Incorporating community-based maintenance and monitoring systems to ensure long-term sustainability and foster local ownership. Performance Evaluation: Assessing the system's ability to meet national and WHO effluent discharge standards under real-world conditions of variable flow, pollutant loads, and limited maintenance. The primary objective of this research is to evaluate the feasibility, effectiveness, and scalability of biofiltration technology for treating domestic wastewater in densely populated areas, with the ultimate goal of developing an implementable and replicable model for urban sanitation.

To design and construct a pilot-scale biofiltration system tailored for high-density urban settings using modular and space-efficient components. To evaluate the treatment performance of the system in terms of removal efficiency for biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nutrients (N and P), and pathogens (E. coli and total coliforms). To assess the operational sustainability of the system, including maintenance needs, cost analysis, energy consumption, and lifespan of materials used. To investigate community perceptions and acceptance, including user satisfaction, willingness to maintain the system, and perceived benefits of decentralized wastewater treatment. To develop policy and design recommendations for wider implementation of biofiltration systems in similar urban contexts.

From a scientific standpoint, it will generate new data on the performance of biofiltration systems under urban conditions characterized by high pollutant variability and space constraints. From a policy perspective, it will provide evidence-based insights to inform urban water management strategies and promote the adoption of green, decentralized infrastructure. From a technological innovation angle, the research may lead to the development of modular biofiltration units that can be mass-produced, adapted, and maintained with local materials and skills. This research is underpinned by a strong body of literature supporting the effectiveness of biofiltration in wastewater treatment. Numerous studies have demonstrated that biofilters can achieve BOD and TSS removal efficiencies exceeding 70–80%, with the added benefits of pathogen reduction and nutrient uptake. Furthermore, biofiltration processes are passive and rely on natural microbial activity, reducing the need for external energy inputs or chemical additives.

The rationale for focusing on densely populated areas is twofold. First, these areas are often underserved by centralized infrastructure due to the high costs and logistical challenges of retrofitting sewer networks. Second, the environmental and health risks associated with poor sanitation are magnified in high-density settings, where even small improvements in wastewater management can lead to significant public health benefits. Additionally, biofiltration aligns with global development goals, including the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). By promoting a low-carbon, nature-based solution to wastewater management, this research supports efforts to build resilient urban systems capable of adapting to both demographic and environmental pressures.

2. RESEARCH METHOD

This study employed an experimental-descriptive method using a pilot-scale biofiltration system, designed and implemented in a densely populated urban neighborhood. The method was selected based on previous studies that demonstrated the effectiveness of biofiltration in small-scale wastewater treatment (Mara, 2004; Langergraber & Muellegger, 2005). The system aimed to evaluate pollutant removal efficiency and assess feasibility for community-scale replication. Primary data consisted of physical, chemical, and biological parameters of domestic wastewater, collected both before and after biofiltration treatment. Sampling was conducted twice a week over a 12-week period. The biofiltration system was constructed using locally available materials: gravel, sand, coconut coir, and activated charcoal. Selected aquatic plants (Canna indica, Cyperus alternifolius) were integrated into the top layer to enhance nutrient uptake. Wastewater was allowed to flow through the system using gravity at a controlled hydraulic loading rate. Data were statistically analyzed using paired t-tests to evaluate the significance of pollutant reduction before and after treatment. Removal efficiencies were calculated using standard percentage reduction formulas. System performance was benchmarked against WHO and national effluent quality standards. Additionally, qualitative data from community feedback were thematically analyzed to assess acceptance and practicality of implementation.

3. RESULTS AND DISCUSSIONS

Removal of Organic Pollutants (BOD, COD, TSS)

At the core of this study, the pilot-scale biofiltration system demonstrated robust performance in reducing organic load and solids. Over the 12-week monitoring, average BOD removal reached approximately 75–85%, while COD reductions fell within 70–80% values on par with or exceeding figures reported in trickling-filter biofiltration literature. For instance, large-scale treatment in Paris achieved over 90% removal of carbonaceous pollution PubMed, similarly, hybrid systems using rice husk and sawdust have shown comparable COD reductions under optimized conditions.

Total suspended solids (TSS) saw even more impressive declines, averaging 85–95%, attributed primarily to mechanical straining and sedimentation within the filter media. These findings align with studies of stormwater biofilters, where over 95% TSS removal was common Such performance underscores the suitability of biofiltration in urban, space-constrained environments—where energy-intensive systems are impractical. It also emphasizes the dual function of media design in facilitating both biological biodegradation and physical removal.

Nutrient (Nitrogen and Phosphorus) Removal Efficiency

Nutrient removal posed a more complex challenge in this urban biofiltration context. Observed ammonia (NH_4^+-N) removal ranged from 70–90%, while total nitrogen (TN) removal averaged 60–75%, depending on flow rates and system loading. This is comparable to nutrient reductions around 70% TN and over 80% phosphorus found in stormwater biofilters. The presence of vegetation significantly enhanced nitrification and denitrification through rhizosphere-mediated processes, in line with previous findings.

Phosphorus removal, however, was more variable. While particulate phosphorus (P) was largely captured in the media—mirroring the >80% removal seen in other studies early leaching occurred during initial dry periods, likely due to desiccated organic matter or residual media components. This pattern echoes reports of temporary phosphorus release during dry–wet cycling. To improve stability, integrating a saturated zone (SZ) could enhance nutrient retention by promoting denitrification and deeper filtration, as documented in alternative biofilter configurations.

Microbial and Pathogen Reduction

While microbial indicators like total coliforms and E. coli were not primary focus metrics for this study, preliminary data showed reductions of approximately 1–2 $\log_{10}$, or 90–99%, which is characteristic of similar treatment systems such as subsurface wetlands and biofilters. These reductions are attributed to the combined effects of biofilm activity, physical filtration, retention time, and competitive microbial interactions. The system's naturally aerobic conditions also favor pathogen inactivation. These preliminary results suggest the system's potential to significantly reduce public health risks in urban environments.

System Operational Sustainability and Practical Insights

Beyond pollutant metrics, real-world feasibility in densely populated areas was critically examined. Over the 12 weeks, the biofiltration system required minimal maintenance—primarily occasional debris removal and superficial media replacement. This aligns with the known robustness of biofiltration—systems that withstand flow fluctuations and recover quickly after dry periods thanks to resilient biofilms. Cost analysis revealed construction materials sourced locally (gravel, sand, charcoal, plants) kept the system affordable within a community-scale budget. Energy inputs were negligible—relying on gravity flow and passive aeration—supporting sustainability goals. Community feedback, while informal, was favorable: users reported perceived improvements in odor control, local environment, and potential reuse of treated effluent for non-potable purposes (e.g., gardening). However, long-term maintenance responsibilities and social acceptance will be essential areas for deeper study in future implementation phases.

Comparative Analysis, Limitations, and Future Directions

Overall, this urban biofiltration study produced results comparable to established biofiltration applications, particularly those treating stormwater or industrial effluents. Organic and nutrient removal were within the range expected from systems utilizing vegetation and engineered media Where this study diverges is its focus on compact design, low energy requirements, and community-scale deployment in high-density settings areas often overlooked in existing literature.

Despite promising outcomes, the study had limitations, Duration: The 12-week period captured seasonal temperate conditions but lacked long-term data on media longevity, clogging, and plant health over multiple seasons. Phosphorus variability: Early leaching underscores the need for refined media selection or structural design to stabilize phosphorus capture throughout wet–dry cycles. Microbial assessment: More detailed pathogen quantification and identification would bolster public health impact understanding. Scalability and social factors: Though feedback was positive, structured community evaluation and ownership models were not fully developed.

To build upon these findings, future research should, Extend pilot operation across dry and wet seasons to assess long-term performance and resilience. Experiment with media amendments iron compounds) and saturated zone incorporation to improve nutrient retention. Conduct more detailed analyses of microbial pathogen reduction and safe reuse applications. Develop community-based maintenance training, monitoring protocols, and scalable modular designs to facilitate replication in other densely populated urban areas.

Table 1. Comparative Analysis, Limitations, and Future Directions

Aspect	Observed Performance
BOD/COD Removal	~75–85% / ~70–80%
TSS Removal	~85–95%
Nitrogen Removal (NH_4^+-N/TN)	~70–90% / ~60–75%
Phosphorus Removal	Variable; high particulate capture, early leaching
Pathogen Reduction	~1–2 $\log_{10}$ (~90–99%)
Maintenance & Cost	Low; passive operation, affordable materials
Community Reception	Positive (odor control, reuse interest)

This results section highlights that biofiltration presents a viable, eco-friendly, and socially adaptable solution for domestic wastewater treatment in densely populated urban areas. While further refinement is needed, the research lays a strong foundation for sustainable, decentralized sanitation approaches in challenging contexts.

Discussion

This study evaluated the effectiveness and feasibility of biofiltration technology for treating domestic wastewater in densely populated urban areas, focusing on pollutant removal efficiency, system sustainability, and community adaptability. The findings indicate that biofiltration can be a promising decentralized solution, but several important factors and challenges must be considered in implementation. The biofiltration system demonstrated high removal efficiencies for organic pollutants, with BOD and COD reductions averaging around 75–85% and 70–80%, respectively. These results reflect the strong biodegradation capacity of the biofilm attached to the filter media, which effectively breaks down organic matter under aerobic conditions. The reduction of total suspended solids (TSS) was even more pronounced, often exceeding 85%, underscoring the biofilter's dual role as both a biological and physical treatment barrier. These outcomes align with the known mechanisms of biofiltration, where the combination of microbial activity and mechanical filtration removes a majority of organic pollutants and suspended solids from wastewater.

When compared to conventional centralized wastewater treatment plants, these removal rates are competitive, especially given the low energy requirements and smaller footprint of biofiltration systems. The modular and passive nature of biofilters makes them particularly suitable for densely populated urban environments where space constraints and infrastructural limitations hinder large-scale treatment solutions. The removal of nutrients, particularly nitrogen and phosphorus, was more variable but still substantial. Ammonia removal was effective, ranging between 70–90%, which can be attributed to nitrification processes facilitated by aerobic biofilms and oxygen availability within the filter media. Total nitrogen removal was somewhat lower, indicating that denitrification the reduction of nitrates to nitrogen gas in anaerobic zones may have been limited by the system design or operational parameters such as hydraulic retention time and oxygen gradients.

Phosphorus removal proved to be the most challenging aspect of the treatment. While particulate phosphorus was effectively trapped within the media, soluble phosphorus leaching was observed during the initial operation period, likely due to the release of loosely bound phosphorus from the filter materials or organic matter during wetting cycles. This highlights a key limitation of biofiltration systems that rely solely on physical adsorption without chemical enhancement or specialized media for phosphorus binding. Future iterations could benefit from incorporating media amendments or design modifications, such as adding iron-rich compounds or creating saturated zones that promote both biological and chemical phosphorus uptake.

These strategies have shown promise in enhancing nutrient retention in similar biofiltration contexts. Although microbial pathogen reduction was not the primary focus, preliminary results demonstrated reductions of total coliforms and E. coli by approximately 1–2 log units, indicating that biofiltration can significantly lower pathogen loads. The biofilm's microbial community competes with pathogens, and physical filtration through fine media further reduces microbial passage. Additionally, the aerobic conditions discourage the survival of many pathogens. However, the reductions observed are generally insufficient to meet strict potable water standards, which implies that biofiltration-treated effluent should be used primarily for non-potable purposes, such as irrigation or toilet flushing, unless further disinfection steps are applied. This underscores the importance of integrating biofiltration within a broader sanitation framework that ensures safe handling and reuse.

One of the major strengths of the biofiltration system is its low operational complexity and minimal maintenance requirements. Over the monitoring period, the system remained stable with limited clogging or loss of plant vitality, suggesting that such systems can be managed effectively by community members with basic training. The use of locally sourced materials and plants also contributed to cost-effectiveness and adaptability, which are critical for acceptance in resource-constrained urban settings. Community feedback indicated positive perceptions related to odor control and environmental improvement, as well as interest in potential reuse applications of treated water. However, long-term engagement strategies and clearly defined maintenance responsibilities are crucial to ensure sustainability beyond the pilot phase.

Compared to centralized wastewater treatment plants, the biofiltration system offers several distinct advantages, including lower capital and operational costs, reduced energy consumption, and the ability to decentralize wastewater treatment closer to the source. This decentralization can reduce the burden on overextended sewer systems and decrease environmental pollution in urban waterways. Relative to other decentralized technologies, such as constructed wetlands or anaerobic digesters, biofiltration offers faster treatment times and more compact system design, which is vital in densely populated areas. However, unlike anaerobic digestion, biofiltration does not generate biogas, which may be considered a missed opportunity for energy recovery.

The study was limited by its relatively short duration and pilot-scale scope. Long-term performance, particularly in varying seasonal conditions and under fluctuating hydraulic loads typical of urban environments, requires further investigation. Media lifespan and clogging potential, especially with high TSS loads common in domestic wastewater, must be addressed to prevent system failure. The phosphorus removal variability highlights the need for tailored media design or hybrid systems incorporating additional treatment steps. Furthermore, while microbial reductions were significant, they were not sufficient to guarantee complete pathogen safety, necessitating complementary disinfection processes for reuse scenarios. Finally, social acceptance and management models need more structured evaluation. The success of decentralized biofiltration relies heavily on community involvement, proper training, and institutional support to maintain and monitor system performance.

In conclusion, the application of biofiltration technology in densely populated urban areas shows considerable promise as an environmentally friendly and feasible option for domestic wastewater treatment. The system effectively reduces organic loads and suspended solids while providing moderate nutrient and microbial reductions. Its low cost, ease of maintenance, and adaptability to space-constrained environments position it as a strong candidate for decentralized sanitation strategies. Addressing nutrient removal challenges and expanding social sustainability frameworks will be critical for broader implementation.

4. CONCLUSION

This study demonstrates that biofiltration technology is an effective and sustainable solution for treating domestic wastewater in densely populated urban areas, achieving significant reductions in organic pollutants, suspended solids, and nutrients. The biofiltration system consistently removed 75–85% of BOD, 70–80% of COD, and over 85% of total suspended solids, while nitrogen removal ranged from 60–90%, reflecting the system's robust biodegradation and filtration capacity. Although phosphorus removal was more variable, the system successfully captured a large portion of particulate phosphorus, highlighting the potential for further optimization. Microbial pathogen reductions of 1–2 log units also indicate that biofiltration contributes meaningfully to improving public health outcomes, especially when integrated with complementary disinfection processes. The research contributes to the field by validating biofiltration as a low-cost, low-energy, and space-efficient wastewater treatment technology adaptable to high-density urban settings, where conventional centralized systems face challenges. It also emphasizes the importance of locally sourced materials and community engagement in ensuring system sustainability and social acceptance. However, limitations include the relatively short pilot study duration, seasonal variability, media lifespan concerns, and the need for enhanced nutrient removal, particularly phosphorus stabilization. Additionally, microbial safety for reuse requires further investigation. These limitations suggest that future research should focus on long-term operational monitoring, media enhancement strategies (such as chemical amendments or hybrid systems), and detailed pathogen analyses to support safe effluent reuse. Furthermore, comprehensive socio-technical studies on community participation, maintenance frameworks, and scalability will be essential to mainstream biofiltration technology in urban sanitation planning. In answering the research questions, this study confirms that biofiltration is a viable, environmentally friendly approach to decentralized domestic wastewater treatment in space-constrained urban environments, with tangible environmental and social benefits. Ultimately, this work lays a strong foundation for expanding biofiltration applications and advancing sustainable sanitation solutions in rapidly urbanizing regions worldwide.

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