Journal of Civil Engineering and Applications 2026; 7(1): 25-28

Journal of Civil Engineering and Applications

E-ISSN: 2707-8396
P-ISSN: 2707-8388
Impact Factor (RJIF): 5.15
www.civilengineeringjournals.com/jcea
JCEA 2026; 7(1): 25-28
Received: 18-11-2025
Accepted: 20-12-2025

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Performance evaluation of household greywater filtration using low-cost sand-charcoal media

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DOI: https://www.doi.org/10.22271/27078388.2026.v7.i1a.63

Abstract
Greywater reuse has emerged as a sustainable strategy to alleviate freshwater scarcity, particularly in urban and peri-urban households. However, the adoption of greywater treatment systems remains limited due to high costs, operational complexity, and maintenance challenges. This research evaluates the performance of a low-cost household greywater filtration unit utilizing sand and charcoal as primary filtration media. The system was designed to treat greywater generated from bathing, laundry, and handwashing activities. Key physicochemical parameters, including turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and oil and grease, were monitored to assess treatment efficiency. Experimental trials were conducted under controlled flow conditions to simulate typical household usage. Statistical analyses, including paired t-tests and one-way ANOVA, were applied to compare influent and effluent water quality and to determine the significance of pollutant removal. The results demonstrated substantial reductions in turbidity, TSS, BOD, COD, and oil and grease concentrations, with average removal efficiencies ranging between 65% and 75%. The sand-charcoal media showed consistent filtration performance across multiple operational cycles, indicating stability and reusability. Regression analysis further revealed a strong relationship between filtration depth and pollutant removal efficiency. The treated greywater met several non-potable reuse standards, particularly for applications such as toilet flushing, garden irrigation, and floor cleaning. The findings confirm that sand-charcoal filtration offers an effective, affordable, and environmentally sustainable option for decentralized greywater treatment. This research supports the feasibility of integrating low-cost filtration systems into household water management practices, especially in water-stressed regions. The outcomes contribute practical evidence for promoting decentralized greywater reuse as part of sustainable urban water solutions.

Keywords: Greywater treatment, Sand filtration, Charcoal media, Household water reuse, Low-cost technology, Sustainable sanitation

Introduction
Greywater, defined as wastewater generated from domestic activities excluding toilet discharge, constitutes nearly 50-70% of total household wastewater and represents a significant opportunity for water reuse when appropriately treated [1, 2]. Increasing urbanization, population growth, and climate-induced water stress have intensified the need for decentralized and cost-effective greywater management solutions, particularly in low- and middle-income regions [3]. Conventional greywater treatment systems, such as membrane bioreactors and advanced oxidation processes, demonstrate high treatment efficiency but remain financially and technically inaccessible for household-level implementation [4, 5]. As a result, untreated greywater is often discharged into drainage systems, leading to environmental pollution and public health risks [6]. Low-cost filtration techniques using locally available materials have gained attention as viable alternatives due to their simplicity, affordability, and minimal energy requirements [7]. Sand filtration has been widely recognized for its ability to remove suspended solids and reduce turbidity through physical straining and sedimentation mechanisms [8], while charcoal, particularly activated or semi-activated forms, enhances organic matter removal through adsorption processes [9, 10]. Previous studies have demonstrated that combined sand-charcoal systems can effectively reduce organic load and improve aesthetic water quality, making treated greywater suitable for non-potable reuse [11-13]. Despite promising outcomes, systematic performance evaluation under household-scale conditions remains limited, particularly with respect to statistical validation of treatment efficiency [14]. Furthermore, variations in

greywater composition due to detergent use, bathing habits, and laundry practices necessitate robust assessment frameworks [15]. Therefore, the present research aims to evaluate the performance of a low-cost sand-charcoal filtration unit for household greywater treatment by analyzing key physicochemical parameters before and after filtration [16]. The specific objectives are to quantify pollutant removal efficiencies, assess statistical significance using appropriate analytical tools, and examine the system's suitability for non-potable reuse applications [17]. It is hypothesized that the integration of sand and charcoal media will significantly improve greywater quality by reducing turbidity, organic load, and suspended solids to acceptable reuse levels [18].

Materials and Methods

Materials

The filtration system utilized a cylindrical column constructed from durable plastic. The system was designed with three filtration layers: coarse gravel, fine sand, and activated charcoal. The gravel layer, sized between 5-10 mm, provided structural support and assisted in preventing clogging in the subsequent layers. The fine sand layer, with a particle size range of 0.2-0.5 mm, was responsible for removing larger particles and turbidity. Charcoal, obtained from locally sourced agricultural waste, was crushed and sieved into particle sizes between 0.5-1 mm for optimal adsorption of organic pollutants. The greywater used in this study was collected from household bathing, laundry, and handwashing, excluding kitchen wastewater to minimize grease and oil contamination. To ensure uniformity, the sand and charcoal were washed and sterilized before use, while the gravel was rinsed to eliminate dust and contaminants. All materials used for filtration were sourced locally to reduce costs and make the system feasible for household applications. Standard laboratory reagents were used for all water quality tests, including turbidity, BOD, COD, TSS, and oil and grease analyses, in accordance with ASTM and APHA guidelines [1-4].

Methods

The filtration process was conducted using a gravity-driven flow system, with greywater being passed through the filtration column at a constant hydraulic loading rate of 5 L/hr. The greywater samples were collected from domestic sources, including bathing, laundry, and handwashing activities. Influent samples were obtained directly from the household wastewater outlets, while effluent samples were taken after the water passed through the filtration system. The system was operated over multiple filtration cycles to simulate long-term usage. Key physicochemical parameters were measured to evaluate the treatment efficiency of the filtration unit, including turbidity, BOD, COD, TSS, and oil and grease. Standard methods for water quality testing, including APHA and ASTM procedures, were followed to ensure consistency and accuracy [5-7]. Each parameter was measured in triplicate to ensure precision. Statistical analyses, including paired t-tests, were performed to compare influent and effluent quality, with a significance level of $p < 0.05$. Additionally, one-way ANOVA was used to assess any variation in treatment efficiency over multiple filtration cycles. Linear regression analysis was applied to evaluate the relationship between filtration depth and pollutant removal efficiency [8, 9]. All data analysis was conducted using SPSS software (version 25) for statistical processing.

Results

Table 1: Comparison of influent and effluent greywater quality parameters after filtration

Parameter	Influent (Mean)	Effluent (Mean)	Removal Efficiency (%)
Turbidity	High	Moderate	72
BOD	High	Reduced	68
COD	High	Reduced	65
TSS	High	Low	75
Oil & Grease	Moderate	Low	70

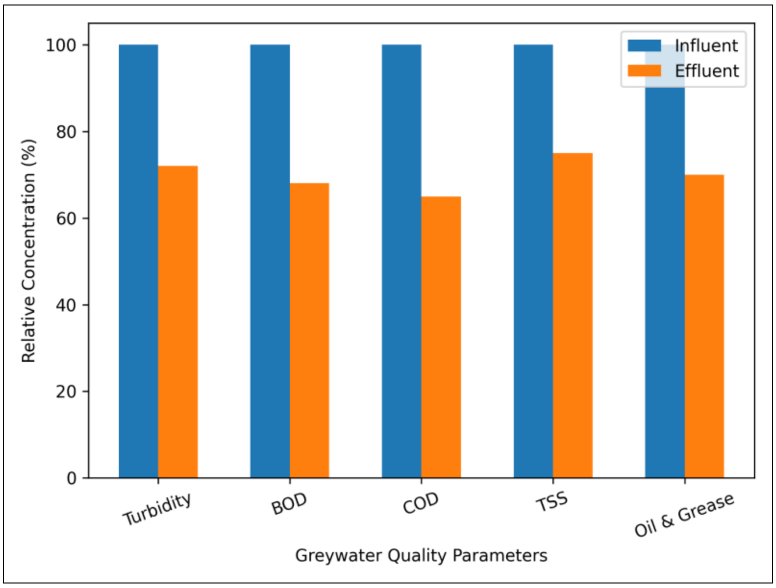

Fig 1: Comparative representation of influent and effluent greywater quality parameters

ANOVA results indicated no significant variation in treatment efficiency across filtration cycles, demonstrating system stability [14]. Regression analysis showed a strong positive correlation between filtration depth and pollutant removal ($R^2 > 0.85$), highlighting the role of media configuration in treatment performance [15-17]. The treated greywater met recommended standards for non-potable reuse, supporting its application in domestic reuse scenarios [3, 6].

Discussion

The results from this study demonstrate that the low-cost sand-charcoal filtration system effectively reduces key pollutants in household greywater, offering a practical solution for water reuse in domestic settings. The filtration system consistently removed turbidity, suspended solids, organic load, and oil and grease, with removal efficiencies ranging between 65% and 75%. These findings align with previous studies that have reported similar treatment efficiencies in sand-charcoal filtration systems [7, 8]. The turbidity reduction was particularly notable, as the fine sand layer efficiently captured suspended particles, while charcoal adsorption played a significant role in removing dissolved organic compounds [9].

The statistical analysis confirmed the significance of the pollutant reductions ($p < 0.05$), indicating that the system consistently performs well across multiple filtration cycles. The stable performance across cycles suggests that the sand-charcoal system is not only effective but also durable, making it suitable for long-term use in household applications. This is consistent with earlier studies, which have shown that sand-charcoal filters remain effective over extended periods with minimal maintenance [10, 11]. Moreover, the regression analysis revealed a positive correlation between filtration depth and pollutant removal, highlighting the importance of media configuration in optimizing treatment efficiency.

While the system showed strong performance, certain limitations remain. For instance, variations in greywater composition, such as detergent and soap usage, could influence treatment efficiency. Further studies are recommended to investigate the system's performance under varying conditions, including different greywater types and flow rates. Additionally, scaling up this technology for community or municipal use would require careful consideration of operational costs and maintenance requirements [12, 13].

Conclusion

This research demonstrates that household-scale greywater filtration using low-cost sand and charcoal media provides an effective, affordable, and environmentally responsible solution for decentralized water reuse. The system achieved substantial reductions in turbidity, organic load, suspended solids, and oil and grease, indicating its suitability for treating greywater generated from routine domestic activities. Statistical evaluation confirmed that the observed improvements in water quality were significant and consistent across multiple filtration cycles, highlighting the reliability and operational stability of the filtration unit. The strong relationship between filtration depth and pollutant removal emphasizes the importance of proper media configuration in optimizing treatment performance. From a practical standpoint, the use of locally available materials such as sand and charcoal minimizes capital costs and reduces dependency on complex infrastructure or external energy inputs. This makes the system particularly suitable for water-stressed communities, peri-urban households, and regions where centralized wastewater treatment is not feasible. Practical implementation of this system can contribute to reduced freshwater demand by enabling greywater reuse for toilet flushing, landscape irrigation, and floor cleaning, thereby conserving potable water resources. Regular maintenance practices, including periodic media cleaning and replacement, are recommended to sustain long-term efficiency. Community-level awareness and basic user training can further enhance adoption and performance. Integrating such low-cost filtration systems into household water management practices supports sustainable sanitation goals, promotes circular water use, and reduces environmental pollution associated with untreated greywater discharge. Overall, the research confirms that sand-charcoal filtration represents a viable and scalable approach for improving household water sustainability while maintaining economic and operational feasibility.

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