Performance Evaluation of Mobile Integrated On-Site Greywater Treatment System

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Abstract:
This research paper presents the development and evaluation of a Mobile Integrated Onsite Greywater Treatment System (MIOGTS) aimed at addressing water scarcity through greywater recycling and reuse. MIOGTS combines primary treatment with settling cum equalization tank and anaerobic baffled reactor (ABR) with secondary treatment utilizing a Bio-rack constructed wetland (CW) system filled with charcoal and gravel as a medium. The study employed synthetic greywater, representative of typical domestic sources, and analyzed its characteristics. The MIOGTS system was designed for an average flow rate of 200 L/d and included ABR and Bio-rack CW units.
The research found that the raw greywater possessed a BOD_5/COD ratio suitable for biological treatment, laying the foundation for the MIOGTS concept. The system's development cost was estimated at 18080/-, making it an economically feasible option. The average total BOD_5 removal efficiency was 78.04%, with ABR and CW contributing 47.40% and 57.93%, respectively. These results suggest the MIOGTS model's effectiveness for greywater treatment.
In conclusion, MIOGTS offers a promising solution for residential greywater treatment, particularly in regions with water scarcity. It demonstrates efficient removal of organic contaminants and suspended particles, making it environmentally friendly and cost-effective. The research provides valuable insights into the development of decentralized greywater treatment systems suitable for households, contributing to sustainable water management.

Keywords: greywater recycling, Mobile Integrated Onsite Greywater Treatment System (MIOGTS), anaerobic baffled reactor (ABR), Bio-rack constructed wetland (CW), water scarcity, decentralized wastewater treatment.

1. Introduction

Addressing water scarcity is a pressing global concern, and one of the most effective strategies is to adopt sustainable practices of recycling and reusing water resources. In this pursuit, the Mobile Integrated Onsite Greywater Treatment System (MIOGTS) emerges as a promising solution. Greywater, generated from activities such as bathing, laundry, and dishwashing, represents a valuable resource that, when treated and recycled, can alleviate the strain on freshwater supplies. MIOGTS introduces a novel approach that combines the efficiency of an Anaerobic Baffle Reactor (ABR) and a Bio-rack Constructed Wetland (CW) with the adsorption capabilities of materials like charcoal and gravel particles. This innovative system is designed to remove organic contaminants from greywater, transforming it into a reusable resource.

In the pursuit of sustainable greywater management, MIOGTS employs a comprehensive approach. It comprises primary treatment through a Settling cum Equilization tank, followed by ABR as the primary biological treatment, and Bio-rack CW as the secondary treatment. The objective of this research is to develop and evaluate a outdoor-scale setup that integrates ABR and Bio-rack CW to treat greywater effectively. Prior to the secondary treatment, greywater undergoes pre-treatment in the settling cum equilization tank, allowing suspended particles to settle and normalize the greywater quality. The synergy of ABR and Bio-rack CW with charcoal and gravel as mediums enhances the treatment efficiency, making it an ideal candidate for greywater management.

While greywater treatment systems have been explored in various contexts, the unique integration of ABR and Bio-rack CW within the MIOGTS framework distinguishes this research. The absence of prior evaluations of MIOGTS in greywater treatment underscores the importance of this study in expanding our understanding of its potential. To appreciate the significance of MIOGTS, it is essential to delve into the principles behind its key components.

ABRs, characterized by multiple upflow reactors interconnected by baffles, create a hydraulic environment that compels wastewater to flow over and under the baffles. This sequential flow from influent to effluent enhances the treatment process. Prior studies have demonstrated the efficacy of ABR in remediating greywater (Yasmin Saif et al., 2021 [1]; Shirish Singha, Raimund Haberl et al., 2008 [2]).

Bio-rack CW, on the other hand, has primarily been utilized for the biological treatment of greywater. Researchers have reported successful removal of organics and nutrients through laboratory-scale and field-scale experiments (M. Sundaravadivel and S. Vigneswaran, 2007 [3]; Chloe Rose Bolton and Dyllon Garth Randall, 2019 [4]; S.M. Sathe and G.R. Munavalli, 2019 [5]).

The development of portable wastewater treatment systems (WWTPs) has shown promise in effectively reusing wastewater while promoting ecological sustainability. Such systems have been applied to greywater treatment with encouraging results (Shervin Jamshidi et al., 2014 [6]; Y Kusumawardani et al., 2020 [7]; Jessica S. Gonzales, 2014 [8]).

Notably, this research fills a gap in the existing literature, as it explores the application of MIOGTS in tropical climatic regions like India, where greywater management solutions are particularly needed. The study aims to construct and assess an outdoor-scale MIOGTS, combining physical and biological treatments to eliminate suspended particles, organics, and nutrients from greywater. Through rigorous experimental research, the study seeks to gauge the performance of this innovative system in addressing the critical challenges of greywater treatment.

In summary, this research embarks on a journey to design, build, and evaluate the Mobile Integrated Onsite Greywater Treatment System (MIOGTS). By combining ABR and Bio-rack CW with innovative materials and methodologies, this study explores the potential of MIOGTS as a cost-effective and sustainable solution for greywater treatment, ultimately contributing to the broader goals of water resource conservation and environmental sustainability.

2. Material and Methods

2.1 Source of Greywater

In this study, greywater was sourced by creating synthetic greywater due to practical constraints. This synthetic greywater served as the feed for the experiments. The synthetic greywater was composed of components typically found in domestic greywater, including bath soap water, laundry soap water, and detergent water. For the preparation of each type of synthetic greywater, specific quantities of soap and detergent were used. Specifically, 7 grams of bath soap, 50 grams of cloth soap, and 40 grams of detergent were added to their respective containers. These formulations aimed to mimic the composition of real-life greywater. To ensure consistent quality for analysis, grab samples of synthetic greywater were taken daily at 11 a.m. throughout the study, which had a total duration of 75 days, with 90 days of actual operation.

2.2 Experimental Set-Up

The outdoor-scale Mobile Integrated Onsite Greywater Treatment System (MIOGTS) was designed and constructed to achieve an average flow rate of 200 liters per day (L/d). MIOGTS consisted of a multi-stage treatment system that incorporated pre-treatment, secondary biological treatment, and an innovative combination of components to enhance greywater treatment efficiency.

The schematic representation and detailed plans for MIOGTS are depicted in Figures 1, and 2, respectively. The system comprised both pre/primary components, including a settling cum equalization tank and an Anaerobic Baffle Reactor (ABR), as well as biological components in the form of a Constructed Wetland (CW). The pre-treatment phase played a crucial role in normalizing the greywater quality and facilitating the settlement of suspended particles. The settling cum equalization tank, with dimensions of 0.970 m in length, 0.610 m in width, and 0.481 m in depth, operated without the use of chemicals and offered an average detention duration of 4 hours. To prevent suspended particles from entering the ABR and further enhancing the greywater quality, a flow control valve-controlled exit was positioned above the sludge zone.

The design and specifications of the ABR and Bio-rack CW system adhered to the guidelines outlined by the National Environmental Engineering Research Institute (NEERI) in 2007. The ABR, a critical component of MIOGTS, effectively reduced suspended and organic debris in wastewater by approximately 70%. Each of the three identical Plexiglas anaerobic baffled reactor compartments had a net volume of 200 liters and dimensions of 0.970 m in length, 0.610 m in width, and 0.481 m in height. Additional vertical baffles were introduced to alter the fluid dynamics within the sludge bed, creating upflow-to-downflow sections. This configuration forced the greywater to flow vigorously under and over the baffles as it progressed from one compartment to the next, ensuring effective treatment.

The effluent from the ABR underwent further treatment in the wetland systems, known as Bio-rack units. These units consisted of rectangular tanks with dimensions of 0.970 m in length, 0.610 m in width, and 0.481 m in height. The bottom layer of the tank was filled with charcoal with a depth of 1828.8 mm, while the top layer contained 8-12.5 mm gravel with the same depth. The uniqueness of this system lay in the incorporation of six U-shaped vertical PVC pipes, collectively referred to as Bio-racks, with an effective height of 481 mm and an outer diameter of 101.6 mm. These PVC pipes were perforated with multiple 1 mm diameter surface holes. The Bio-racks served as a support matrix for vegetation, promoting microbial growth and enhancing the treatment process.

During the initial phase of plantation, six Canna indica plants were introduced into the Bio-rack's support matrix. The selection of Canna indica was based on several key factors, including its ability to remove pollutants, aesthetic and decorative value, local availability, and suitability for growth in tropical climates. Flow regulating valves were installed at both the input and exit points to control the liquid flow within the Bio-rack CW system.

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Following figures 1, and 2 illustrate the design and models of the MIOGTS system, showcasing the integration of its various components and treatment stages:

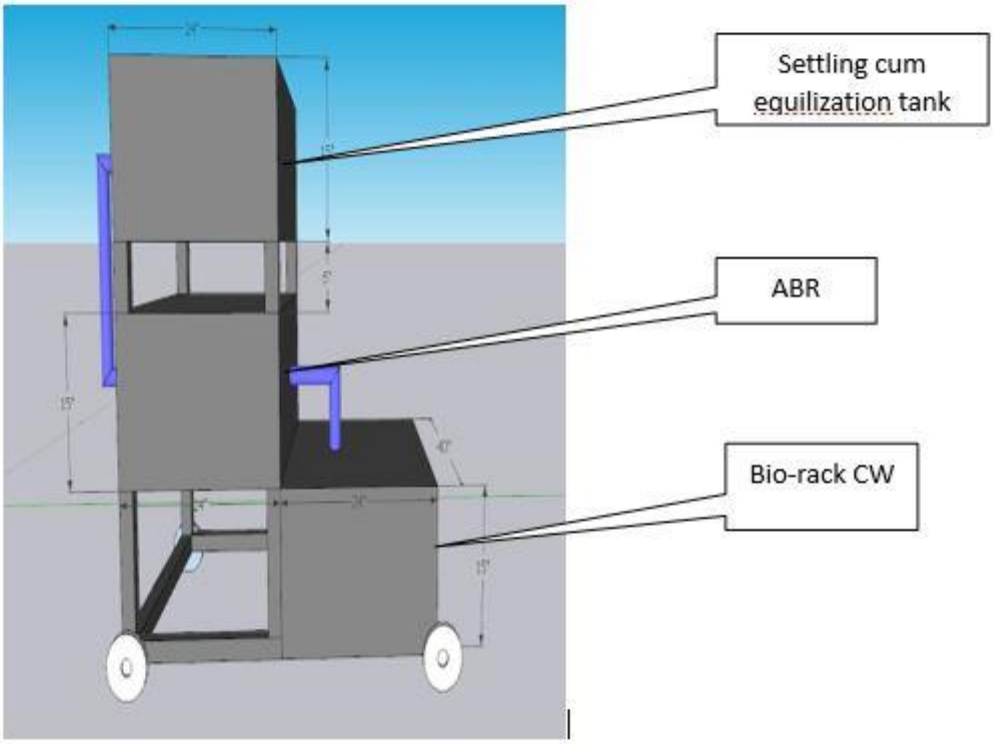

Fig. No. 1 – Schematic Diagram of MIOGTS

Fig. No. 2 – Photographic view of field scale MIOGTS

2.3 Operation of the System

The operation of the greywater treatment system was designed to maintain a gravity flow throughout its various units, with both the Anaerobic Baffle Reactor (ABR) and Bio-rack Constructed Wetland (CW) operating in a downflow mode. The system was operated in a sequential batch mode, and the operational steps were as follows:

1. A synthetic greywater solution of 200 liters was prepared by adding 7 grams of bath soap, 50 grams of cloth soap, and 40 grams of detergent, simulating the composition of domestic greywater.
2. The control valve of the equalization tank was opened to allow the flow of synthetic greywater into the system through the downflow.
3. The flow from the outlet of the equalization tank was equally distributed into both the ABR and Bio-rack CW using control valves.
4. A drip system was employed to uniformly supply treated greywater from the ABR to the secondary biological system, which also operated in downflow mode. The effluent from the equalization cum settling tank passed through the ABR and Bio-rack CW, retained by control valves to maintain a constant Hydraulic Retention Time (HRT).
5. Steps 1 to 4 were repeated for each batch, with the Organic Loading Rate (OLR) being maintained at a constant level to ensure consistent and reliable results. Each of the organic loadings was designed to have an HRT of 4 hours.
6. Samples were collected on a daily basis from the equalization cum settling tank, ABR, and Bio-rack CW through the sampling ports located in their respective units for subsequent analysis.

2.4 Planning of Experiment

The experiment was divided into two distinct phases: the initial phase and the established phase, each with its specific objectives and observations.

In the initial phase, the focus was on the establishment of plant roots and the growth of vegetation to a specific height. To facilitate plant growth, treated greywater was utilized. Canna indica plants were initially planted in six U-shaped vertical PVC pipes, which were assembled into a rack filled with charcoal and gravel filter media. These plants were continually supplied with treated greywater containing the necessary BOD_5. The growth of roots and plant height were closely monitored, and the initial phase was deemed complete when the vegetation had grown to an average height of 0.6 meters with a dense root structure, typically taking three weeks.

After the initial phase, the system transitioned into batch mode operation for the treatment of greywater. Performance assessment studies were carried out to ensure that the organic loading rates (OLR) in both the ABR and Bio-rack CW remained consistent. The system was then supplied with synthetic greywater, and its performance was evaluated using various quality indicators, including pH, turbidity, chloride, alkalinity, BOD_5, and COD. These parameters were analyzed using analytical techniques referenced in the Alpha standards. During the performance evaluation, it was recognized that the system provided pre-treatment for turbidity and biological treatment for pH and nutrient removal.

Sampling sites were strategically selected to assess the quality of greywater following both pre-treatment and biological treatment. Samples were collected from the equalization cum settling tank, ABR and Bio-rack CW. Each sampling event involved the collection of three samples to ensure representative data. The system operated with a 4-hour Hydraulic Retention Time (HRT) and a constant OLR, as specified by the NEERI manual. The outdoor-scale MIOGTS model was designed for a family of five, adhering to package treatment unit standards. PVC tanks were selected for the outdoor-scale MIOGTS units, and their surface area conformed to NEERI guidelines. Synthetic greywater was used in this study to assess the potential of the ABR and Bio-rack CW under constant OLR conditions.

3. Results and Discussion

3.1 Greywater Characterization

In this study, synthetic greywater was meticulously prepared, and its key characteristics are presented in Table 1. The characterization of greywater is essential for assessing the effectiveness of the treatment process. The results demonstrate the following parameters for raw greywater (GW) as well as the treated greywater from the Anaerobic Baffle Reactor (ABR TGW) and the Constructed Wetland (CW TGW):

Table No. 1 : Characteristics of raw and treated greywater

Sr.No	Parameter	unit	Raw GW	ABR TGW	CW TGW
1	pH	-	7.85±0.32	7.55 ±0.16	7.38 ± 0.16
2	Turbidity	NTU	3.90625 ±2.0429	2.28 ± 0.88	1.75 ± 0.768
3	Alkalinity	mg/l	225.588±61.3375	188 ± 54.0156	162 ± 44.7813
4	Chloride	mg/l	31.46 ±5.97119	22.063 ± 4.43623	16.65688 ± 4.826
5	BOD_5	mg/l	155 ± 49	77 ± 19.6	31 ±7.4
6	COD	mg/l	230.5 ± 46.2	180 ± 37.2	135.2 ± 4.72

1. pH: Greywater is slightly alkaline in nature, with a pH ranging from 7.38 to 7.85. These pH levels are within the acceptable range for biological treatment processes.
2. Turbidity: Raw greywater exhibited a relatively high turbidity with an average of 3.91 NTU. However, after treatment in the ABR and Bio-rack CW, the turbidity significantly decreased to 2.28 NTU and 1.75 NTU, respectively. This indicates effective removal of suspended particles during the treatment process.
3. Alkalinity: The alkalinity of greywater was relatively high, with a mean value of 225.59 mg/l. Treatment in the ABR and Bio-rack CW reduced alkalinity to 188 mg/l and 162 mg/l, respectively.
4. Chloride: The chloride content in raw greywater averaged at 31.46 mg/l. Following treatment in the ABR and Bio-rack CW, chloride levels decreased to 22.06 mg/l and 16.66 mg/l, respectively.
5. BOD_5 (Biochemical Oxygen Demand): Raw greywater exhibited a BOD_5 ranging from 90 mg/l to 240 mg/l, with an average of 155 mg/l. Treatment in the ABR reduced BOD_5 to 77 mg/l, and the subsequent treatment in the Bio-rack CW further lowered it to 31 mg/l.
6. COD (Chemical Oxygen Demand): The COD of raw greywater ranged from 148 mg/l to 304 mg/l, with an average of 230.5 mg/l. Treatment in the ABR resulted in a reduction to 180 mg/l, and the Bio-rack CW treatment further lowered it to 135.2 mg/l.

The BOD_5/COD ratio for greywater ranged from 0.55 to 0.70, indicating that the greywater was well-suited for biological treatment. Additionally, the data reflects the consistent quality of raw greywater throughout the research period. Notably, the greywater exhibited high turbidity, low chloride content, and alkaline characteristics. These findings emphasize the importance of including processes for the removal of suspended particles and organic materials in the treatment scheme.

The observed improvements in pH, turbidity, alkalinity, chloride, BOD_5, and COD after treatment stages in the ABR and CW indicate the effectiveness of the MIOGTS system in enhancing the quality of greywater. The subsequent sections will delve into the performance of the individual treatment components and provide a comprehensive analysis of the results.

3.2 Pre-Treatment

Table 1 provides a comprehensive overview of greywater quality following the equalization and Anaerobic Baffle Reactor (ABR) treatment stages. Notable fluctuations in turbidity, Biochemical Oxygen Demand (BOD_5), and Chemical Oxygen Demand (COD) removal are evident throughout the course of the study. The results indicate that the pre-treatment process implemented in this research yielded significant improvements in greywater quality. On average, turbidity decreased by 32%, BOD_5 by 47%, and COD by 20%. These findings demonstrate the effectiveness of the pre-treatment method in enhancing greywater quality, making it suitable for further treatment in the Constructed Wetland (CW) system.

3.3 CW-Based Secondary Treatment

Table 1 also presents the greywater quality following equalization and the ABR treatment phases, emphasizing the impact of the CW-based secondary treatment. The results indicate that, on average, turbidity decreased by 23%, BOD_5 by 57%, and COD by 21% after the Bio-rack CW treatment. These substantial reductions in key parameters highlight the efficiency of the Bio-rack CW system in further enhancing greywater quality. The pre-treatment method employed in this study successfully prepared greywater to meet the necessary quality standards for input into the Bio-rack CW system.

Figure 3 illustrates the variations in turbidity, BOD_5, and COD removal efficiency observed during the course of the study. The data reveals that the total removal efficiency for these parameters, in the entire treatment process from equalization to CW treatment, reached 49% for turbidity, 78% for BOD_5, and 37% for COD. These results underscore the capacity of the Mobile Integrated Onsite Greywater Treatment System (MIOGTS) to significantly improve the quality of greywater, rendering it suitable for reuse and environmentally friendly disposal.

The comprehensive treatment process, involving both pre-treatment and CW-based secondary treatment, contributes to the substantial reduction in suspended particles, organic contaminants, and turbidity in greywater. These findings are essential for understanding the feasibility of implementing MIOGTS as an effective and sustainable solution for greywater treatment in tropical climates like India. The subsequent section will further discuss the implications of these results and their significance in addressing water scarcity and sustainability challenges.

4. Conclusions

The comprehensive research and experimentation conducted on the Mobile Integrated Onsite Greywater Treatment System (MIOGTS) have provided valuable insights into the feasibility and effectiveness of this innovative approach to greywater treatment. The following conclusions have been drawn from the results and discussions presented above:

1. **Biological Treatment Potential**: The analysis of raw greywater (GW) revealed a BOD_5/COD ratio ranging from 0.55 to 0.70, indicating that it possesses the necessary characteristics for biological treatment. This finding underscores the potential for employing biological processes to treat greywater effectively and sustainably.
2. **System Components**: MIOGTS has been successfully developed as a multi-component system, comprising an Anaerobic Baffle Reactor (ABR), Bio-rack Constructed Wetland (CW), and a settling cum equalization tank. This integrated design allows for the efficient removal of suspended particles, organic contaminants, and turbidity from greywater.

3. **Cost-Effective Solution**: The cost of developing the MIOGTS system was determined to be 18,080 Indian Rupees (INR). This relatively low cost makes it an affordable and practical solution for residential greywater treatment, particularly for households with five members.
4. **BOD_5 Removal Efficiency**: The MIOGTS system demonstrated excellent performance in terms of BOD_5 removal. The average total BOD_5 removal efficiency achieved was 78.04%. Notably, the ABR component of the system contributed significantly to this success, with an average BOD_5 removal efficiency of 47.40%. The subsequent CW treatment stage further enhanced BOD_5 removal, achieving an average efficiency of 57.93%. These results highlight the system's effectiveness in reducing organic contaminants in greywater.
5. **Residential Applicability**: The MIOGTS model is well-suited for residential use, designed to cater to a family of five members. Its cost-effectiveness and efficient performance make it a practical choice for treating greywater generated in residential buildings. With a payback period estimated at ten years, the system offers a reasonable return on investment, encouraging its adoption in residential settings.
6. **Sustainability and Water Scarcity**: Implementing MIOGTS as a greywater treatment solution contributes to sustainability efforts and addresses water scarcity challenges. By recycling and reusing greywater, the system reduces the strain on freshwater resources and minimizes the environmental impact associated with wastewater discharge.
7. **Tropical Climate Adaptation**: The study fills a critical gap in research by evaluating greywater treatment systems in tropical climatic regions like India. The successful development and performance assessment of MIOGTS under such conditions provide valuable insights for addressing the unique challenges posed by tropical climates.
8. **Further Research and Implementation**: While this research has yielded promising results, there is room for further investigation and real-world implementation of MIOGTS. Long-term monitoring and broader deployment in various residential settings could provide additional data on system performance and user experiences.

In conclusion, the Mobile Integrated Onsite Greywater Treatment System (MIOGTS) offers an affordable, efficient, and environmentally friendly solution for treating greywater in residential buildings. With its robust performance in terms of BOD_5 removal and cost-effectiveness, MIOGTS has the potential to significantly contribute to sustainable water management practices in tropical climates and beyond. Further research, development, and adoption of such innovative greywater treatment systems are essential steps toward conserving water resources, reducing pollution, and promoting a more sustainable future. MIOGTS represents a promising advancement in addressing the growing global challenges of water scarcity and environmental sustainability.

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