Design and development of an innovative Rainwater Greywater Filter

Mrunal Meshram and Mahek Mulani

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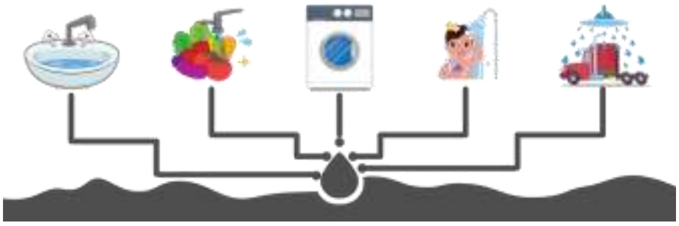
Abstract- The increasing demand for sustainable and decentralized water treatment solutions has highlighted the need for low-cost filtration systems capable of treating alternative water sources such as rainwater and greywater. This study proposes the design of an innovative multi-stage filtration system that integrates natural filtration materials with selective functional enhancements to improve water purification efficiency. The proposed system consists of sequential layers of gravel, coarse sand, fine sand, TiO_2-coated sand, and zeolite, supported by a cotton separation layer and followed by a ceramic candle microfilter and copper mesh outlet. Natural materials provide mechanical filtration, adsorption, and ion exchange, while the TiO_2-coated sand introduces photocatalytic degradation of organic contaminants. The system is designed as a gravity-driven prototype suitable for small-scale and decentralized applications. By combining conventional natural filtration media with advanced functional materials, the proposed filter aims to enhance turbidity removal, chemical adsorption, and microbial reduction while maintaining affordability and environmental sustainability. The concept demonstrates the potential of hybrid natural–engineered filtration systems as practical solutions for potable and non-potable water treatment in resource-limited environments.

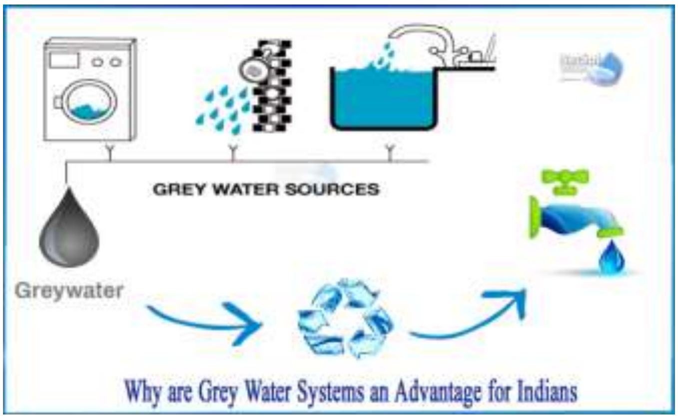
I. INTRODUCTION

Access to safe and clean water remains one of the most significant global challenges, particularly in regions facing increasing water demand, pollution of freshwater sources, and limited treatment infrastructure. Population growth, urbanization, and climate variability have intensified pressure on available water resources, making it essential to explore alternative water sources such as rainwater and greywater. Although rainwater harvesting and greywater reuse can supplement conventional water supplies, these sources often contain suspended particles, organic contaminants, and microorganisms that make them unsuitable for direct use without adequate treatment.



Conventional water filtration systems commonly use natural media such as gravel, sand, and activated carbon to remove suspended solids and improve water quality. These materials are widely adopted in decentralized treatment systems due to their low cost, availability, and simplicity of operation. Filtration mechanisms including mechanical straining, adsorption, and sedimentation allow these materials to reduce turbidity and particulate contamination effectively. However, traditional filtration media alone may not sufficiently remove dissolved pollutants, chemical contaminants, or pathogenic microorganisms required for potable water standards.

Recent studies have explored the use of advanced materials and natural adsorbents to enhance filtration efficiency. Materials such as zeolite have demonstrated strong ion-exchange capabilities for removing ammonium and certain heavy metals, while photocatalytic materials such as titanium dioxide (TiO_2) can degrade organic contaminants under light exposure. Additionally, ceramic microfilters and antimicrobial materials have been investigated to improve microbial removal in small-scale water treatment systems.



In this study, an innovative multi-stage filtration system is proposed for treating rainwater and greywater by integrating natural filtration materials with functional enhancement layers. The system incorporates sequential layers of gravel, coarse sand, fine sand, TiO_2-coated sand, and zeolite to achieve progressive filtration and adsorption. A cotton layer supports the filtration media, while a ceramic candle filter provides final microfiltration, supported by a copper mesh outlet with antimicrobial properties. The proposed gravity-driven system is designed to be cost-effective, sustainable, and suitable for decentralized applications. By combining natural filtration media with selective functional materials, the system aims to improve water purification efficiency while maintaining simplicity and affordability.

II. LITERATURE REVIEW

1. S. D. Muktiningsih

Muktiningsih presents a comprehensive review of gravity-based filtration systems used to treat harvested rainwater. The study explains that simple filters composed of pre-screening layers, gravel, sand, and adsorption media are widely used because of their low cost and minimal energy requirements. The review highlights how variations in layer thickness, grain size, and media arrangement influence turbidity removal and suspended solid reduction. It also emphasizes that while sand and gravel effectively remove particulate matter, additional adsorption and disinfection stages are required to remove organic contaminants and pathogens. The paper notes that maintenance practices and the quality of incoming rainwater significantly affect system performance. Overall, the study concludes that simple gravity filters are effective for basic treatment but require enhancement to achieve potable water standards.

2. L. L. B. De Jesus

De Jesus proposes a rainwater harvesting system specifically designed for the environmental and socio-economic conditions of Mindoro, Philippines. The study evaluates rainfall patterns and water demand to determine appropriate system design and storage requirements. The proposed design integrates first-flush diversion, rainwater conveyance, and modular filtration units suitable for household or community use. Emphasis is placed on the importance of community participation and the use of locally available materials for long-term sustainability. The research highlights the role of filtration and disinfection in ensuring that harvested rainwater becomes safe for domestic use. Overall, the study demonstrates that region-specific rainwater harvesting systems can provide reliable and sustainable water supplies when properly designed and maintained.

3. P. D. Dathan, K. S., C. P. Anantha Krishnan, and J. Assif Ali

Dathan and colleagues developed a low-cost water filtration system using natural and locally available materials such as gravel, sand, pine bark, plant-based sorbents, and charcoal. The study demonstrates that proper layering of these materials significantly reduces turbidity and suspended particles in water. The authors emphasize that natural filtration media can improve water clarity and basic quality while remaining affordable for rural communities. The research also discusses the importance of pre-treatment methods such as sedimentation or coagulation to extend filter life. However, the study notes that natural materials alone cannot ensure complete microbial removal without additional disinfection. Overall, the work validates the effectiveness of natural materials as a baseline filtration approach for decentralized water treatment systems.

4. P. H. Tjahjanti

Tjahjanti investigates the potential of banana peels as a natural biosorbent for removing contaminants from water. The study explains that banana peels contain cellulose, hemicellulose, and lignin, which provide functional groups capable of adsorbing pollutants through ion exchange and surface interactions. Experimental results show that processed banana peel can reduce turbidity and remove certain dyes or metal ions from contaminated water. The research also highlights the importance of preprocessing methods such as drying, grinding, and chemical activation to enhance adsorption capacity. Despite its advantages as a low-cost and abundant material, banana peel has lower adsorption efficiency compared to engineered materials like activated carbon. Therefore, the study suggests using banana peel as a supplementary filtration medium rather than a primary treatment component.

5. F. Katre et al.

Katre and co-authors present the design of an economical water purifier constructed using natural and waste materials such as charcoal, zeolite, coconut shells, and agricultural residues. The study demonstrates that these materials can effectively reduce turbidity and improve taste and odor in contaminated water. The authors emphasize the importance of affordability and the use of locally available waste materials to create sustainable filtration systems. Prototype testing showed promising results in improving basic water quality parameters. However, the study also acknowledges that such systems require additional treatment steps to achieve potable water quality. Overall, the research highlights the potential of waste-derived materials for developing low-cost community water purification systems.

6. Anna Cescon and Jia-Qian Jiang

Cescon and Jiang provide a detailed review of filtration processes and alternative filter media used in modern water treatment systems. The study compares traditional filtration media such as sand and anthracite with alternative materials including zeolite, glass media, and activated alumina. The authors analyze the physical and chemical properties of these media and their influence on particle removal efficiency and hydraulic performance. The review also discusses operational factors such as head-loss development, backwashing requirements, and long-term stability of filter media. Furthermore, the paper highlights the growing interest in functionalized media capable of removing chemical contaminants in addition to particulate matter. The study concludes that alternative and engineered filter materials can significantly improve water treatment efficiency when properly integrated into filtration systems.

7. R. D. D. Dalawampu et al.

Dalawampu and co-authors developed and tested a rainwater filtration system aimed at improving water quality for households in the National Capital Region of the Philippines. The system incorporates pre-screening, sedimentation, and layered filtration using gravel and sand to remove contaminants. Field tests showed significant reductions in turbidity and improvement in basic water quality parameters. The study also considers practical aspects such as catchment contamination sources, seasonal rainfall variations, and community maintenance practices. Results demonstrate that well-designed filtration systems can make harvested rainwater suitable for domestic use. The research highlights the importance of integrating filtration with disinfection to achieve safe drinking water standards.

8. Tara T. Ross, Mohammad A. Alim, and Ataur Rahman

Ross, Alim, and Rahman conducted a long-term evaluation of a filtration system designed to produce drinking water from harvested rainwater in rural areas. The study monitored system performance over an extended period to assess seasonal variations in water quality. Results showed that combining pre-treatment, filtration, and disinfection can successfully produce potable water from rainwater sources. The research emphasizes the importance of turbidity reduction before disinfection because high turbidity reduces the effectiveness of treatment methods. The authors also provide operational guidelines including maintenance intervals and cleaning procedures. Overall, the study confirms that properly designed filtration systems can reliably provide safe drinking water in rural environments.

9. M. P. Samuel and A. C. Mathew

Samuel and Mathew developed and experimentally evaluated a filtration system designed for producing drinking water from harvested rainwater. Their research involved constructing a prototype and testing its performance in reducing turbidity, color, and microbial contamination. The results showed significant improvement in water quality after passing through multiple filtration stages. The study also emphasizes the importance of regular maintenance and proper system operation to sustain filtration efficiency. Detailed design recommendations such as layer thickness and flow rate are provided to guide practical implementation. The authors conclude that combining filtration with additional disinfection steps can help achieve safe drinking water standards.

10. Tariq Judeh, Isam Shahrour, and Fadi Comair

Judeh, Shahrour, and Comair present a smart rainwater harvesting system designed for arid and semi-arid regions. The study integrates rainwater collection, storage, filtration, and automated monitoring using sensors and digital control systems. The proposed framework aims to improve reliability and water quality through real-time monitoring and automated treatment processes. Simulation results show that smart monitoring systems can significantly improve water supply reliability and contamination control. The authors also discuss the potential integration of advanced filtration media within automated treatment systems. Overall, the study highlights the importance of combining material innovations with intelligent monitoring technologies for sustainable water management.

Novelty of work: The novelty of this study lies in the integration of natural filtration media with selectively enhanced functional materials in a compact gravity-driven filtration system designed for rainwater and greywater treatment. Unlike conventional filtration units that rely mainly on sand and gravel, the proposed system incorporates zeolite, TiO_2-coated sand, and ceramic microfiltration to enhance contaminant removal efficiency. The design adopts a hybrid approach combining sustainable natural materials with engineered filtration layers, enabling improved adsorption, photocatalytic degradation of organic pollutants, and enhanced microbial removal within a single filtration column. The use of cotton and mesh-supported layered architecture ensures proper media arrangement while maintaining gravity-driven operation without external energy input. Additionally, the system emphasizes low-cost, locally available materials, making it suitable for decentralized water treatment in rural and resource-limited regions. By combining natural filtration, functionalized materials, and microfiltration in a modular structure, the study proposes a practical and sustainable approach to improving the quality of harvested rainwater and greywater.

III. PROBLEM STATEMENT

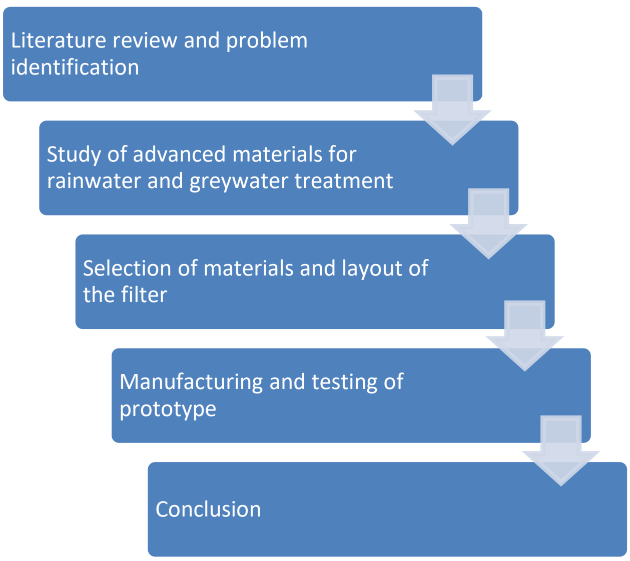
- Rainwater and graywater contain suspended solids, organic contaminants, chemical residues, and pathogenic microorganisms, making them unsafe for direct use.
- Existing low-cost filters using only sand, gravel, and charcoal improve clarity but fail to remove dissolved pollutants and microbes to potable standards.
- High-end purification technologies, while effective, are too costly and complex for decentralized use.
- Thus, there is a need for a low-cost, multi-functional filtration system that uses advanced materials to enhance adsorption, catalytic degradation, and disinfection.

IV. OBJECTIVES

The aim of the study is to develop and evaluate a low-cost, multi-stage water purification system that integrates traditional filtration media with advanced functional materials to produce potable-quality water from rainwater and graywater. The primary objectives are:

- To design and construct a multi-layer filtration unit incorporating gravel, sand, activated carbon, zeolite, and muslin/cloth pre-filtration.
- To synthesize and integrate functionalized biochar as an enhanced adsorbent for organic and chemical contaminants.
- To prepare and immobilize TiO_2-coated sand or ceramic media for photocatalytic degradation of pollutants under natural or UV light.
- To incorporate a selective MOF additive to improve targeted chemical adsorption capability.
- To install ceramic microfiltration and SODIS as final disinfection stages to ensure microbial safety.
- To evaluate the performance of the developed system in terms of turbidity reduction, organic load removal, chemical polishing, and microbial inactivation.

RESEARCH METHODOLOGY



V. DESIGN AND LAYOUT

The design of a gravity-driven filtration system is primarily based on the principles of mechanical filtration, adsorption, and biological or chemical treatment. In multi-layer filtration systems, different materials are arranged sequentially so that each layer performs a specific purification function. Coarse materials such as gravel and coarse sand are generally placed at the top layers to remove large suspended particles and prevent clogging of finer media. As water moves downward through the system, progressively finer materials such as fine sand and adsorption media further remove smaller particles and dissolved contaminants.

The filtration process mainly occurs through straining, sedimentation, adsorption, and ion exchange mechanisms. Straining removes larger suspended solids by trapping them between the pores of the filter media, while sedimentation allows heavier particles to settle within the void spaces of the media layers. Adsorption media such as activated carbon or zeolite provide a large surface area that helps remove dissolved organic compounds, odors, and certain chemical pollutants. Zeolite additionally contributes through ion exchange, which enables the removal of ammonium ions and some heavy metals present in contaminated water.

In advanced filtration systems, functionalized materials such as TiO_2-coated sand can be incorporated to introduce photocatalytic activity. Titanium dioxide acts as a photocatalyst that can degrade organic contaminants when exposed to light, thereby enhancing the purification efficiency of the filter. Similarly, ceramic candle filters are widely used as a polishing stage because of their micro-porous structure, which allows them to remove fine suspended particles and microorganisms from water.

The overall layout of the filtration system must ensure uniform water distribution, sufficient contact time with filtration media, and stable support for the filter layers. Support materials such as cotton layers or mesh structures are often used to prevent mixing of filter media and to maintain proper positioning of the filtration stages. By carefully arranging different natural and functional materials within the filtration column, a multi-stage purification system can be developed that improves water quality while maintaining a simple, energy-free operation suitable for small-scale and decentralized water treatment applications.

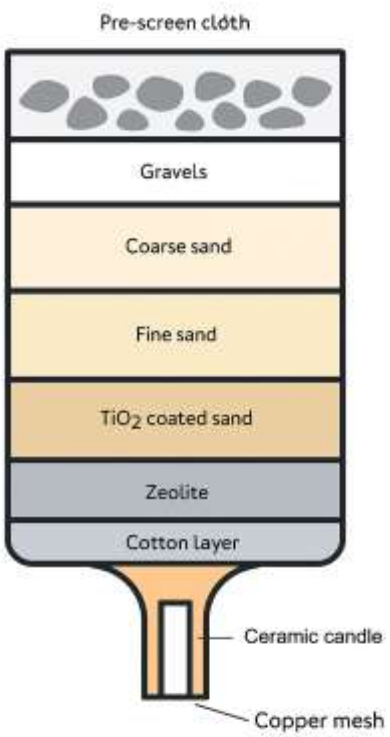


Fig. Schematic Diagram of the proposed system.

Material Specifications:

❖ **Pre-screen cloth (muslin / polypropylene nonwoven)**

- Thickness: 0 mm (thin sheet), but cover/mesh only — place as inlet screen.
- Purpose: stop leaves/large debris; protects media.
- Volume / mass: negligible.

❖ **Gravel / pebbles**

- Thickness: 50 mm (5.0 cm) ± 10 mm
- Purpose: coarse settling, prevent channeling, distribute flow.
- Packed volume: A × 0.050 m ≈ 1.57 L
- Approx mass: 1.57 L × 1.6 kg/L ≈ 2.5 kg

❖ **Coarse sand**

- Thickness: 100 mm (10.0 cm) ± 10 mm
- Purpose: first depth filtration (larger suspended solids).
- Volume: A × 0.100 m ≈ 3.14 L
- Approx mass: 3.14 L × 1.6 kg/L ≈ 5.0 kg

❖ **Fine sand**

- Thickness: 150 mm (15.0 cm) ± 10–20 mm
- Purpose: fine particulate removal; major turbidity reduction.
- Volume: A × 0.150 m ≈ 4.71 L
- Approx mass: 4.71 L × 1.6 kg/L ≈ 7.5 kg

❖ **TiO_2-coated sand**

- Thickness: 50 mm (5.0 cm) ± 10 mm
- Purpose: immobilized photocatalytic layer for organic degradation / microbial assistance (sun/UV).
- Volume: A × 0.050 m ≈ 1.57 L
- Approx mass: 1.57 L × 1.6 kg/L ≈ 2.5 kg
- TiO_2 required (rough): 50–150 g of TiO_2 powder to coat ~1–2 kg sand (depends on coating method)

❖ **Zeolite (clinoptilolite)**

- Thickness: 50 mm (5.0 cm) ± 10 mm
- Purpose: ion exchange / ammonium and some heavy-metal uptake; polishing ionic species.
- Volume: A × 0.050 m ≈ 1.57 L
- Approx mass: 1.57 L × 0.9 kg/L ≈ 1.4 kg

❖ **Cotton layer / fine cloth (separator above chamber)**

- Thickness: negligible (~2–5 mm compressible pad)
- Purpose: support/retain fine media, protect ceramic area, prevent fines from falling.
- Mass: negligible

❖ **Ceramic candle filter (porous clay element)**

- Immersed length: depends on candle, typically 100–150 mm submerged length into the chamber.
- Purpose: microfiltration (bacteria / fine particulates).
- Installation: candle mouth connects to outlet; ensure full submersion and seal to prevent bypass.

❖ **Copper mesh (antimicrobial support / last-contact piece)**

- Thickness: thin mesh strip (0.5–2 mm thick / mesh sheet) placed at the very outlet or wrapped around candle spout.
- Purpose: secondary antimicrobial effect, discourages biofilm, and can be used as an electrical grounding/antimicrobial contact if desired.
- Mass: small (grams).

V. MANUFACTURING OF THE COMPONENT

VI. EXPERIMENTAL TESTING

Conclusion

- This study presented the design and conceptual development of a multi-stage gravity-driven filtration system for the treatment of rainwater and greywater using a combination of natural and functionalized filtration materials.
- The proposed system integrates layers of gravel, sand, TiO_2-coated sand, and zeolite along with supporting cotton layers and a ceramic candle filter to achieve progressive removal of suspended solids, organic contaminants, and microorganisms. The sequential arrangement of filtration media enables multiple purification mechanisms such as mechanical straining, adsorption, ion exchange, and microfiltration within a single compact unit.
- The design emphasizes the use of locally available natural materials combined with selected engineered enhancements, ensuring that the system remains cost-effective, sustainable, and suitable for decentralized applications. By incorporating advanced materials such as TiO_2-coated sand and zeolite into a traditional filtration framework, the proposed system aims to improve contaminant removal efficiency compared to conventional household filters.
- Overall, the developed filtration concept demonstrates the potential of hybrid filtration systems that combine natural media with functional materials to improve water treatment performance.

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