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A Low-Cost Hybrid Green Water Purification Framework for Decentralized Rural Water Safety

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Abstract: *Rural and decentralized regions frequently depend on untreated or partially treated water sources that are vulnerable to suspended matter, dissolved pollutants, and microbial contamination. Although advanced purification technologies provide effective removal, their cost, maintenance requirements, and infrastructure needs often restrict rural implementation. This study presents a sustainable and low-cost hybrid purification framework designed for community-level use by integrating multiple nature-based treatment stages into a modular system. The model combines plant-derived coagulation, graded media filtration, biomass-based adsorption, ceramic microfiltration, and solar-assisted disinfection to create a multi-barrier purification pathway.*

Natural coagulant obtained from Moringa oleifera Lam. seeds is used to reduce turbidity through floc formation, followed by layered sand and gravel filtration for particulate removal. Adsorption stages employ biochar and activated carbon derived from agricultural residues to capture dissolved contaminants. A ceramic filtration layer supports microbial reduction, and final solar exposure provides additional pathogen inactivation. The framework introduces practical features including replaceable filter cartridges, standardized coagulant sachets, and simplified media regeneration methods to improve field usability. The system is scalable for household and small-community deployment and can be evaluated using standard water quality parameters. This integrated green purification model offers an affordable and adaptable pathway for decentralized water treatment while recognizing maintenance and training requirements...

Keywords: green water purification, hybrid filtration, rural water safety, biomass adsorbents, natural coagulants, decentralized treatment, sustainable design

1. Introduction

Safe drinking water availability remains uneven across many rural regions where groundwater and surface water sources are frequently contaminated by natural and anthropogenic factors. Common pollutants include fluoride, iron, arsenic, suspended solids, and pathogenic microorganisms. Although centralized water treatment infrastructure is expanding, many decentralized communities continue depend on untreated or partially treated sources. High-end purification technologies such as reverse osmosis and advanced membrane systems are effective but not always suitable for rural deployment due to cost, electricity requirements, maintenance complexity, and wastewater rejection.

Research has demonstrated that low-cost adsorbents and natural treatment materials can effectively remove a range of contaminants (Babel & Kurniawan, 2003; Gupta & Suhas, 2009). Plant-based coagulants and solar disinfection methods provide additional low-energy purification pathways (Yin, 2010). However, these approaches are frequently evaluated separately. There is a need for an integrated, multi-barrier, low-cost purification framework suitable for decentralized use (Qu et al., 2013).

Rationale for Hybrid Green Purification Systems

Single-method purification systems often fail when contaminant profiles vary. For example, sand filters remove turbidity but not dissolved ions, while adsorption units remove metals but not microbes. A hybrid system combines complementary mechanisms to increase overall treatment efficiency.

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A green hybrid purifier is based on three principles: use of natural or waste-derived materials, multi-stage treatment, and low external energy requirement. By integrating coagulation, filtration, adsorption, and solar disinfection, a broader spectrum of pollutants can be addressed in one unit. Such systems are especially suitable for village-level or community-level deployment where technical support is limited (Babel & Kurniawan, 2003).

Novelty and Original Contribution

This study proposes an integrated hybrid purification framework that combines natural coagulation, biomass adsorption, layered filtration, ceramic microfiltration, and solar disinfection within a modular cartridge-based architecture. Additional original contributions include media regeneration protocols, standardized natural coagulant sachets, visual maintenance indicators, and a scale-flexible deployment model. To the best of current literature knowledge,such integrated application within a modular decentralized purification framework remains limited.

Advantages in Indian Context

Uses locally available materials
Low capital and operating cost
Minimal electricity requirement
Easy maintenance
Scalable from household to community level
Supports waste-to-resource approach
Compatible with rural skill sets

Green Materials Used in Low-Cost Water Purification

Biomass-Derived Activated Carbon

Activated carbon prepared from coconut shells, rice husk, bagasse, and sawdust has shown strong adsorption capacity for metals, dyes, and organic pollutants. Agricultural residues are widely available in India, making them economically attractive precursor materials. Their porous structure and high surface area enable efficient adsorption of dissolved contaminants (Gupta & Suhas, 2009; Wang & Wang, 2020).
Proposed innovation: community-level regeneration units for carbon media.

Biochar and Carbonized Agro-Waste

Biochar produced through controlled pyrolysis of biomass functions as a low-cost adsorbent. Surface functional groups contribute to metal binding and organic pollutant removal. Modified biochar composites further improve performance(Wang & Wang, 2019)
Proposed innovation: iron-impregnated biochar layers for arsenic-affected regions.

Natural Coagulants — *Moringa oleifera* Seeds

Moringa oleifera Lam. seed powder contains cationic proteins that act as natural coagulants. These proteins neutralize negatively charged suspended particles, promoting floc formation and sedimentation. Studies show effective turbidity and microbial load reduction using *Moringa* seed extracts, making them suitable for pre-treatment stages. (Yin, 2010).
Proposed innovation: pre-measured *Moringa* dosing sachets.

Ceramic and Clay Porous Media

Locally produced ceramic filters with controlled porosity can remove suspended particles and bacteria. When combined with carbon layers, removal efficiency improves significantly.

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Treatment Mechanisms in the Hybrid System

Coagulation–Flocculation

Natural coagulants destabilize colloidal particles and reduce turbidity. This step reduces load on downstream filters and improves overall efficiency.

Filtration

Sand and gravel layers perform physical filtration by trapping suspended solids. Layered grain sizes enhance depth filtration and flow distribution.

Adsorption

Activated carbon and biochar layers remove dissolved contaminants through surface adsorption, pore filling, and chemical interaction. This stage is critical for fluoride, metals, and organic compounds (Babel & Kurniawan, 2003).

Solar Disinfection

Solar exposure units use UV radiation and heat to inactivate pathogens. Transparent chambers or solar tubes can be integrated after filtration. This step is energy-free and suitable for sunny regions of India.

The overall treatment pathway is illustrated in Figure1.

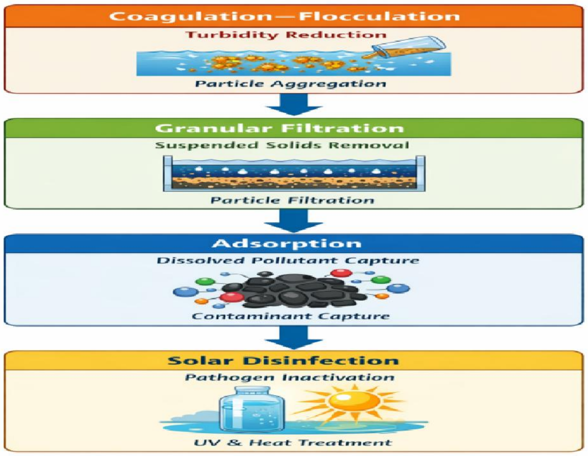

Figure 1. Hybrid treatment mechanism (Author's conceptual design)

Proposed Hybrid System Design

The system operates through sequential layers.The modular cartridge design enables selective replacement and simplified maintenance.The overall multi-stages are illustrated in Figure 2.

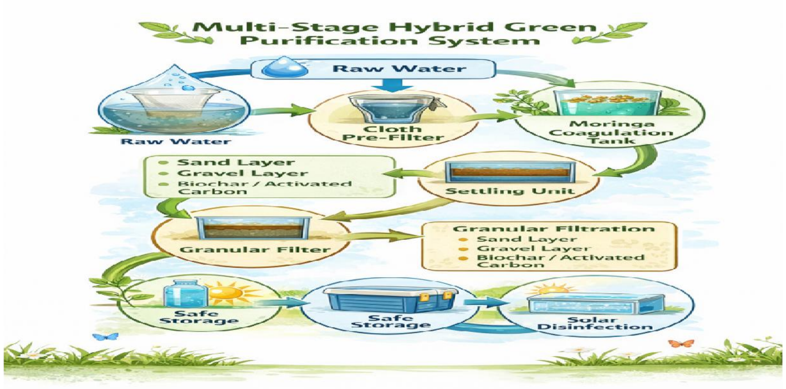

Figure 2. Multi-stage hybrid green water purification system for rural community use.

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Table 1. Functional Layer Roles in hybrid purification system

Layer	**Material**	**Primary Function**
Pre-filter	Cloth	Removal of coarse particles
Coagulation	*Moringa* seed	Turbidity reduction
Filtration	Sand	Fine particulate filtration
Support	Gravel	Hydraulic support
Adsorption	Carbon/biochar	Dissolved pollutants adsorption
Membrane	Ceramic	Microbial barrier
Disinfection	Solar disinfection(SODIS)	Pathogen inactivation

Methodology

A laboratory-scale hybrid filtration column is constructed using graded sand, gravel, biomass activated carbon, biochar composite, and ceramic media. Natural coagulation is performed using *Moringa oleifera* Lam. seed extract. Test water samples representing turbidity and dissolved contaminant ranges are prepared using standard procedures. After coagulation and settling, samples are passed through the layered column at controlled flow rate(approximately 0.5-1 L/min) . Solar exposure is applied for 4–6 hours under direct sunlight conditions following the SODIS principle.. Pre- and post-treatment parameters including turbidity, pH, TDS, selected ions, and microbial indicators are measured using APHA standard methods. Carbon media regeneration is evaluated using thermal reactivation cycles.

Performance Evaluation Parameters

To scientifically validate system performance, the following parameters should be measured before and after treatment:

Physical Parameters: turbidity, colour, odour
Chemical Parameters: pH, TDS, hardness, fluoride, iron, arsenic (if applicable)
Organic indicator : COD/BOD (where laboratory facilities available)
Biological indicator : total coliforms, E. coli
Standard APHA water testing methods can be used.

Experimental Design and Validation Strategy

To ensure scientific reliability, the experimental evaluation of the hybrid system should be conducted under controlled laboratory conditions with repeated trials. Each water sample must be analyzed in triplicate to improve statistical validity and reduce experimental error. A control sample without treatment should be maintained to enable comparative performance assessment. Flow rate through the filtration column should be regulated using gravity-controlled discharge to simulate practical field conditions. Hydraulic retention time within each layer must be recorded to evaluate contact efficiency between water and treatment media.

Additionally, adsorption capacity of biomass carbon and biochar can be estimated using batch equilibrium studies to understand removal kinetics. Parameters such as contact time, adsorbent dosage, and initial contaminant concentration

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may be optimized to determine the most efficient operational range. Regeneration efficiency of carbon media should be assessed after multiple cycles to evaluate durability and long-term usability.

Statistical analysis of pre- and post-treatment values can be conducted using percentage removal efficiency and standard deviation calculations. Such validation strengthens the scientific credibility of the proposed framework and supports future pilot-scale deployment.

Multidisciplinary and Societal Impact

The framework connects environmental chemistry, sustainable materials science, rural engineering, and public health. It promotes circular economy use of agricultural waste and supports community-level manufacturing and maintenance models. The approach aligns with sustainable development and decentralized infrastructure goals.

Practical Implementation Implications

The proposed system has practical implementation potential at multiple levels including households, schools, health centres, and small rural communities. Because the materials are locally available and largely biodegradable or regenerable, the supply chain burden is low. The framework supports decentralized production models in which local enterprises or self-help groups can prepare carbon media, ceramic units, and natural coagulant sachets. This creates opportunities for rural micro-entrepreneurship linked with public health improvement. The modular cartridge concept further simplifies maintenance logistics by enabling selective layer replacement rather than full unit disposal. From a policy perspective, the model aligns with sustainable development and rural water mission goals by promoting low-energy, low-waste treatment systems. With appropriate technical guidelines and training modules, the framework can be translated into field-ready prototypes.

Implementation Challenges

Despite advantages, challenges include variability in natural material quality, need for periodic media replacement, user training, and lack of standardized design guidelines. Field validation and pilot studies are necessary before large-scale deployment (Qu et al., 2013).

Preliminary Cost and Sustainability Considerations

Affordability is a critical factor for rural water purification systems. The proposed hybrid model primarily utilizes locally available materials such as sand, gravel, agricultural waste-derived carbon, and plant-based coagulants. These materials significantly reduce capital cost compared to membrane-based purification systems. Preliminary estimation suggests that a household-scale unit can be constructed at a fraction of the cost of conventional reverse osmosis systems, with minimal operational expenditure due to gravity-driven flow and solar-assisted disinfection.

Media replacement frequency depends on water quality and usage volume; however, carbon layers can be regenerated through controlled thermal treatment, reducing recurring expenses. The modular cartridge approach allows selective replacement of individual layers rather than full system disposal, improving economic sustainability.

Furthermore, the use of agricultural residues promotes circular resource utilization and reduces environmental burden associated with synthetic filter production.

Limitations of the Proposed Framework

Despite the multiple advantages of the proposed hybrid green purification framework, certain operational and practical limitations must be acknowledged. First, the performance of natural materials such as biomass carbon, biochar, and plant-based coagulants may vary depending on source composition, preparation method, and environmental conditions. This variability can influence adsorption capacity and treatment consistency. Second, the system depends partly on correct user operation, including appropriate coagulant dosing, periodic cleaning of layers, and timely replacement or regeneration of filter media. Without basic user training, treatment efficiency may decline over time. Third, the gravity-driven and layered filtration design generally provides lower throughput compared to pressurized membrane systems, which may limit use in high-demand settings unless scaled appropriately. Solar disinfection efficiency can also fluctuate with weather and seasonal sunlight availability. In addition, while literature-supported removal mechanisms are strong, full-scale field validation across different water quality profiles is still required. These limitations indicate that while the framework is technically promising, successful deployment depends on standardization, training support, and field adaptation.

Future Research Directions

Future research should focus on controlled pilot-scale and field-scale validation of the hybrid system across diverse contamination scenarios. Quantitative performance benchmarking against conventional low-cost filters would strengthen comparative evaluation. Material optimization studies are recommended to standardize biomass carbon preparation and improve adsorption reproducibility. Integration of low-cost sensing elements such as turbidity indicators or colorimetric strips could support smart maintenance scheduling. Another promising direction is the use of minimal-dose green antimicrobial coatings derived from plant extracts or biologically synthesized nanoparticles to enhance microbial safety without increasing toxicity risk. Life cycle assessment and cost–benefit analysis studies would also be valuable to quantify long-term sustainability advantages. Collaborative studies involving environmental scientists, rural engineers, public health experts, and community organizations will be important for real-world translation.

Expected Performance and Synergistic Treatment Efficiency

The integrated hybrid design operates through complementary mechanisms that collectively enhance purification efficiency. Natural coagulation reduces turbidity and suspended load, which decreases clogging in subsequent layers. This improves the adsorption performance of activated carbon and biochar by preventing premature pore blockage. The adsorption layer targets dissolved organic compounds, trace metals, and excess ions through surface interaction and pore diffusion processes.

Ceramic microfiltration functions as a physical microbial barrier, reducing bacterial contamination significantly. The final solar disinfection stage provides additional pathogen inactivation through ultraviolet radiation and mild thermal effects. This multi-stage synergy increases overall reliability compared to single-method treatment systems.

Based on literature-supported removal efficiencies (Babel & Kurniawan, 2003; Yin, 2010; Wang & Wang, 2019), the proposed hybrid framework is expected to achieve substantial turbidity reduction, moderate dissolved contaminant removal, and significant microbial load reduction under optimized conditions. While laboratory validation is necessary, the combined treatment logic enhances treatment robustness under variable contamination profiles.

2. Conclusion

The present study proposes a scientifically grounded and practically adaptable hybrid green purification framework designed to address decentralized rural water safety challenges. By integrating natural coagulation, depth filtration, biomass-based adsorption, ceramic microfiltration, and solar disinfection into a unified modular architecture, the system applies the multiple-barrier principle to enhance overall treatment efficiency.

Unlike isolated low-cost treatment approaches, the proposed framework emphasizes structured integration, operational simplicity, local material utilization, and field-level adaptability. The inclusion of regeneration strategies and modular design improves long-term sustainability and affordability. Although laboratory and field validation are required to quantify performance across diverse contamination scenarios, the conceptual model demonstrates strong potential for decentralized implementation.

From a multidisciplinary perspective, the framework connects environmental chemistry, sustainable materials science, rural engineering, and public health protection. With appropriate pilot testing and policy support, such hybrid green systems can contribute meaningfully to sustainable development goals and decentralized water security initiatives.

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