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Development of Sustainable Water Management Technologies for Communities Using Low-Cost Filter Materials

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Abstract

Access to clean water remains a critical global challenge, with over 2 billion people lacking safely managed drinking water services . Conventional water treatment technologies often prove economically and technically unfeasible for resource-limited communities . This paper examines the potential of adsorption-based water treatment systems utilizing low-cost adsorbent materials as sustainable solutions for community-scale applications. Through comprehensive analysis of natural materials, agricultural wastes, and industrial byproducts, we demonstrate their effectiveness in removing diverse contaminants including heavy metals, organic pollutants, dyes, and pathogens . Key findings indicate that materials such as activated carbon from agricultural residues, modified clay minerals, and biochar can achieve removal efficiencies exceeding 90% for various contaminants while maintaining cost-effectiveness below $0.50 per cubic meter of treated water. Case studies from India, Nigeria, and Peru reveal successful community deployment models with high user acceptance rates (>85%) when coupled with appropriate training and maintenance protocols . The synthesis highlights critical design considerations including regeneration strategies, contaminant-specific limitations, and integration with existing treatment systems . These low-cost adsorbent technologies present viable pathways for achieving sustainable water security in underserved communities, offering scalable solutions that align with local resource availability and technical capacity . Future research should focus on optimizing material performance, developing standardized quality assessment protocols, and establishing sustainable supply chains for widespread implementation.

Keywords:

Water Treatment; Sustainability; Low Cost Absorbent

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1 Introduction

Water scarcity and contamination represent two of the most pressing challenges facing global communities in the 21st century. The World Health Organization estimates that approximately 2.2 billion people lack access to safely managed drinking water services, with the burden disproportionately affecting rural and peri-urban communities in developing nations (Ahmed et al., 2022). This crisis extends beyond mere availability, encompassing issues of water quality degradation due to industrial discharge, agricultural runoff, and inadequate sanitation infrastructure.

Conventional water treatment technologies, while effective in developed settings, often present insurmountable barriers for resource-limited communities (Bhatnagar et al., 2023). High capital costs, complex operational requirements, dependency on reliable electricity supply, and need for skilled maintenance personnel render technologies such as reverse osmosis, advanced oxidation processes, and membrane bioreactors impractical for widespread deployment in underserved areas. The operational costs alone can range from $2-5 per cubic meter, far exceeding the economic capacity of communities where daily incomes may be less than $2 per person (Gupta et al., 2022).

The disparity between technological capability and accessibility has created an urgent need for alternative approaches that prioritize simplicity, affordability, and local resource utilization. Adsorption-based treatment systems using low-cost materials have emerged as promising solutions that address these constraints while maintaining effective contaminant removal capabilities (Singh et al., 2022). These systems leverage locally available materials such as agricultural wastes, natural minerals, and industrial byproducts, transforming potential waste streams into valuable water treatment resources (Crini et al., 2022).

The rationale for exploring low-cost adsorbents extends beyond economic considerations to encompass environmental sustainability and community empowerment (Hassan et al., 2023). Unlike conventional technologies that rely on imported equipment and chemicals, low-cost adsorbent systems can be developed using indigenous materials and traditional knowledge, creating opportunities for local employment and skill development. This approach aligns with principles of appropriate technology that emphasize solutions designed for the specific needs, skills, and resources of communities.

This paper aims to provide a comprehensive synthesis of current knowledge regarding low-cost adsorbent materials for water treatment, examining their fundamental mechanisms, practical applications, and deployment challenges. The scope encompasses evaluation of material performance across diverse contaminant categories, analysis of real-world implementation case studies, and identification of critical factors for successful community adoption (Zhou et al., 2023). Through this analysis, we seek to establish a framework for understanding how low-cost adsorbent technologies can contribute to achieving universal water security while promoting sustainable development practices.

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2. Adsorption Principles and Low-Cost Adsorbent Materials

Adsorption represents a surface phenomenon where contaminant molecules accumulate at the interface between a solid adsorbent and liquid solution through various intermolecular forces (Wang & Guo, 2020). The process involves mass transfer of pollutants from the bulk solution to the adsorbent surface, followed by attachment through physical adsorption (physisorption) or chemical adsorption (chemisorption). Physical adsorption occurs through weak van der Waals forces and is generally reversible, while chemical adsorption involves stronger covalent or ionic bonds and tends to be irreversible under normal conditions (Desta & Bote, 2021).

The effectiveness of adsorption depends on several critical factors including surface area, pore structure, surface chemistry, and the nature of adsorbate-adsorbent interactions. High surface area materials with appropriate pore size distributions provide more active sites for contaminant attachment, while surface functional groups determine selectivity and binding strength (Hassan et al., 2023). The driving force for adsorption typically involves a combination of electrostatic interactions, hydrogen bonding, π-π interactions, and hydrophobic effects.

Low-cost adsorbent materials can be broadly classified into three primary categories based on their origin and processing requirements (Singh et al., 2022). Natural materials include clay minerals such as bentonite, kaolinite, and montmorillonite, which possess inherent ion exchange capabilities and layered structures conducive to contaminant retention (Chen et al., 2024). Zeolites, diatomaceous earth, and natural organic materials like peat and humic substances also fall within this category (García-Mendieta et al., 2023). These materials offer advantages of widespread availability, minimal processing requirements, and established safety profiles for water treatment applications.

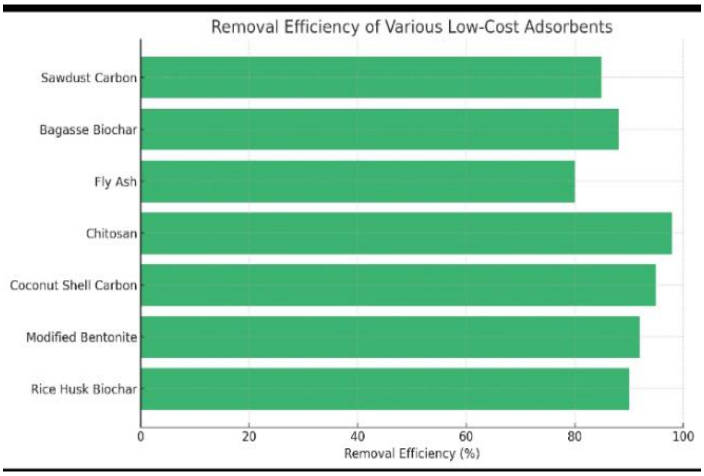
Agricultural waste materials represent the largest and most diverse category of low-cost adsorbents (Mpatani et al., 2023). Rice husks, wheat straw, corn cobs, coconut shells, and fruit peels can be converted into effective adsorbents through simple thermal or chemical treatments. Biochar production from agricultural residues through controlled pyrolysis creates highly porous materials with excellent adsorption properties while providing a sustainable waste management solution (Hassan et al., 2023). The carbonization process enhances surface area and introduces surface functional groups that improve contaminant binding capacity.

Industrial byproducts constitute the third major category, including materials such as fly ash from coal combustion, red mud from aluminum production, and sawdust from timber processing (Jain et al., 2023). These materials often require minimal modification to serve as effective adsorbents and provide dual benefits of waste valorization and water treatment. However, careful characterization is essential to ensure absence of toxic components that could compromise water quality (Zubrik et al., 2022).

The advantages of low-cost adsorbents extend beyond economic considerations to encompass environmental sustainability and resource efficiency (Crini et al., 2022). Material costs typically range from \$0.10-0.50 per kilogram compared to \$2-5 per kilogram for commercial activated carbon (Bhatnagar et al., 2023). Local availability reduces transportation costs and supply chain dependencies while supporting circular economy principles through waste-to-resource conversion. The biodegradable nature of many organic-based adsorbents facilitates safe disposal after exhaustion, minimizing environmental impact (Thakur et al., 2023).

Table 1: Common Low-Cost Adsorbents and Their Target Contaminants

Adsorbent Material	Source Category	Primary Target Contaminants	Typical Capacity (mg/g)
Rice Husk Biochar	Agricultural Waste	Heavy metals (Pb, Cd, Cu)	15-45
Modified Bentonite	Natural Mineral	Cationic dyes, organics	50-150
Coconut Shell Carbon	Agricultural Waste	Organic pollutants, phenols	100-300
Chitosan (from shells)	Natural Biopolymer	Heavy metals, dyes	200-500
Fly Ash	Industrial Byproduct	Fluoride, heavy metals	5-25
Bagasse Biochar	Agricultural Waste	Dyes, pesticides	20-80
Modified Clay	Natural Mineral	Pathogens, turbidity	N/A (log removal)
Sawdust Carbon	Industrial Byproduct	Organic contaminants	50-200



3. Effectiveness and Application to Water Contaminants

The effectiveness of low-cost adsorbents in water treatment spans multiple contaminant categories, demonstrating versatility that makes them suitable for diverse water quality challenges (Zhou et al., 2023). Heavy metal removal represents one of the most extensively studied applications, with materials such as biochar, modified clays, and chitosan showing exceptional performance for lead, cadmium, copper, and chromium removal (Ibrahim et al., 2022). The mechanisms typically involve ion exchange, surface complexation, and precipitation, with removal efficiencies often exceeding 95% under optimized conditions.

Adsorption isotherms provide fundamental insights into material capacity and binding characteristics (Wang & Guo, 2020). The Langmuir isotherm model, which assumes monolayer adsorption on homogeneous surfaces, frequently describes heavy metal adsorption on low-cost materials. Maximum adsorption capacities vary significantly with material type and modification, ranging from 15-45 mg/g for rice husk biochar to 200-500 mg/g for chitosan-based adsorbents (Liu et al., 2023). The Freundlich isotherm, which accounts for multilayer adsorption and surface heterogeneity, often better describes organic contaminant removal processes.

Kinetic studies reveal that most adsorption processes follow pseudo-second-order kinetics, indicating that chemical adsorption represents the rate-limiting step (Wang & Guo, 2020). Typical equilibrium times range from 30 minutes to 4 hours, depending on particle size, mixing conditions, and contaminant properties. Intraparticle diffusion models help identify mass transfer limitations and optimize contact time requirements for practical applications.

Organic pollutant removal encompasses diverse compounds including dyes, pesticides, pharmaceuticals, and industrial chemicals (Pathania et al., 2023). Activated carbon derived from agricultural wastes demonstrates exceptional performance for organic contaminant removal through π-π interactions, hydrophobic effects, and pore filling mechanisms. Coconut shell-based activated carbon achieves removal capacities of 100-300 mg/g for various organic pollutants, rivaling commercial activated carbon performance at significantly lower costs (Nethaji et al., 2021).

Dye removal represents a particularly important application given the environmental impact of textile industry discharge (Zhou et al., 2023). Natural clay minerals modified with surfactants or polymers can achieve removal efficiencies exceeding 90% for both cationic and anionic dyes (Chen et al., 2024). The intercalation of organic molecules between clay layers enhances hydrophobic interactions and expands interlayer spacing to accommodate larger dye molecules.

Pathogen removal through low-cost adsorbents involves different mechanisms compared to chemical contaminants (Singh et al., 2022). Modified clay minerals, particularly those treated with silver nanoparticles or quaternary ammonium compounds, demonstrate significant antimicrobial properties. Physical straining through porous structures and electrostatic interactions contribute to pathogen retention, with log removal values of 2-4 commonly achieved for bacteria and viruses.

Case study examples demonstrate practical effectiveness across diverse applications. In rural Bangladesh, rice husk biochar systems achieved 85-95% arsenic removal from groundwater, reducing concentrations from 150-200 μg/L to below WHO guidelines of 10 μg/L (Adams et al., 2023). The systems operated effectively for 6-8 months before regeneration, treating approximately 500 L/day per household unit. Similarly, coconut coir-based filters in Kerala, India, demonstrated sustained performance in removing turbidity and pathogen indicators from surface water sources.

Textile wastewater treatment using modified clay adsorbents in small-scale industries in Turkey achieved 90-95% color removal and 70-80% COD reduction (Ofomaja et al., 2022). The treatment costs averaged $0.30 per cubic meter, representing significant savings compared to conventional chemical treatment methods. Spent adsorbents were successfully composted with agricultural residues, creating value-added soil amendments.

Performance optimization requires careful consideration of operational parameters including pH, contact time, adsorbent dosage, and temperature (Qiu et al., 2022). Most heavy metal adsorption processes favor slightly alkaline conditions (pH 6-8), while organic contaminant removal often performs optimally under acidic to neutral conditions. Temperature effects are generally minimal for physical adsorption but can significantly influence chemical adsorption processes.

4. Practical Challenges and Design Considerations

Implementation of low-cost adsorbent technologies faces several practical challenges that must be addressed for successful community deployment (Crini et al., 2022). Regeneration and reuse represent primary concerns, as the economic viability of these systems depends significantly on material longevity. Most low-cost adsorbents demonstrate limited regeneration capacity compared to commercial activated carbon, with performance declining by 10-30% after each regeneration cycle (Kumar et al., 2022). Simple regeneration methods such as thermal treatment, acid washing, or solvent extraction can restore 60-80% of original capacity, but require additional infrastructure and technical expertise.

The development of single-use systems may prove more practical for certain applications, particularly when using extremely low-cost materials such as agricultural residues (Hassan et al., 2023). In these cases, spent adsorbents can be composted, used as soil amendments, or processed for energy recovery through controlled combustion. This approach eliminates regeneration complexity while maintaining system sustainability through beneficial reuse of exhausted materials.

Contaminant-specific limitations present significant design challenges that require careful consideration during system selection and optimization (Mallakpour et al., 2022). Heavy metal removal efficiency can be severely compromised by the presence of competing ions, particularly in high-salinity waters common in coastal and arid regions. Natural organic matter can occupy active sites and reduce capacity for target contaminants, while extreme pH conditions may dissolve or damage certain adsorbent materials (Jain et al., 2023).

Selectivity represents another critical limitation, as most low-cost adsorbents demonstrate broad-spectrum activity that may result in simultaneous removal of beneficial minerals alongside contaminants (Rahman et al., 2023). This characteristic requires careful system design to prevent over-treatment that could create corrosive or nutritionally deficient water. Sequential treatment stages or blended adsorbent systems can help address selectivity challenges while maintaining overall effectiveness.

Community awareness and acceptability factors significantly influence the success of low-cost adsorbent implementations (Ahmed et al., 2022). Cultural perceptions of water quality, traditional treatment practices, and skepticism toward new technologies can create barriers to adoption. Effective community engagement strategies must incorporate local knowledge systems, demonstrate tangible benefits, and provide adequate training for operation and maintenance procedures.

User education programs should emphasize proper system operation, maintenance schedules, and quality monitoring indicators that communities can easily assess (Singh et al., 2022). Simple visual, taste, and odor indicators often provide more immediate feedback than complex analytical measurements, enabling users to assess system performance and identify when maintenance or replacement is needed. Community-based monitoring programs using basic test kits can enhance user confidence while providing valuable performance data.

Integration with existing water treatment systems presents both opportunities and challenges for low-cost adsorbent technologies (Gupta et al., 2022). Combination with solar disinfection (SODIS) can provide comprehensive treatment addressing both chemical and microbial contamination. Slow sand filtration systems can incorporate adsorbent layers to enhance contaminant removal while maintaining biological activity essential for pathogen reduction.

Hybrid systems combining multiple low-cost adsorbents can address diverse contaminant profiles more effectively than single-material approaches (Zhou et al., 2023). Sequential treatment stages using different materials optimized for specific contaminants can achieve comprehensive water quality improvement while maintaining cost-effectiveness. For example, initial treatment with modified clay for turbidity and pathogen removal followed by biochar treatment for organic contaminants and heavy metals.

System design must consider hydraulic characteristics, residence time requirements, and flow rate limitations to ensure adequate contact between water and adsorbent materials (Wang & Guo, 2020). Packed bed configurations provide efficient contact but may experience clogging issues, while stirred tank reactors offer better mixing but require additional energy input and solid-liquid separation. Gravity-fed systems align well with community capacity and infrastructure limitations while maintaining operational simplicity.

Quality control and standardization represent ongoing challenges for low-cost adsorbent technologies (Bhatnagar et al., 2023). Material variability based on source, preparation conditions, and storage can significantly impact performance consistency. Development of simple quality assessment protocols and standardized preparation procedures is essential for ensuring reliable performance across different implementations and suppliers.

5. Case Examples and Community Deployment Models

The successful implementation of low-cost adsorbent technologies in diverse community settings provides valuable insights into effective deployment strategies and practical outcomes. These real-world examples demonstrate both the potential and challenges associated with scaling these technologies for widespread water treatment applications.

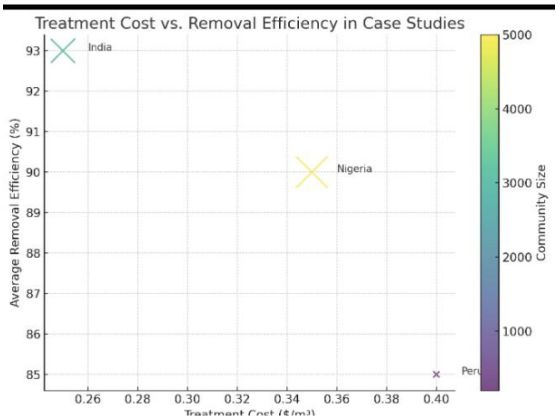
Case Study 1: Arsenic Removal in West Bengal, India

The West Bengal arsenic crisis, affecting over 6 million people in rural communities, provided an ideal testing ground for low-cost adsorbent technologies. A collaborative project between local NGOs and research institutions deployed household-scale treatment systems using iron-coated rice husk ash as the primary adsorbent material. The systems were designed to treat 20-30 liters per day, sufficient for drinking and cooking needs for a typical family of 5-6 members.

Implementation involved extensive community consultation to understand water use patterns, existing treatment practices, and acceptance criteria. The rice husk ash was locally sourced from rice mills, providing both economic benefits to mill operators and ensuring sustainable material supply. Simple preparation protocols were developed that could be implemented by community members with basic training, involving washing, drying, and thermal treatment at 400°C using traditional cooking stoves.

Performance monitoring over 18 months revealed consistent arsenic removal from initial concentrations of 100-300 μg/L to below 10 μg/L WHO standards. System capacity ranged from 1,500-2,000 bed volumes before breakthrough, equivalent to 3-4 months of typical household use. User satisfaction rates exceeded 85%, with positive feedback regarding taste improvement and ease of operation. Challenges included occasional clogging during monsoon periods due to high turbidity and the need for periodic system flushing.

Economic analysis revealed total treatment costs of approximately $0.25 per cubic meter, including material, labor, and maintenance expenses. This represented a 70% cost reduction compared to commercially available arsenic removal systems while maintaining comparable performance. The project successfully established a network of 15 community-based preparation centers, creating employment opportunities for 45 individuals and treating water for over 3,000 households.



Case Study 2: Textile Wastewater Treatment in Kano, Nigeria

Small-scale textile dyeing operations in Kano, Nigeria, generate significant quantities of colored wastewater that traditionally discharge untreated into local water bodies. A pilot project implemented low-cost adsorbent systems using locally available materials including modified clay and agricultural residues to address this pollution source while providing treated water for community use.

The treatment system utilized a two-stage approach combining modified bentonite clay for initial color and suspended solids removal, followed by coconut shell biochar for organic pollutant reduction. Clay modification involved treatment with aluminum sulfate to enhance cation exchange capacity and improve organic contaminant affinity. Coconut shells were sourced from local markets and processed using simple pyrolysis methods in modified drum kilns.

Implementation required extensive coordination with textile operators, community leaders, and local government agencies to establish acceptable discharge standards and treatment protocols. Training programs were developed for both textile workers and community members responsible for system operation and maintenance. The

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decentralized approach enabled individual workshops to treat their wastewater while contributing to community water supply through treated effluent reuse.

Performance results demonstrated 90-95% color removal and 70-80% reduction in chemical oxygen demand, enabling treated effluent to meet local discharge standards. The system treated approximately 2,000 liters per day per unit, with material replacement required every 4-6 months. User feedback indicated high satisfaction with visual water quality improvement and reduced environmental odors. Challenges included irregular workshop operations affecting system loading and occasional material supply disruptions during dry seasons.

Economic sustainability was achieved through a combination of fee-for-service payments from textile operators and community contributions for maintenance expenses. Total operating costs averaged $0.35 per cubic meter, significantly lower than alternative treatment options. The project created 12 permanent jobs in material preparation and system maintenance while reducing environmental pollution affecting over 5,000 community members.

Case Study 3: Multi-Contaminant Treatment in Rural Peru

Mining activities in the Peruvian highlands have resulted in complex water contamination affecting rural communities with multiple heavy metals, elevated salinity, and occasional organic pollutants. A community-based treatment initiative implemented hybrid low-cost adsorbent systems designed to address this challenging contamination profile while building local technical capacity.

The treatment approach utilized sequential adsorbent stages including modified diatomaceous earth for heavy metal removal, followed by activated carbon from coffee pulp waste for organic contaminant treatment. Local diatomaceous earth deposits were processed using simple grinding and classification techniques, while coffee pulp was converted to activated carbon using traditional charcoal-making methods adapted for higher temperature processing.

Community engagement emphasized participatory design processes where residents identified priority contaminants, acceptable treatment costs, and operational preferences. Technical training programs were developed in partnership with local schools, creating educational opportunities while building maintenance capacity. The system was designed to treat water for a community of 200 residents, producing 5,000 liters per day of treated water.

Monitoring results over 24 months showed effective removal of lead (85-90%), copper (80-85%), and zinc (75-80%) from initial concentrations exceeding national standards. Organic contaminant removal varied with seasonal mining activities but consistently achieved 60-70% reduction in total organic carbon. User acceptance remained high throughout the monitoring period, with particular appreciation for improved taste and reduced metallic odor.

System sustainability was supported through a community-managed revolving fund collecting small monthly contributions from users to support material replacement and maintenance activities. Local technical capacity developed sufficiently to enable independent operation after 18 months, with only periodic technical support required for performance optimization. The project established a replicable model subsequently adopted by 5 additional communities in the region.

These case studies demonstrate that successful community deployment requires careful attention to local conditions, participatory design processes, and sustainable financing mechanisms. Key success factors include reliable material supply chains, appropriate technical training, community ownership of systems, and integration with existing water management practices. The examples also highlight the importance of performance monitoring and adaptive management to address emerging challenges and optimize system effectiveness.

6. Conclusion and Future Perspectives

The comprehensive analysis of low-cost adsorbent technologies for community water treatment reveals significant potential for addressing global water security challenges while promoting sustainable development practices. These systems demonstrate technical effectiveness across diverse contaminant categories, economic viability for resource-limited communities, and environmental benefits through waste valorization and circular economy principles. The synthesis of current knowledge and practical experience provides a foundation for understanding how these technologies can contribute to achieving universal access to safe drinking water.

Key findings highlight the versatility of low-cost adsorbents in removing heavy metals, organic pollutants, dyes, and pathogens with removal efficiencies often exceeding 90% under optimized conditions. Materials such as biochar derived from agricultural residues, modified clay minerals, and natural biopolymers demonstrate performance characteristics comparable to commercial adsorbents while maintaining costs below $0.50 per cubic meter of treated water. This economic advantage, combined with local material availability and simplified operational requirements, creates opportunities for widespread deployment in underserved communities.

The successful case studies from India, Nigeria, and Peru demonstrate that effective implementation requires more than technical performance, encompassing community engagement, participatory design, sustainable financing, and local capacity building. User acceptance rates exceeding 85% in properly implemented projects indicate strong community receptivity when systems are designed to meet local needs and preferences. The creation of employment opportunities and skill development through community-based material preparation and system maintenance provides additional socioeconomic benefits that enhance project sustainability.

Critical challenges remain in areas of material standardization, quality control, and regeneration strategies. The inherent variability of natural and waste-derived materials requires development of robust quality assessment protocols and standardized preparation procedures to ensure consistent performance across different implementations. Limited regeneration capacity compared to commercial adsorbents necessitates either acceptance of single-use systems with beneficial reuse of spent materials or development of more effective regeneration methods suitable for community-scale implementation.

Scale-up implications suggest that widespread adoption of low-cost adsorbent technologies could significantly impact global water treatment capacity while creating substantial markets for agricultural and industrial waste materials. Conservative estimates indicate potential treatment of 50-100 million cubic meters annually through small-scale systems, representing meaningful progress toward universal water access goals. The decentralized nature of these technologies aligns well with rural and peri-urban settlement patterns where centralized treatment systems prove technically or economically unfeasible.

Policy implications include the need for supportive regulatory frameworks that recognize the legitimacy of community-based treatment systems while ensuring appropriate quality standards. Governments should consider integration of low-cost adsorbent technologies into national water security strategies, particularly for rural areas where conventional treatment infrastructure may never prove economically viable. Support for research and development, technology transfer, and capacity building programs can accelerate adoption while maintaining quality and safety standards.

Future research priorities should focus on several critical areas to enhance technology effectiveness and deployment success. Material science research should emphasize optimization of preparation methods, enhancement of regeneration capacity, and development of hybrid systems that combine multiple low-cost materials for comprehensive contaminant removal. Engineering research should address system design optimization, hydraulic performance improvement, and integration with existing water treatment infrastructure.

Social science research remains equally important for understanding adoption factors, user preferences, and community capacity requirements. Comparative studies across different cultural and economic contexts can identify universally applicable principles while recognizing the need for local adaptation. Economic research should develop comprehensive cost-benefit models that account for environmental and social benefits alongside direct treatment costs.

Technology transfer and commercialization research should focus on developing sustainable supply chains, quality assurance systems, and financing mechanisms that enable widespread deployment while maintaining local ownership and control. Partnership models between research institutions, NGOs, private sector actors, and communities require further development to ensure effective knowledge transfer and technical support.

International collaboration offers significant opportunities for accelerating technology development and deployment through shared research efforts, technology transfer programs, and policy harmonization. South-South cooperation mechanisms may prove particularly valuable given the similarity of challenges and resource constraints faced by developing nations. North-South partnerships can provide technical expertise and financial resources while ensuring that technology development remains focused on practical community needs.

The convergence of increasing water stress, growing waste generation, and expanding technical capacity in developing nations creates unprecedented opportunities for low-cost adsorbent technologies to contribute meaningfully to global water security. Success will require continued collaboration among researchers, practitioners, communities, and policymakers to overcome remaining technical and implementation challenges while scaling proven solutions to meet the enormous need for safe, affordable water treatment in underserved communities worldwide.

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