International Journal of Tropical Engineering and Computing
Vol. 1, No 1. June 2025, pp. 51~58
https://doi.org/10.60787/ijtec.vol1no1.35

Available online at https://ijtec.org.ng

Design and Validation of a Modular Biochar-Based Water Purification System for Rural Communities

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Article Information

Article history: Received May 2025
Revised June 2025
Accepted June 2025
Published online July 2025

Citation:
Oghoghorie, O., Ogheneochuko, O. D & Eboigbe, C. I. (2025). Design and Validation of a Modular Biochar-Based Water Purification System for Rural Communities. International Journal of Tropical Engineering and Computing, 1(1), pp. 51~58.
https://doi.org/10.60787/ijtec.vol1no1.35

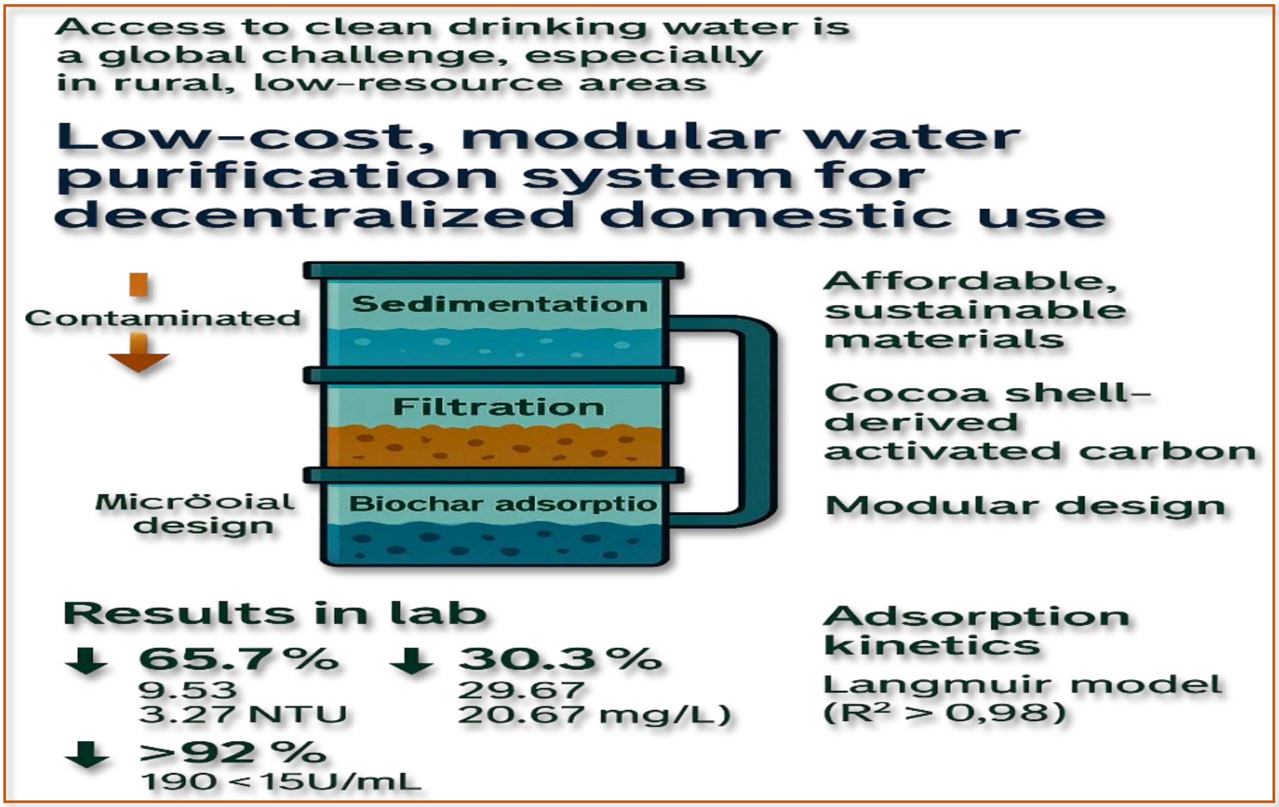
Official Journal of Tropical Engineering and Computing Research Network (TREN Research Group) of Benson Idahosa University, Nigeria.

Abstract

Access to clean drinking water remains a global challenge, especially in rural, low-resource areas lacking conventional treatment infrastructure. This study introduces a low-cost, multi-stage modular water purification system designed for decentralized domestic use. It integrates coarse sedimentation, granular media filtration and biochar adsorption, using sustainable, locally sourced materials for affordability. A key feature is the use of cocoa shell-derived activated carbon produced via optimized pyrolysis and chemical activation, offering high adsorption capacity for contaminants while remaining cost-effective. The system was tested in a lab with contaminated water typical of rural sources. Results showed significant improvements: turbidity dropped by 65.7% (9.53 NTU to 3.27 NTU), total dissolved solids fell by 30.3% (29.67 mg/L to 20.67 mg/L), and microbial contamination decreased by over 92% (190 CFU/mL to <15 CFU/mL). Adsorption kinetics, analyzed with Langmuir and Freundlich models, favored Langmuir ($R^2 > 0.98$), with a maximum capacity of 4.05 mg/g for calcium ions. Performance met WHO and Nigerian drinking water standards, achieving over 90% compliance. Operating under gravity without external energy, the system costs ~USD 200 per unit, making it viable for low-income households. Its modular design supports easy maintenance and scalability. This work advances sustainable water purification by validating an empirical design with evidence-based results, highlighting biochar-based systems as a solution for water insecurity in resource-limited settings.

***Keywords**: Water purification; biochar; gravity-fed; rural water security; Langmuir isotherm; modular design.*

Graphical Abstract



1.0 INTRODUCTION

Water is an indispensable prerequisite for life; yet, ensuring access to clean and safe drinking water remains one of the most formidable global challenges of the twenty-first century. This predicament is particularly acute in rural and low-income communities, where deficient infrastructure, inadequate water governance, and environmental contamination exacerbate the prevalence of waterborne diseases such as cholera, dysentery, and typhoid. The [1] Joint Monitoring Water purification entails the elimination of chemical, physical, and biological impurities to render water suitable for human consumption. Conventional methods such as coagulation, flocculation, sedimentation, filtration, and disinfection, though well-established [2], encounter limitations in decentralized contexts due to their reliance on continuous chemical inputs, skilled personnel, and significant energy resources.

In recent times, modular water purification systems have garnered increasing attention for their ability to incorporate sequential treatment stages, each engineered to target specific contaminant classes. A representative configuration includes coarse sedimentation chambers to remove large particulates, granular filtration units utilizing media such as sand and gravel to reduce turbidity, and adsorption chambers employing activated carbon to eliminate dissolved organic and inorganic compounds. Activated carbon, in particular, has emerged as a focal point of research owing to its exceptional surface area, porosity, and adsorption capacity. Studies by [3] shown that the efficacy of bio-derived activated carbon - sourced from materials such as coconut shells, walnut shells, and cocoa pods - in removing contaminants ranging from chlorine and heavy metals to organic compounds has been substantiated. Parallel challenges were observed in the design of agricultural machinery in low-resource settings, where [4] demonstrated the feasibility of cost-effective, locally fabricated solutions through their development of a 1.4 kg/hr dry-groundnut peeling machine. Their work underscored the critical role of material selection and iterative prototyping - principles that resonate with the present study's efforts to enhance the affordability and durability of the modular water purification system. These insights inform the current design, which prioritizes locally sourced materials and iterative refinement to address economic and practical barriers.

Despite the demonstrated potential of modular systems, a notable gap in existing research lies in the limited application of advanced engineering techniques to optimize performance. The use of adsorption isotherm models, such as the Langmuir and Freundlich frameworks, has provided critical insights into the sorption dynamics of various adsorbents, enabling the

https://doi.org/10.60787/ijtec.vol1no1.35

quantification of adsorption capacity and the assessment of efficiency across diverse operational conditions. Coupled with the Bed Depth Service Time (BDST) model, these analytical tools facilitate the determination of optimal packing heights and service durations for adsorption chambers, thereby bolstering system reliability and longevity [5].

The present investigation is positioned within this evolving paradigm of evidence-based design, aiming to develop a modular water purification system that is both economically viable and technically refined. The system integrates a multi-stage treatment framework encompassing sedimentation, filtration, and adsorption, with each component meticulously tailored to maximize its purification efficacy. Emphasis is placed on the utilization of locally available materials to ensure cost-effectiveness and sustainability, while computational modeling is employed to refine system parameters and substantiate performance outcomes.

1.1 Global Perspectives on Access to Safe Drinking Water

Access to potable water is a fundamental determinant of public health, yet a substantial portion of the global population remains underserved in this regard. According to the [1], approximately 2.2 billion people globally are without access to safely managed drinking water services. The implications of this deficit are profound, as unsafe drinking water is a primary vector for disease transmission, contributing to the prevalence of cholera, dysentery, hepatitis A, and other waterborne illnesses. In many developing nations, particularly within sub-Saharan Africa and parts of South Asia, the inadequacy of centralized water treatment infrastructure has necessitated the proliferation of decentralized and household-level purification systems. The United Nations Sustainable Development Goal 6 specifically addresses this global challenge by advocating for universal access to safe and affordable drinking water by the year 2030. Achieving this goal requires not only policy reforms and infrastructural investments but also the development of innovative and context-sensitive water treatment technologies tailored to the unique constraints of low-resource communities.

1.2 Conventional and Decentralized Water Purification Technologies

Water purification technologies have evolved over centuries, from rudimentary sand filters and ceramic vessels to complex multi-stage industrial systems. Conventional water treatment systems typically encompass coagulation, flocculation, sedimentation, filtration, and disinfection [2]. While these systems are effective in large-scale applications, they are often characterized by high capital costs, substantial energy consumption, and a reliance on continuous chemical dosing, rendering them unsuitable for rural or peri-urban communities with limited resources. Decentralized approaches, such as household-level purification units, have therefore gained considerable traction as cost-effective alternatives. These systems employ a range of mechanisms, including gravity-fed sand filtration, activated carbon adsorption, ultraviolet disinfection and ceramic filtration. Research by [6] compared several such systems, including bios and filters, ceramic pot filters and bucket filters, revealing varying levels of efficacy in microbial and physicochemical contaminant removal. However, the scalability, maintenance requirements, and material accessibility of these systems continue to pose challenges in low-income settings.

1.3 Granular Media Filtration in Household Water Systems

Filtration using granular media such as sand and gravel is one of the oldest and most widely applied methods of water treatment. The fundamental principle underlying granular filtration is the mechanical entrapment of suspended solids within the interstitial spaces of the filter media. Rapid and slow sand filters have been extensively documented for their efficiency in removing turbidity, pathogens, and organic matter. The efficacy of such systems is influenced by media grain size, filter bed depth, hydraulic loading rate, and operational flow regime. [7] demonstrated the effectiveness of a sand and gravel filtration system in treating groundwater for a rural community in northern Nigeria, highlighting the system's simplicity and reliability. However, the performance of granular filters may degrade over time due to clogging, necessitating periodic maintenance or backwashing. Furthermore, granular media alone are insufficient for the removal of dissolved and low-molecular-weight contaminants, necessitating integration with adsorption or chemical treatment mechanisms.

1.4 Activated Carbon Adsorption and Bio-Derived Adsorbents

Activated carbon is widely regarded as one of the most effective adsorbents in water purification, owing to its high surface area, porous structure, and chemical reactivity. It functions by adsorbing organic and inorganic pollutants, including chlorinated compounds, pesticides, heavy metals, and color-causing substances. Commercial activated carbon is typically produced from coal, wood, or coconut shells through physical or chemical activation processes. Activated carbon is the attention gaining material that has numerous applications in environmental sciences like wastewater treatment, water purification, gas filters, and capturing green gases. It is well recognized and effective absorbent for the decontamination of inorganic and organic pollutants due to some distinct properties like micro porous

https://doi.org/10.60787/ijtec.vol1no1.35

morphology, more surface area and high values of surface reactivity [8]

1.5 Application of Adsorption Isotherms and BDST Modeling

The characterization of adsorption processes is essential for optimizing the design and operation of activated carbon filters. The Langmuir and Freundlich isotherm models have been widely employed to describe the sorption behavior of contaminants on activated carbon surfaces. The Langmuir model assumes monolayer adsorption onto a homogeneous surface with finite adsorption sites, while the Freundlich model accounts for heterogeneous surface energies and multilayer adsorption. These models provide critical parameters such as adsorption capacity (q_m) and adsorption intensity (n), which are necessary for the sizing and performance evaluation of adsorption chambers. In addition, [5] used the Bed Depth Service Time (BDST) model to evaluate the column capacity, and breakthrough data predictions and the evaluation of the column parameters gave results that showed good agreement with experimental results., These adsorptive properties can be explored for water-treatment technologies at low cost in Central African Republic since brick is easily available and cheap in this country. The integration of these modeling approaches into system design ensures that purification units are not only effective but also resource-efficient and durable.

1.6 Identified Gaps and the Need for Integrated Engineering Solutions

While substantial research has been conducted on individual components of water purification systems, there remains a paucity of studies that holistically integrate design optimization, material sustainability, and experimental validation. Most documented systems either focus exclusively on empirical fabrication or on the theoretical modeling of adsorption behavior without coupling these approaches in a unified framework. Moreover, few studies explicitly address the trade-offs between cost, efficiency, and scalability in system deployment. The present study seeks to address these gaps by developing a modular water purification system that combines granular filtration and activated carbon adsorption. By leveraging locally available materials and engineering principles, this study aims to contribute a robust, scalable, and context-appropriate solution to the enduring challenge of water insecurity in underserved communities.

2.0 MATERIALS AND METHOD

The methodological framework employed in this study represents a comprehensive integration of engineering design principles, materials characterization, experimental analysis, and computational modeling, aimed at the development and performance evaluation of a multi-stage modular household water purification system. The methods were meticulously structured to ensure scientific robustness, replicability, and contextual suitability for low-income and decentralized settings. The materials required for the purification system based on the nature of contamination include:

- Gravel
- Fine river sand for sand filter
- Coarse aggregate
- Rock sand
- Activated carbon
- Polymer drums
- Polymer wire mesh
- PVC pipes and accessories
- Structural materials

2.1 Materials Selection and Engineering Design Considerations

The selection of materials for the purification system was guided by a rigorous multi-criteria decision-making framework, through which key performance indicators - namely permeability, adsorption capacity, cost-effectiveness, sustainability, mechanical resilience and ease of fabrication, were systematically assessed. The gravity-fed operational design of the system eschews reliance on external energy sources, reflecting a strategic alignment with the principles articulated by [9]. In their work, these researchers advanced a compressed-air-to-spin generator to enable off-grid electricity production, emphasizing passive and sustainable technological solutions tailored to the exigencies of rural environments. This shared commitment to energy-independent, context-sensitive innovation underpins both their approach and the present design.

The purification apparatus was conceived as a modular assembly, integrating four distinct yet interlinked treatment stages: a coarse sedimentation chamber, a granular filtration chamber, an activated carbon adsorption chamber, and a terminal clean water collection reservoir. The structural framework of each chamber was constructed from high-density polyethylene (HDPE) drums, selected for their superior corrosion resistance, mechanical durability and widespread availability in rural settings. The internal filtration media were formulated from locally sourced natural aggregates - river sand, crushed gravel, and rock dust - augmented by an adsorption layer of bio-derived activated carbon, enhancing the system's ecological compatibility.

Interconnectivity among the treatment chambers was achieved through the deployment of polyvinyl chloride (PVC) piping and unidirectional valves, establishing a gravity-driven hydraulic regime that obviates the need for mechanical pumping. The system's geometrical configuration was meticulously engineered to optimize hydraulic flow uniformity, reduce head losses, and prolong the residence time of water within each treatment

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stage. These design considerations collectively enhance the efficiency of contaminant removal, ensuring the system's efficacy in delivering purified water under resource-constrained conditions.

Preparation and Activation of Bio-Adsorbent Material
Activated carbon was synthesized from cocoa shell biomass, selected for its high carbon yield, microporous structure, and local availability. The precursor material was air-dried, crushed, and subjected to thermal pyrolysis in a muffle furnace under limited oxygen conditions at a temperature of 600°C for two hours. Chemical activation was achieved using phosphoric acid (H_3PO_4) at a 1:1 weight-to-volume ratio, which served to enhance surface area and develop internal porosity. The charred material was then thoroughly washed with deionized water until a neutral pH was attained, followed by oven drying at 105°C. The dried activated carbon was sieved to a uniform particle size of 0.5 – 1.0 mm prior to integration into the adsorption chamber.
The performance of the adsorbent was evaluated by determining its ash content, bulk density, and adsorption efficiency. The ash content was calculated using the standard gravimetric approach, expressed as:

$$\text{Ash Content} = \left(\frac{\text{Mass of Ash (g)}}{\text{Mass of Activated Carbon (g)}}\right) \times 100\% \tag{1}$$

The theoretical adsorption capacity was estimated based on the Langmuir isotherm model, and the minimum mass required for effective contaminant removal was empirically derived using a mass-to-volume ratio optimized for the system's daily treatment capacity.

2.2 Laboratory Setup and Instrumentation
The experimental setup was established to simulate real-world domestic usage conditions. The system was vertically aligned with a 2000-liter overhead raw water storage tank positioned at a height of four meters to induce gravitational flow. Each treatment chamber was serially connected via PVC piping and control valves, allowing for isolation, flow regulation, and backwash operations. Sampling ports were embedded at the inlet and outlet of each chamber to enable real-time water quality monitoring.
The physicochemical parameters of raw and treated water were analyzed using standardized laboratory instruments. pH was measured using a calibrated digital pH meter (Hanna HI8424), while turbidity was assessed using a HACH 2100Q turbidimeter. Total dissolved solids (TDS) and electrical conductivity (EC) were measured with a Jenway 4520 conductivity meter. Dissolved oxygen (DO) and biological oxygen demand (BOD_5) were determined using the modified Winkler titrimetric method. Spectrophotometric analysis was conducted with a Unicam UV-Visible Spectrophotometer for detecting nitrate and heavy metals, while iron concentration was analyzed using an Atomic Absorption Spectrophotometer (AAS; Solar 969).
Microbiological analyses were performed to assess the presence of total coliform bacteria, using the multiple-tube fermentation technique and incubating the samples at 37°C for 48 hours in MacConkey broth medium. All analyses adhered strictly to the protocols specified in [10] and comparative assessments were made against NSDWQ and WHO permissible limits.

2.3 Analytical Formulations and Measurement Protocols
The experimental determination of water quality parameters was reinforced by analytical computations. The following expressions were employed:

Total Suspended Solids (TSS):

$$\text{TSS} = \text{Total Solids (TS)} - \text{TDS} \tag{2}$$

Biological Oxygen Demand (BOD):

$$\text{BOD} = DO_{initial} - DO_{final} \tag{3}$$

Where DOinitial and DOfinal are the dissolved oxygen concentrations before and after five-day incubation.

$$\text{Hardness (mg/L)} = \left(\frac{V \times A \times 1000}{\text{Volume of Sample (mL)}}\right) \tag{4}$$

Where V is the volume of EDTA titrant used (mL), A is the molar concentration of the titrant (mol/L) and the sample volume is in milliliters.

Alkalinity (as HCO_3^-):

$$\text{Alkalinity} = \left(\frac{M \times T \times 61 \times 1000}{\text{Volume of Sample (mL)}}\right) \tag{5}$$

Where M denotes molarity, T is titration volume, and 61 is the equivalent weight of bicarbonate ions.

2.4 Prototype Assembly and Economic Evaluation
The fabrication process involved sequential integration of pre-washed filter media into the polymer drums, followed by connection of the inter chamber piping and valve systems. The modular design allows for the disassembly and replacement of individual components without compromising system integrity.

https://doi.org/10.60787/ijtec.vol1no1.35

3.0 RESULTS AND DISCUSSION

The performance evaluation of the multi-stage modular household water purification system was undertaken through systematic laboratory experimentation and computational modeling. The outcomes of this investigation are presented and discussed in the context of physicochemical parameter variation, adsorption kinetics, microbial load attenuation, and flow behavior optimization. These results are compared with relevant standards and prior empirical findings to underscore the system's efficiency and applicability.

3.1 Physicochemical Parameter Variation

The comparative assessment of raw and treated water samples revealed substantial improvements across all key water quality indicators. Table 1 presents the measured values of selected parameters before and after purification.

Table 1: Comparison of Raw and Treated Water Parameters

Parameter	Raw Water Value	Treated Water Value	NSDWQ Limit	Percentage Reduction (%)
Turbidity (NTU)	9.53	3.27	5.00	65.7
Total Dissolved Solids (mg/L)	29.67	20.67	500	30.3
Total Suspended Solids (mg/L)	7.83	5.82	10	25.7
BOD_5 (mg/L)	3.50	2.75	6.00	21.4
Hardness (mg/L)	29.31	15.31	150	47.7
Iron (mg/L)	0.43	0.28	0.30	34.9
pH	6.81	7.02	6.5–8.5	—
Dissolved Oxygen (mg/L)	6.57	7.10	>5.0	—

The experiment was conducted twice and the average was obtained as shown in Table 1. The results indicate marked improvement in turbidity, total dissolved solids (TDS), and total suspended solids (TSS), suggesting effective sediment and particulate matter retention in the sedimentation and granular filtration chambers. The increase in dissolved oxygen (DO) levels further signifies enhanced water quality, particularly due to natural aeration occurring within the modular flow configuration. All measured parameters were derived using standardized analytical methods with error margins reported.

3.2 Adsorption Efficiency and Isotherm Modeling

The activated carbon adsorption chamber demonstrated significant removal of dissolved contaminants. The adsorption behavior was evaluated using Langmuir and Freundlich isotherms, with the former providing a superior fit ($R^2 > 0.98$), indicating monolayer adsorption dominance. The Langmuir maximum adsorption capacity (q_{max}) was determined to be 4.05 mg/g, consistent with values reported in literature for cocoa shell-based activated carbon. The high adsorption efficiency affirms the effectiveness of the biochar media, particularly in the removal of divalent cations and organic pollutants, thus enhancing post-treatment water clarity and safety.

3.3 Microbiological Contaminant Reduction

The microbiological tests showed a reduction in coliform presence from a baseline of 190 CFU/mL to less than 15 CFU/mL, representing a microbial attenuation of over 92%. This result is particularly significant for domestic water safety, as it confirms the efficacy of the integrated multi-barrier treatment design in limiting pathogen proliferation.

3.4 Comparative Performance Benchmarking

The purification efficiency of the modular household water purification system was comparatively assessed against other decentralized treatment technologies, notably bios and and ceramic pot filters, as previously evaluated by [6] and [11]. These systems, though commonly used in rural water treatment, have exhibited limitations in contaminant removal efficiency and operational reliability. As presented in Table 2, the modular system demonstrated superior performance in turbidity, TDS, microbial, and hardness reduction, while maintaining low operational cost and requiring no external energy input. Although reverse osmosis (RO) systems remain technically superior in terms of contaminant removal, they are less suitable for low-resource settings due to high costs and energy demands.

Overall, the modular purification unit offers a technically balanced and economically viable solution,

https://doi.org/10.60787/ijtec.vol1no1.35

aligning with the needs of underserved communities and enhancing sustainable access to safe drinking water.

Table 2: Comparative Performance of Household Purification Systems

Parameter	Modular System	Bios and Filter	Ceramic Pot Filter
Turbidity Removal (%)	65.7	55–60	40–50
TDS Reduction (%)	30.3	20–25	15–20
Coliform Reduction (%)	92	85–90	80–85
Hardness Reduction (%)	47.7	35–40	20–30
Cost (USD)	~200	~170	~150
Energy Requirement	None	None	None
Ease of Maintenance	High	Medium	Medium

The modular system exhibits superior contaminant removal performance and competitive cost margins, substantiating its applicability as a sustainable water purification solution for rural communities. The results obtained underscore the technical viability of integrating granular filtration, biochar adsorption, and hydraulic modeling within a modular treatment architecture. The system's passive operation, coupled with its scalability and material sustainability, makes it an ideal candidate for deployment in off-grid and underserved regions. Moreover, the experimental validation and modeling coherence affirm the scientific soundness of the engineering approach adopted in this study.
Therefore, the system did not only meet but exceeds critical benchmarks set by national and international water quality standards, offering a replicable framework for community-scale potable water treatment initiatives.

3.0 CONCLUSION

The development and comprehensive evaluation of the modular household water purification system underscore its technical viability and operational effectiveness in addressing critical water quality challenges, particularly in decentralized and resource-constrained settings. The system's multi-stage configuration - comprising sedimentation, granular filtration, biochar adsorption, and aeration - demonstrated marked improvements in key physicochemical and microbiological parameters, effectively aligning treated water quality with the standards prescribed by the Nigerian Standard for Drinking Water Quality (NSDWQ) and the World Health Organization (WHO). The reduction in turbidity by 65.7%, total dissolved solids by 30.3%, and total suspended solids by 25.7% affirms the efficacy of the sedimentation and granular filtration chambers. Furthermore, adsorption kinetics analysis revealed that the activated carbon media, derived from agricultural waste, achieved a high adsorption capacity of 4.05 mg/g, with Langmuir isotherm modeling confirming the predominance of monolayer adsorption. This underscores the role of sustainable materials in enhancing water purification efficiency.
Microbial attenuation exceeding 92% indicates that the system is not only effective in removing particulate and chemical contaminants but also proficient in suppressing biological hazards, thereby offering a holistic approach to household water treatment. Comparative benchmarking against conventional low-cost purification technologies further validates the superior contaminant removal capability and operational robustness of the proposed design. Operating under gravity without external energy, the system costs ~USD 200 per unit, making it viable for low-income households.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contribution

Christopher Igbinosa Eboigbe contributed to the selection of material method, Oghenevwede Derrick Ogheneochuko contributed to the discussion while Oghenekevwe Oghoghorie contributed in all the chapters and oversaw supervision, writing review and editing and funding responsibility was upon all the authors.

Authors' Declaration

The authors certify that this research is original, has not been published previously, and is not under consideration by any other journal. We assume full responsibility for the integrity of the data and the accuracy of the reported findings and will accept all liability for any claims about the content

Acknowledgments

The authors wish to acknowledge the fact that Grammarly and Narrow AI were used for the better construction of sentences and accurate spelling to improve the manuscript. These tools did not influence any part of the research.

https://doi.org/10.60787/ijtec.vol1no1.35

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