
DESIGN AND PERFORMANCE EVALUATION OF A DUAL-MEDIA FILTRATION SYSTEM USING PALM KERNEL SHELL ACTIVATED CARBON FOR WASTEWATER TREATMENT

Aminu Ohueyi Ahmed^{1,*}, Mohammed Aliyu Aliyu¹, Abdullahi Mohammed Dalhatu¹,
Umar Abdullahi¹, Yakubu Joseph Nlira¹

¹Ahmadu Bello University, Zaria, Nigeria

Email: ohueyi23@gmail.com*, maliualiyu@gmail.com, mabdullahi556@gmail.com, abuafreen14@gmail.com,
josephyakubu1090@gmail.com

*Corresponding author: Aminu Ohueyi Ahmed

DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

The increasing demand for cost-effective and sustainable wastewater treatment technologies in developing regions has necessitated the exploration of locally available materials for tertiary treatment applications. This study presents the design and performance evaluation of a laboratory-scale dual-media filtration system incorporating palm kernel shell-derived activated carbon (PKS-AC) and sharp sand for the treatment of effluent from the Ahmadu Bello University (ABU), Zaria stabilization pond. The filtration column was constructed using a layered configuration of coarse sand, activated carbon, and fine sand to facilitate combined processes of physical filtration and adsorption. Wastewater samples were collected from the final discharge point of the maturation pond and analyzed before and after filtration for selected physicochemical parameters, including turbidity, nitrate concentration, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (TDS). The results indicate substantial improvements in effluent quality after treatment. Turbidity was reduced from 13.0 NTU to 2.6 NTU, nitrate concentration decreased from 35.0 mg/L to 15.6 mg/L, COD was lowered from 3000 mg/L to 800 mg/L, and BOD decreased from 150 mg/L to 90 mg/L. Additionally, a moderate reduction in TDS was observed. The enhanced performance of the system is attributed to the synergistic interaction between the sand filtration layers and the adsorption capacity of PKS-AC. The findings demonstrate that the developed dual-media filtration system offers an efficient, low-cost, and sustainable solution for tertiary wastewater treatment, particularly in institutional and resource-constrained environments.

Keywords: Dual-media filtration; Palm kernel shell; Activated carbon; Wastewater treatment; Adsorption; Sand filtration

1. INTRODUCTION

Access to safe and reliable water remains a critical global challenge, particularly in developing countries where rapid urbanization, population growth, and limited infrastructure increasingly strain water resources and wastewater management systems (Onu et al., 2023). Wastewater generated from domestic, institutional, and industrial activities contains suspended solids, organic matter, nutrients, and pathogenic microorganisms, all of which pose significant environmental and public health risks if inadequately treated (Etsuyankpa et al., 2024).

Conventional wastewater treatment processes primarily target the removal of settleable solids and biodegradable organic matter. However, these processes may not adequately eliminate residual contaminants such as nutrients, turbidity, and dissolved pollutants. Consequently, the discharge of insufficiently treated wastewater can contribute to eutrophication, deterioration of water quality, and increased risks to aquatic ecosystems and public health (Kato & Kansha, 2024).

In many developing regions, including Nigeria, wastewater treatment systems rely predominantly on low-cost technologies such as waste stabilization ponds due to their simplicity and low operational requirements. While these systems are effective in reducing biochemical oxygen demand (BOD) and pathogen loads under optimal conditions, they often fail to remove turbidity, nutrients, and residual organic pollutants (Kayode et.al, 2023; Mara, 2013; Nwinyi et al., 2020). This

limitation is evident in the wastewater treatment system at Ahmadu Bello University (ABU), Zaria, where stabilization ponds are unable to consistently meet regulatory standards for effluent discharge.

To address these challenges, tertiary treatment processes are required to further polish the effluent before discharge or reuse. Advanced treatment methods such as membrane filtration and commercial activated carbon adsorption are highly effective but often economically prohibitive in low-resource settings. Consequently, there is growing interest in the development of cost-effective and sustainable treatment alternatives using locally available materials. Agricultural residues, in particular, have been widely investigated due to their abundance, low cost, and potential for conversion into effective adsorbents (Ali, 2012; Yahya et al., 2015).

Palm kernel shell (PKS), an abundant by-product of palm oil processing in Nigeria, has emerged as a promising precursor for activated carbon production due to its high carbon content, mechanical strength, and favorable adsorption properties (Abioye & Ani, 2015). When processed through carbonization and activation, PKS can produce activated carbon with a highly porous structure and large surface area capable of adsorbing organic and inorganic pollutants. In addition to adsorption, granular media filtration using sharp sand is effective in removing suspended particles and reducing turbidity through mechanisms such as straining, sedimentation, and adsorption.

The integration of adsorption and filtration processes into a dual-media system can enhance overall treatment efficiency through complementary mechanisms. In such systems, sand layers act as pre-filters that remove suspended solids and protect the adsorptive media from clogging, while activated carbon removes dissolved contaminants.

This study therefore focuses on the design and performance evaluation of a dual-media filtration system comprising palm kernel shell-derived activated carbon and sharp sand for the tertiary treatment of wastewater from Ahmadu Bello University, Zaria. The study aims to assess the effectiveness of the system in improving key physicochemical parameters and to demonstrate its potential as an affordable and sustainable wastewater treatment solution for institutional and resource-constrained environments.

This study aligns with the ICESID 2026 conference themes of Innovative Resource Utilization and Management and Sustainable Materials Synthesis, Processing and Recycling through the conversion of agricultural waste into a value-added adsorbent for wastewater treatment.

2. MATERIALS AND METHODS

2.1 Study Area and Sample Collection

The study was conducted using wastewater obtained from the waste stabilization pond system located within Ahmadu Bello University (ABU), Zaria, Nigeria. The stabilization pond receives wastewater from residential hostels, laboratories, administrative facilities, and other institutional sources, making it representative of mixed domestic and institutional effluent.

Wastewater samples were collected from the final discharge point of the maturation pond using clean, sterilized high-density polyethylene (HDPE) containers. The samples were transported to the laboratory in insulated containers and stored at approximately 4 °C before analysis to minimize biological and chemical changes. All analyses were conducted in accordance with standard procedures to ensure data reliability and reproducibility.

2.2 Preparation of Filtration Materials

2.2.1 Palm Kernel Shell Activated Carbon (PKS-AC)

The Palm kernel shells were obtained from a local palm oil processing site as shown in Figure 1. The shells were thoroughly washed with distilled water to remove impurities and then sun-dried to reduce moisture content. The dried shells were subjected to carbonization at approximately 400 °C in a furnace under limited oxygen conditions, producing char material as shown in Figure 2. The carbonized material was further activated through steam activation at elevated temperatures (800-950°C), during which superheated steam was introduced to promote pore development and increase adsorption capacity. The activation process followed the reaction $C + H_2O \rightarrow CO + H_2$, resulting in a highly porous adsorbent material, enhancing pore development and surface area. After activation, the material was

washed repeatedly with distilled water to remove residual impurities and then dried at room temperature. The resulting activated carbon was ground and sieved to obtain uniform particle size suitable for adsorption processes as shown in Figure 3. FTIR characterization of the activated carbon revealed the presence of hydroxyl (O-H), carbonyl (C=O), aromatic (C=C), amine (N-H), and alkyne (C≡C) functional groups on the adsorbent surface. These functional groups provide active adsorption sites that facilitate the removal of dissolved contaminants from wastewater.

Carbonization and activation were conducted at the Metallurgy Foundry Laboratory, Ahmadu Bello University, because a temperature-controlled furnace was available to maintain the required thermal conditions. Furnace temperature was monitored throughout the process to ensure consistency and reproducibility.



Figure 1: Sourced palm kernel shell from Sabo Tasha, Kaduna



Figure 2: Palm kernel shell (Carbonized charcoal) Sourced at Metallurgy Foundry Laboratory A.B.U Zaria



Figure 3: The Grinded Palm kernel shell charcoal (Activated Charcoal). Sourced at metallurgy foundry laboratory A.B.U. Zaria.

Although FTIR characterization was conducted to evaluate the surface chemistry of the adsorbent, advanced characterization techniques such as Brunauer-Emmett-Teller (BET) surface area analysis, scanning electron microscopy (SEM), and iodine number determination were not performed due to equipment and resource limitations. Nevertheless, the FTIR results confirmed the presence of hydroxyl, carbonyl, aromatic, and amine functional groups that are commonly associated with adsorption processes. Future studies should incorporate BET, SEM, and iodine number analyses to

provide a more comprehensive assessment of the porosity, surface morphology, and adsorption potential of the palm kernel shell activated carbon.

2.2.2 Sharp Sand Preparation

Sharp sand was sourced locally and washed thoroughly with distilled water to remove silt, clay, and organic impurities. The cleaned sand was dried and sieved to obtain uniform particle sizes. Fine sand (approximately 1.18 mm grain size) and coarse sand (approximately 2.00 mm grain size) were prepared to ensure effective filtration and proper drainage within the system.

2.3 Design and Construction of the Filtration Column

A laboratory-scale vertical filtration column was designed and fabricated using a cylindrical plastic container. The column was constructed with a layered dual-media configuration consisting of:

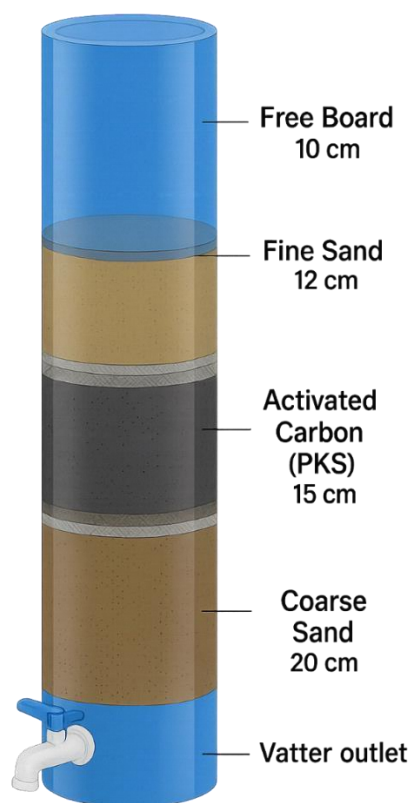
- Coarse sand layer (20 cm) – support and drainage
- Activated carbon layer (15 cm) – adsorption of dissolved contaminants
- Fine sand layer (12 cm) – removal of suspended solids
- Freeboard (10 cm) – influent distribution and aeration

The layers were arranged sequentially from bottom to top, and fine mesh screens were placed between layers to prevent intermixing of media. The total effective volume of the column was approximately 0.000213 m³. The volume was calculated using a column radius of 0.038 m and media depths of 0.020 m, 0.015 m and 0.012 m for coarse sand, activated carbon and fine sand respectively.

2.4 Experimental Setup

The filtration system was operated in a gravity-driven mode, where wastewater was introduced at the top of the column and allowed to flow downward through the media layers. The design ensured adequate contact time between the wastewater and the filter media to facilitate both physical filtration and adsorption processes. The setup is shown in Figure 4. The filtration column had an effective media volume of approximately 0.000213 m³ (0.213 L). Approximately 0.5 L of wastewater was introduced into the filtration column during each experimental run under gravity-flow conditions. The study was designed primarily as a proof-of-concept investigation focusing on contaminant removal performance rather than hydraulic optimization. Consequently, operational parameters such as flow rate, hydraulic loading rate, hydraulic retention time (HRT), and empty-bed contact time (EBCT) were not monitored during the experiment. This limitation restricts detailed evaluation of process hydraulics and scale-up

potential. Future studies should quantify these parameters and assess their influence on treatment



efficiency.

Figure 4: Schematic diagram of the dual-media filtration column

2.5 Analytical Methods

The performance of the filtration system was evaluated by analyzing physicochemical parameters before and after treatment. The parameters measured include:

- ❖ **pH** – measured using a calibrated pH meter
- ❖ **Turbidity** – determined using a nephelometric turbidity meter
- ❖ **Total Dissolved Solids (TDS)** – measured using a TDS/conductivity meter
- ❖ **Biochemical Oxygen Demand (BOD)** – determined using the standard 5-day incubation method
- ❖ **Chemical Oxygen Demand (COD)** – determined using reflux titration method
- ❖ **Nitrate concentration** – determined using colorimetric methods

All analyses were conducted in accordance with standard laboratory procedures to ensure accuracy and consistency of results. The present study was conducted as a preliminary laboratory-scale proof-of-concept investigation to evaluate the feasibility of using palm kernel shell activated carbon and sharp sand as a dual-media filtration system for tertiary wastewater treatment. The reported influent and effluent values were obtained from a single experimental run and therefore do not include measures of variability such as standard deviation or confidence intervals. Consequently, the reported treatment efficiencies should be interpreted as indicative of system performance under the tested conditions rather than as statistically representative values. The absence of replicate runs constitutes a limitation of the present study. Future investigations should incorporate replicated experiments and statistical analyses to quantify variability, establish confidence levels, and improve the reliability and reproducibility of the findings.

3. RESULTS AND DISCUSSION

3.1 Performance of the Dual-Media Filtration System

The performance of the dual-media filtration system was evaluated by comparing key physicochemical parameters of wastewater before and after treatment. The results are presented in Table 1.

Table 1: Performance of Dual-Media Filtration System

Parameter	Raw Water	Treated Water	Removal Efficiency (%)
Turbidity (NTU)	13.0	2.6	80
Nitrate (mg/L)	35.0	15.6	55
BOD (mg/L)	150	90	40
COD (mg/L)	3000	800	73
TDS (mg/L)	216	160.5	25
PH	6.89	6.79	-

Table 2: Comparison of Treated Effluent Quality with Typical Discharge Guidelines

Parameter	Treated Effluent	Guideline Value
pH	6.79	6-9
Turbidity (NTU)	2.6	<5
Nitrate (mg/L)	15.6	<50
TDS (mg/L)	160.5	<500
BOD (mg/L)	90	<30
COD (mg/L)	800	<90

Source: Adapted from WHO (2017) potable water guidelines and commonly adopted wastewater discharge criteria used for comparison purposes.

A substantial reduction in turbidity from 13.0 NTU to 2.6 NTU (80%) was observed after treatment. This high removal efficiency can be attributed primarily to the fine sand layer, which acts as a physical barrier, trapping suspended and colloidal particles via straining and sedimentation. Additionally, the layered arrangement of the filter enhances particle capture by promoting gradual filtration, reducing the likelihood of particle breakthrough. The achieved turbidity level falls within acceptable limits for improved water clarity, indicating effective removal of suspended solids. Similar turbidity reductions have been reported in sand-activated carbon filtration systems used for polishing municipal and institutional wastewater (Fayad & Radhi, 2024; Mara, 2013).

The system achieved a 73% reduction in COD and a 40% reduction in BOD. COD represents the total quantity of oxidizable substances present in wastewater, whereas BOD represents the biodegradable fraction of organic matter. The higher COD removal observed in this study suggests substantial removal of dissolved organic pollutants by the activated carbon layer. The BOD/COD ratio increased from approximately 0.05 before treatment to 0.11 after treatment, indicating a modest improvement in wastewater biodegradability. However, the observed reductions should not be interpreted solely as evidence of selective adsorption of biodegradable and non-biodegradable compounds, since changes in biodegradability may also have contributed to the results. Similar reductions in COD and BOD have been reported for agricultural waste-derived activated carbons used in wastewater treatment applications (Devi et al., 2023).

Nitrate concentration decreased from 35.0 mg/L to 15.6 mg/L, representing a removal efficiency of 55%. Although activated carbon is generally more effective for organic pollutant removal

than nutrient removal, several studies have demonstrated moderate nitrate adsorption by biomass-derived activated carbons. The observed nitrate reduction in the present study may be attributed to adsorption mechanisms reported in the literature; however, no surface charge or zeta potential measurements were conducted to confirm the specific adsorption mechanism.

The filtration system achieved a 25% reduction in TDS, decreasing from 216 mg/L to 160.5 mg/L.

The relatively lower removal efficiency observed for TDS compared with turbidity and COD is expected because dissolved salts and ionic species are generally more difficult to remove through adsorption and filtration processes alone. Activated carbon preferentially adsorbs organic compounds rather than dissolved inorganic constituents (Hendricks, 2016). The moderate decrease in TDS suggests partial removal of dissolved contaminants through adsorption and physical retention mechanisms within the filter media.

The pH changed slightly from 6.89 to 6.79 after treatment, indicating that the filtration process did not significantly alter the acid-base characteristics of the wastewater. Maintaining near-neutral pH conditions is advantageous because extreme pH changes can affect adsorption efficiency and subsequent biological treatment processes. Previous studies have also reported minimal pH variation following treatment with biomass-derived activated carbons, particularly when no strong chemical activation agents remain on the adsorbent surface (Abioye & Ani, 2015; Yahya et al., 2015). The pH stability observed in this study therefore supports the suitability of the PKS-AC filtration system for wastewater polishing applications.

Furthermore, as shown in Table 2, comparison with commonly adopted wastewater discharge guidelines indicates that the treated effluent satisfied recommended limits for pH, turbidity, nitrate, and TDS. However, BOD and COD values remained above typical discharge standards, suggesting that additional polishing or biological treatment may be necessary before final discharge or reuse.

3.2 Compliance with Effluent Quality Guidelines

The treated wastewater exhibited substantial improvements in quality compared with the raw influent. Turbidity decreased from 13.0 NTU to 2.6 NTU, nitrate concentration decreased from 35.0 mg/L to 15.6 mg/L, and TDS decreased from 216 mg/L to 160.5 mg/L. These treated values comply with commonly adopted guideline limits for treated wastewater and water reuse applications.

Despite these improvements, BOD and COD concentrations remained relatively high at 90 mg/L and 800 mg/L respectively. Although the filtration system achieved 40% BOD removal and 73% COD removal, the residual concentrations indicate that significant quantities of biodegradable and non-biodegradable organic matter remained in the treated effluent. Consequently, the developed dual-media filtration system should be viewed primarily as a polishing treatment technology rather than a standalone wastewater treatment solution. Additional biological treatment or advanced polishing processes may be required before direct discharge into receiving water bodies.

The guideline values are presented solely to provide context for treatment performance and do not constitute regulatory compliance standards for wastewater discharge.

3.3 Mechanisms of Pollutant Removal

The improved performance of the dual-media system can be attributed to the synergistic interaction between filtration and adsorption mechanisms, as illustrated in the filter configuration.

- ❖ Physical Filtration:
Sand layers remove suspended particles through straining and sedimentation
- ❖ Adsorption:
PKS activated carbon removes dissolved contaminants via surface interactions
- ❖ Protective Layering:
Sand reduces clogging and enhances contact efficiency in the carbon layer

This combined mechanism ensures efficient removal of both particulate and dissolved pollutants, making the system more effective than single-media filtration approaches.

3.4 Engineering Implications

The results demonstrate that the developed dual-media filtration system:

- ❖ Achieves significant contaminant removal efficiency
- ❖ Utilizes low-cost and locally available materials
- ❖ Operates without the need for complex energy inputs
- ❖ Offers potential for scalability in institutional settings

From an economic perspective, the proposed system utilizes palm kernel shell, an agricultural by-product that is widely available in Nigeria and often discarded as waste. The use of locally sourced materials significantly reduces media procurement costs when compared with commercial activated carbon. Furthermore, the filtration system operates entirely under gravity flow conditions and therefore requires no external energy input during operation. Although a detailed techno-economic analysis was beyond the scope of this study, the material and operational requirements suggest that the system offers a low-cost alternative for tertiary wastewater treatment in institutional and resource-constrained settings.

4. Conclusion

This study successfully designed and evaluated a laboratory-scale dual-media filtration system utilizing palm kernel shell-derived activated carbon (PKS-AC) and sharp sand for tertiary wastewater treatment. The system demonstrated significant improvement in effluent quality, confirming its effectiveness as a low-cost and sustainable treatment technology.

The filtration process achieved substantial reductions in key physicochemical parameters, including turbidity (80%), nitrate (55%), chemical oxygen demand (73%), and biochemical oxygen demand (40%). A moderate reduction in total dissolved solids was also observed, while pH remained relatively stable, indicating that the treatment process did not adversely affect the chemical balance of the water. These results highlight the ability of the system to remove both suspended and dissolved contaminants through combined filtration and adsorption mechanisms.

The performance of the system is attributed to the synergistic interaction between the sand layers, which provide physical filtration and particle retention, and the activated carbon layer, which facilitates adsorption of organic and inorganic pollutants. The use of palm kernel shell as a precursor for activated carbon further enhances the sustainability of the system by utilizing an abundant agricultural waste material.

Overall, the developed dual-media filtration system offers a practical, efficient, and environmentally friendly solution for improving wastewater quality, particularly in institutional and resource-constrained settings.

No significant media breakthrough was observed during the experimental period. However, the relatively short duration of operation did not permit detailed assessment of adsorbent exhaustion or long-term filtration performance. As adsorption sites become progressively occupied, gradual reduction in treatment efficiency may occur. Future studies should therefore investigate media breakthrough characteristics, regeneration potential, and adsorbent lifespan under continuous operating conditions. In addition, studies on the regeneration and reuse of palm kernel shell activated carbon are recommended to improve long-term cost-effectiveness and sustainability.

REFERENCES

- Abioye, A. M., & Ani, F. N. (2015). Recent development in the production of activated carbon electrodes from agricultural waste biomass for supercapacitors: A review. *Renewable and Sustainable Energy Reviews*, 52, 1282–1293.
- Ali, I. (2012). New generation adsorbents for water treatment. *Chemical Reviews*, 112(10), 5073–5091.
- Devi, R., Kumar, V., Kumar, S., Bulla, M., Jatrana, A., Rani, R., Mishra, A. K., & Singh, P. (2023). Recent advancement in biomass-derived activated carbon for waste water treatment, energy storage, and gas purification: a review. *Journal of Materials Science*, 58(30), 12119–12142.

- Etsuyankpa, B., Augustine, A., Musa, S., Mathew, J., Haruna, I., Adamu Makanta, S., & Mamman, A. (2024). An Overview of Wastewater Characteristics, Treatment and Disposal: A Review. *Journal of Applied Sciences and Environmental Management*, 28, 1553–1572. <https://doi.org/10.4314/jasem.v28i5.28>
- Fayad, M., & Radhi, A. (2024). *Influence of aeration and double media filter of carbon and sand on the efficiency of river water treatment*. 43, 467–474.
- Hendricks, D. (2016). *Fundamentals of water treatment unit processes: physical, chemical, and biological*. Crc Press.
- Kato, S., & Kansha, Y. (2024). Comprehensive review of industrial wastewater treatment techniques. *Environmental Science and Pollution Research*, 31(39), 51064–51097.
- Kayode, O. S., Adayi, L. E., & Sanni, I. M. (2023). *Assessment of Ahmadu Bello University , Zaria Waste Stabilization Pond Efficiency through Principal Component Analysis with R Programming*. 13(1), 20–27.
- Mara, D. (2013). *Domestic wastewater treatment in developing countries*. Routledge.
- Nwinyi, O. C., Uyi, O., Awosanya, E. J., Oyeyemi, I. T., Ugbenyen, A. M., Muhammad, A., Alabi, O. A., Ekwunife, O. I., Adetunji, C. O., & Omoruyi, I. M. (2020). Review of drinking water quality in Nigeria: towards attaining the sustainable development goal six. *Annals of Science and Technology*, 5(2), 58–77.
- Onu, M. A., Ayeleru, O. O., Oboirien, B., & Olubambi, P. A. (2023). Challenges of wastewater generation and management in sub-Saharan Africa: A Review. *Environmental Challenges*, 11, 100686. <https://doi.org/https://doi.org/10.1016/j.envc.2023.100686>
- WHO. (2017). *Potable reuse: Guidance for producing safe drinking-water*. World Health Organization.
- Yahya, M. A., Al-Qodah, Z., & Ngah, C. W. Z. (2015). Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: A review. *Renewable and Sustainable Energy Reviews*, 46, 218–235.