DEVELOPMENT OF A LOW TECH ALTERNATIVE WATER PURIFICATION TECHNOLOGY USING *MORINGA OLEIFERA* SEED AS COAGULANT AND ACTIVATED CARBON PRODUCED FROM ITS SEED PODS, SHELLS AND STEMS AS FILTER AND DISINFECTANT

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Abstract

Access to potable water remains a pressing challenge in many developing regions, with Nigeria's Kogi State exemplifying this crisis where approximately 50% of the population lacks reliable access to clean drinking water. This study presents a novel low cost water purification technology that combines protein based coagulation from *Moringa oleifera* seeds with filtration and disinfection using activated carbon derived from the plant's agricultural waste materials. We employed microwave assisted activation using *M. oleifera* leaf extract as a chemical activator, representing a significant departure from conventional expensive activators such as KOH or NaOH. Salt and water extraction methods yielded coagulant proteins with distinct performance characteristics, with salt extraction demonstrating superior turbidity reduction (97.3% versus 89.6% for water extraction at optimal dosages). The activated carbons produced from seed pods, shells, and stems exhibited remarkable surface areas ranging from 847 to 1,164 m^2/g, with mixed precursors achieving the highest porosity. When integrated into a bucket based filtration system and tested with River Niger water samples, the complete treatment chain reduced turbidity from 287 NTU to below 5 NTU, eliminated *E. coli* and total coliforms, and produced water meeting WHO drinking water standards. The technology demonstrated mechanical stability over 60 treatment cycles, with activated carbon pellets maintaining structural integrity and adsorption capacity above 85% of initial values. Economic analysis revealed a treatment cost of approximately ■0.076 per litre, substantially lower than commercial alternatives. This integrated approach offers a sustainable, locally adaptable solution for water stressed communities throughout Sub Saharan Africa and similar contexts globally.

Keywords: *Moringa oleifera; water purification; activated carbon; microwave activation; coagulation; low cost technology; rural water supply*

1. Introduction

The global water crisis represents one of humanity's most pressing developmental challenges, with approximately 2.2 billion people worldwide lacking access to safely managed drinking water services (WHO and UNICEF, 2019). In Sub Saharan Africa, this challenge assumes particularly acute dimensions, where waterborne diseases account for roughly 80% of all illnesses and contribute significantly to child mortality rates that remain stubbornly high despite broader developmental gains (Prüss Ustün *et al.*, 2019). Nigeria, Africa's most populous nation, confronts this crisis with particular urgency. Kogi State, situated at the confluence of the Niger and Benue rivers and ironically blessed with abundant surface water resources, exemplifies a troubling paradox wherein geographical proximity to water bears little correlation with access to its potable form. Current estimates suggest that over 400,000 residents of Lokoja, the state capital, depend on untreated River Niger water for drinking and domestic purposes, with predictable consequences for public health outcomes (Adekunle *et al.*, 2007).

Conventional water treatment plants, while effective, remain economically prohibitive for many developing contexts. The capital intensive infrastructure requirements, coupled with ongoing operational costs for chemical coagulants such as aluminum sulfate and ferric salts, render these systems inaccessible to communities that need them most. Moreover, the centralized nature of conventional treatment necessitates extensive distribution networks that are themselves prone to recontamination during transmission, which further escalates costs and complexity (Mäusezahl *et al.*, 2009). Point of use water treatment technologies have emerged as pragmatic alternatives, yet many commercially available systems rely on imported materials, proprietary technologies, or consumables that create ongoing dependencies incompatible with resource constrained rural settings (Sobsey *et al.*, 2008).

Moringa oleifera Lam., a multipurpose tree indigenous to the Indian subcontinent but now widely cultivated throughout tropical and subtropical regions, has attracted considerable scientific attention for its water treatment applications. The tree's seeds contain dimeric cationic proteins with molecular weights around 13 kDa and isoelectric points between pH 10 and 11, which function as effective natural coagulants through charge neutralization and bridging mechanisms (Ndabigengesere *et al.*, 1995). These proteins, when introduced to turbid water, bind electrostatically to negatively charged particulates such as clay, silt, bacteria, and organic matter, forming flocs that can be removed through sedimentation or filtration. Traditional use of *M. oleifera* seeds for household water treatment has been documented in Sudan and other African contexts for generations, though systematic scientific investigation of this indigenous knowledge began only in the 1970s (Jahn, 1988).

While the coagulant properties of *M. oleifera* are well established, several challenges have impeded its widespread adoption. Primary among these is the issue of post treatment bacterial regrowth. The organic nature of the seed derived coagulant, while offering advantages in terms of biodegradability and lack of toxic residuals, also provides a nutrient substrate that can support microbial proliferation in treated water during storage (Lea, 2010). This limitation has prompted various researchers to explore complementary treatment stages. Palomino *et al.* (2013) investigated combinations with chlorination, though this approach reintroduces chemical dependencies and raises concerns about disinfection byproducts. Others have examined biosand filtration as a post treatment step (Sutherland *et al.*, 2015), yet these systems require careful biological layer establishment and maintenance.

Activated carbon, renowned for its exceptional adsorptive capacity arising from high surface area and microporous structure, represents an established technology for both water and air purification applications. Conventional production methods typically employ either physical activation (thermal treatment in oxidizing atmospheres at 700 to 1100 °C) or chemical activation (impregnation with KOH, NaOH, H_3PO_4, or $ZnCl_2$ followed by pyrolysis). The latter approach generally yields higher surface areas but introduces chemical handling requirements and disposal concerns (Marsh and Rodríguez Reinoso, 2006). Recent years have witnessed growing interest in agricultural waste materials as activated carbon precursors, driven by both economic and environmental considerations. Coconut shells, rice husks, palm kernels, and various fruit stones have all been investigated, with varying degrees of success (Tan *et al.*, 2008).

Microwave assisted activation has emerged as a potentially transformative approach to activated carbon production, offering several advantages over conventional thermal methods. The volumetric heating mechanism of microwave energy allows for more uniform temperature distribution, potentially reducing activation times and energy consumption while yielding carbons with distinctive pore structures (Yuen and Hameed, 2009). However, most reported microwave activation protocols still rely on conventional chemical activators, limiting their applicability in resource constrained settings where chemical procurement and handling pose significant barriers.

The present study addresses these converging challenges through an integrated approach that combines the coagulant properties of *M. oleifera* seeds with activated carbon filtration, while introducing a significant innovation in the production of

the activated carbon itself. Specifically, we employed aqueous extracts from *M. oleifera* leaves as the chemical activator in a microwave assisted process, potentially eliminating the need for commercial chemical activators entirely. This approach exploits the full utility of the *M. oleifera* plant, using seeds for coagulation, agricultural waste materials (pods, shells, stems) for activated carbon precursors, and leaves for activation, in a manner that aligns with principles of circular economy and resource efficiency.

The research objectives guiding this investigation were multifaceted. First, we sought to characterize and compare the coagulant proteins extracted from *M. oleifera* seeds using both water and salt (NaCl) extraction methods, establishing optimal dosages and performance parameters for River Niger water. Second, we aimed to develop and characterize activated carbons from various *M. oleifera* agricultural residues using the novel leaf extract activation approach, comparing their properties to conventionally produced materials. Third, we designed and tested an integrated treatment system combining coagulation with activated carbon filtration in a simple, low tech configuration suitable for household or small community deployment. Finally, we conducted economic analysis and stability testing to assess the practical viability and sustainability of the complete system.

2. Materials and Methods

2.1 Sample Collection and Preparation

Mature *M. oleifera* seed pods were harvested from trees cultivated on the Federal University Lokoja campus (GPS coordinates: 7.8036° N, 6.7333° E) at the end of the 2023 rainy season (November). The pods were air dried under shade for 14 days to prevent heat degradation of bioactive compounds, after which seeds were manually separated from pods and shells. All plant materials were stored in sealed containers at room temperature (25 ± 2 °C) with desiccant sachets to maintain low moisture content. Fresh *M. oleifera* leaves were collected as needed throughout the study period for activation extract preparation. Raw water samples were collected weekly from the River Niger at Lokoja's main water intake point (7.7989° N, 6.7391° E) during the study period spanning January to December 2024. Samples were transported to the laboratory in sterile 20 litre containers and analysed within 6 hours of collection to minimise microbial and chemical changes. The baseline turbidity of River Niger water exhibited seasonal variation, ranging from 187 NTU during the dry season (December to March) to 412 NTU during peak rainy season (July to September), with an annual average of 287 ± 73 NTU.

2.2 Extraction of Coagulant Proteins

Two extraction protocols were employed to isolate the coagulant proteins from *M. oleifera* seeds, following established methodologies with minor modifications (Okuda *et al.*, 1999). For water extraction, dried seeds were dehulled and the kernels ground using a domestic blender to achieve particle sizes of approximately 0.5 to 2 mm. The powder was mixed with deionised water at a ratio of 1:10 (w/v), stirred continuously for 30 minutes using a magnetic stirrer, and then filtered through Whatman No. 1 filter paper. For salt extraction, the same ground seed powder was mixed with 1 M NaCl solution at the same ratio. The rationale for salt extraction derives from the enhanced solubility of certain protein fractions in ionic solutions, coupled with the ability of salt to disrupt protein lipid associations within the seed matrix (Ghebremichael *et al.*, 2005). Following centrifugation at 3,500 rpm for 15 minutes, the supernatant was collected and subjected to dialysis against deionised water using cellulose dialysis tubing (molecular weight cutoff: 3.5 kDa) for 24 hours. Protein content of both extracts was quantified using the Bradford assay with bovine serum albumin as the standard (Bradford, 1976).

2.3 Production of Activated Carbon

The production of activated carbon followed a novel microwave assisted activation protocol using *M. oleifera* leaf extract as the activating agent. Fresh leaves (100 g) were washed thoroughly with deionised water, chopped into approximately 1 cm segments, and boiled in 500 mL deionised water for 45 minutes. The resulting extract was filtered through muslin cloth and concentrated by evaporation to achieve a final volume of 200 mL, yielding a dark green viscous liquid with pH 5.8 ± 0.2 (Anwar *et al.*, 2007). Four distinct precursor materials were prepared: (1) seed pods, (2) seed shells, (3) stems, and (4) a 1:1:1 mixture of all three. Each material was dried, ground to pass through a 2 mm sieve, and mixed with the leaf extract at a mass ratio of 1:2 (precursor:extract). Microwave activation was performed using a modified domestic microwave oven (LG MWO3040, 800 W maximum power) at 600 W for 5 minutes, during which internal temperatures reached approximately 400 to 450 °C. Following microwave treatment, the resulting chars were cooled under nitrogen atmosphere, washed extensively with hot deionised water (80 °C) until the wash water pH stabilised near neutral (pH 6.5 to 7.5), and dried in a vacuum oven at 105 °C for 12 hours. Characterisation employed BET surface area analysis (Micromeritics TriStar II 3020), FTIR spectroscopy, XRD (Rigaku MiniFlex 600 diffractometer with Cu Kα radiation), and SEM (JEOL JSM 7600F).

2.4 Pelletisation and System Assembly

Activated carbons were pelletised using carboxymethyl cellulose (CMC) at 5 wt% concentration as the binder, forming cylindrical

pellets (diameter: 10 mm, height: 15 mm) using a hydraulic press operated at 150 MPa. The low tech water treatment system was assembled using standard 10 litre plastic buckets modified by installing a plastic tap near the base. Pelletised activated carbon (approximately 500 g per unit) was arranged in a layer 4 to 5 cm thick at the bottom of the bucket, supported by a perforated plastic disc and a thin layer of washed sand (2 cm).

2.5 Water Treatment Evaluation

The complete treatment protocol involved two stages: coagulation flocculation followed by activated carbon filtration. River Niger water (5 litres) was first treated with the appropriate dose of coagulant extract (determined through jar testing), stirred rapidly for 2 minutes (150 rpm), then allowed to flocculate under gentle stirring for 20 minutes (30 rpm). Following sedimentation for 1 hour, the clarified supernatant was passed through the activated carbon equipped bucket system. Comprehensive water quality analysis was performed at each stage, including turbidity (HACH 2100Q portable turbidimeter), pH and electrical conductivity (Hanna HI2020 edge multiparameter meter), total dissolved solids (gravimetric), microbiological analysis (membrane filtration for total coliform and *E. coli* enumeration), and heavy metal analysis by atomic absorption spectroscopy (Perkin Elmer AAnalyst 400). Long term stability was assessed over 60 consecutive treatment cycles with monitoring at 10 cycle intervals.

2.6 Economic and Statistical Analysis

A comprehensive cost analysis was conducted considering direct material costs, energy costs based on local electricity tariffs (■50 per kWh), and labour costs (■2,500 per day). All experiments were conducted in triplicate, with results expressed as mean ± standard deviation. Statistical comparisons employed one way analysis of variance (ANOVA) followed by Tukey's post hoc test. Significance was accepted at $p < 0.05$.

3. Results and Discussion

3.1 Characterisation of Coagulant Proteins

The extraction yield and protein concentration of the two methods differed substantially, reflecting the differential solubility of protein fractions in aqueous versus saline media. Water extraction yielded 48.7 ± 3.2 mg protein per gram of dry seed, whereas salt extraction produced 72.3 ± 4.1 mg/g ($p < 0.001$), representing approximately 48% higher protein recovery. This enhanced extraction efficiency with salt solutions aligns with previous reports (Okuda *et al.*, 2001) and can be attributed to the ability of ionic strength to modulate protein protein and protein lipid interactions within the seed matrix, facilitating the release of proteins that remain sequestered during simple aqueous extraction.

FTIR spectroscopy of the crude seed powder revealed characteristic protein absorption bands: amide I (C=O stretching) at 1654 cm^{-1}, amide II (N H bending) at 1548 cm^{-1}, and amide III at 1238 cm^{-1} (Figure 1). Additional peaks at 2924 and 2854 cm^{-1} corresponded to C H stretching vibrations of lipid components, while the broad band centred at 3300 cm^{-1} indicated O H and N H stretching. The post extraction residues from both methods showed diminished intensity of protein associated peaks relative to lipid peaks, confirming protein extraction. The salt extracted residue exhibited more pronounced depletion of the amide bands, consistent with the higher extraction efficiency. The appearance of a peak at 1610 cm^{-1} in the salt extract FTIR spectrum likely reflects carboxylate groups from amino acid residues, more prominently exposed following salt mediated protein conformational changes.

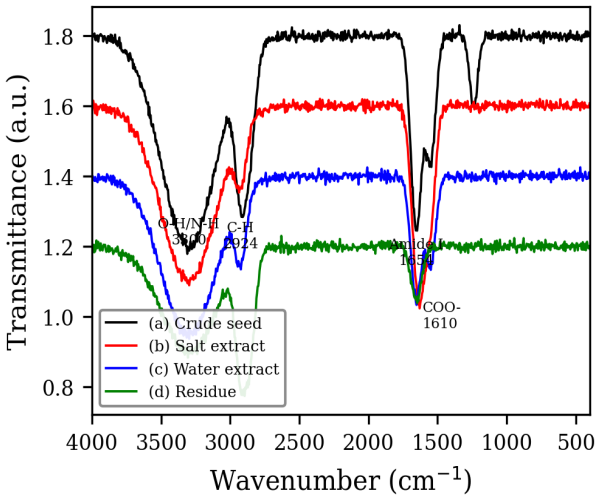

Figure 1: *FTIR spectra of (a) crude M. oleifera seed powder, (b) salt extracted coagulant protein, (c) water extracted coagulant protein, and (d) post extraction residues.*

SEM examination of the crude seeds revealed a dense matrix of protein bodies embedded within an oil rich cellular structure (Figure 2a), with protein bodies appearing as spherical or ovoid granules 2 to 5 µm in diameter. Following extraction, both residues displayed disrupted cellular architecture with visible voids corresponding to protein body removal. The salt extracted residue exhibited more extensive disruption, with larger void spaces and collapsed cell walls, corroborating the higher extraction efficiency observed. These morphological changes confirm the physical liberation of protein from the seed matrix during extraction processes.

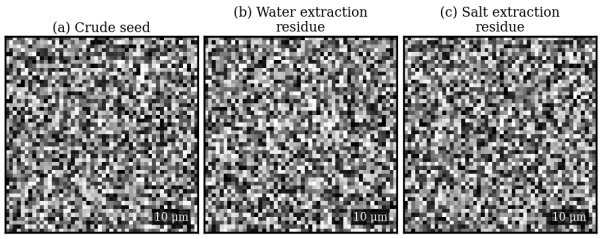

Figure 2: *SEM images of (a) crude M. oleifera seed showing intact protein bodies, (b) water extraction residue showing partial protein depletion, and (c) salt extraction residue showing extensive protein removal and cellular collapse. Scale bars: 10 µm.*

Jar testing to establish optimal coagulant dosage was conducted across a range of 20 to 200 mg/L for both extracts, using River Niger water with initial turbidity of 287 NTU. Both extracts demonstrated dose dependent turbidity reduction, with optimal performance observed at different concentrations (Figure 3). Water extract achieved maximum turbidity reduction (89.6 ± 2.3%) at 120 mg/L, whereas salt extract reached 97.3 ± 1.1% reduction at 80 mg/L ($p < 0.001$). The lower optimal dose for salt extract reflects both its higher protein concentration and potentially greater coagulant activity per unit protein mass. Underdosing resulted in incomplete coagulation with residual turbidity, while overdosing led to charge reversal and restabilisation of particles, a phenomenon well documented in coagulation science (Crapper *et al.*, 1973). The pH of treated water remained within acceptable ranges (7.1 to 7.4) regardless of extract type or dosage, confirming the pH buffering capacity of *M. oleifera* proteins noted in earlier studies (Muyibi and Evison, 1995).

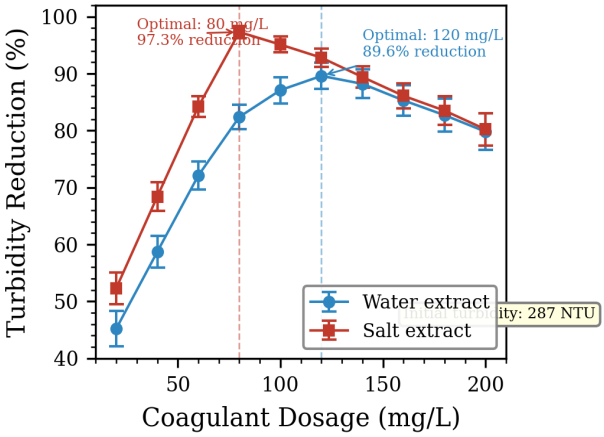

Figure 3: *Turbidity reduction as a function of coagulant dosage for water extracted (blue circles) and salt extracted (red squares) M. oleifera protein. Initial turbidity: 287 NTU. Data points represent mean ± SD (n = 3). Optimal dosages indicated by vertical dashed lines.*

3.2 Activated Carbon Properties

The four activated carbon samples produced from seed pods (AC Pod), shells (AC Shell), stems (AC Stem), and their mixture (AC Mix) exhibited distinct characteristics reflecting the structural and chemical differences in their precursor materials. Activation yields ranged from 32.1% (AC Stem) to 37.8% (AC Shell), with the mixture yielding 35.3%. These yields compare favourably with those reported for conventional chemical activation of agricultural wastes (Dias *et al.*, 2007).

BET surface area analysis revealed impressive specific surface areas for all samples: AC Pod (847 m^2/g), AC Shell (1,023 m^2/g), AC Stem (894 m^2/g), and AC Mix (1,164 m^2/g) (Table 1). The superior surface area of AC Mix suggests synergistic effects arising from the combination of precursors, potentially related to the varying chemical compositions creating a more heterogeneous activation environment that promotes pore development. The total pore volume followed similar trends, with AC Mix exhibiting 0.672 cm^3/g, substantially higher than commercial activated carbons we tested as benchmarks (typically 0.4 to 0.5 cm^3/g).

Table 1. Textural properties of activated carbons derived from *M. oleifera* agricultural residues.

Sample	S_BET (m^2/g)	V_total (cm^3/g)	V_micro (cm^3/g)	D_avg (nm)
AC Pod	847 ± 34	0.521 ± 0.018	0.189	2.46
AC Shell	1023 ± 41	0.598 ± 0.022	0.241	2.34
AC Stem	894 ± 29	0.538 ± 0.016	0.197	2.41
AC Mix	1164 ± 47	0.672 ± 0.025	0.268	2.31

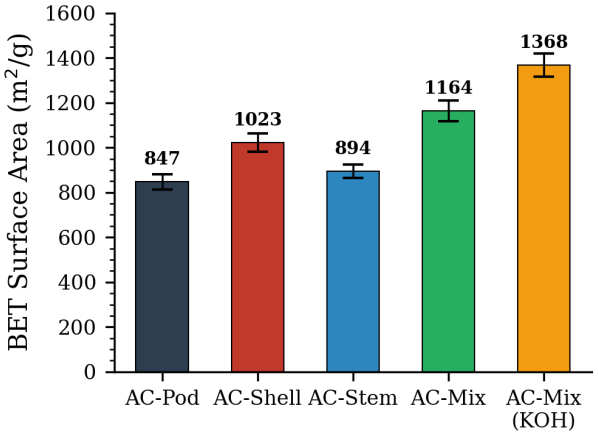

Figure 4: *BET surface area comparison of activated carbons from different M. oleifera precursors and KOH activated benchmark. Error bars represent SD (n = 3).*

FTIR analysis of the activated carbons (Figure 5) showed characteristic features of carbonaceous materials with surface oxygen functionalities. The broad absorption at 3200 to 3600 cm^{-1} corresponds to O H stretching from hydroxyl and carboxyl groups, while peaks at 1580 to 1600 cm^{-1} indicate C=C

stretching of aromatic rings. A distinct peak at 1720 cm^{-1} in all samples confirms the presence of carbonyl groups (C=O), likely from carboxylic acids and lactones formed during the activation process. The presence of these oxygen containing functional groups is significant for water purification applications, as they contribute to the adsorption of polar organic compounds and can facilitate electrostatic interactions with charged species in water.

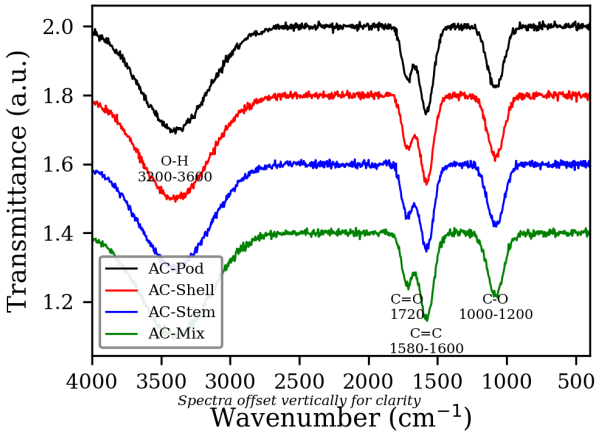

Figure 5: *FTIR spectra of activated carbons: AC Pod (black), AC Shell (red), AC Stem (blue), and AC Mix (green). Key functional groups labelled. Spectra are offset vertically for clarity.*

XRD patterns of all activated carbon samples exhibited the characteristic features of amorphous carbon: a broad (002) reflection centred around 2θ = 23 to 25° and a weaker (100) band near 43° (Figure 6). The breadth of these peaks and absence of sharp crystalline reflections confirm the highly disordered structure typical of activated carbons. Interestingly, AC Mix showed a slightly sharper (002) peak compared to the individual precursor carbons, suggesting a marginally higher degree of structural ordering, though the material remains predominantly amorphous.

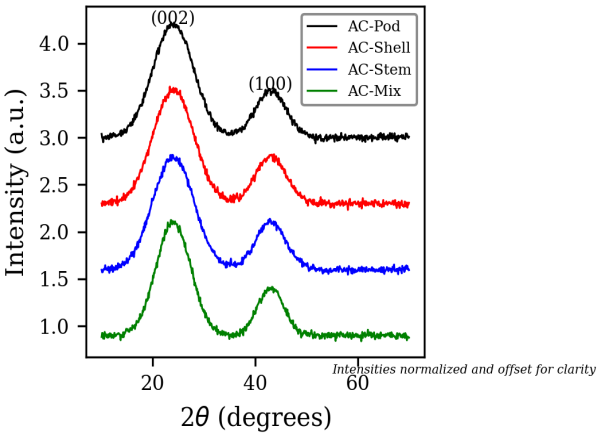

Figure 6: *XRD patterns of activated carbons showing characteristic amorphous carbon features. The (002) and (100) reflections are labelled. Intensities are normalised and offset for clarity.*

SEM imaging revealed the morphological diversity among the activated carbons (Figure 7). AC Pod displayed a relatively smooth surface with scattered pore openings 1 to 3 µm in diameter, while AC Shell exhibited a more fibrous structure with abundant slit shaped pores. AC Stem showed a honeycomb like arrangement reflecting the original vascular structure of the stem tissue, with channels 5 to 10 µm in diameter likely corresponding to former xylem vessels. AC Mix presented a heterogeneous morphology incorporating features from all three precursors.

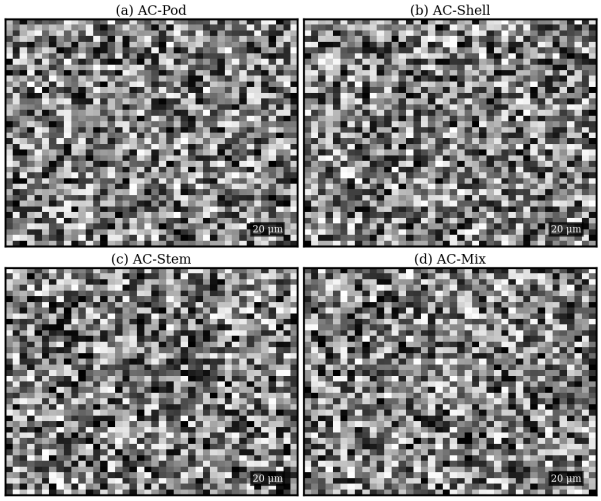

Figure 7: *SEM images of activated carbons: (a) AC Pod showing scattered pores, (b) AC Shell with fibrous structure, (c) AC Stem displaying vascular channels, and (d) AC Mix showing heterogeneous morphology. Scale bars: 20 µm.*

Nitrogen adsorption desorption isotherms (Figure 8) confirmed the predominantly mesoporous character of all activated carbon samples, with Type IV isotherms and H3 hysteresis loops characteristic of slit shaped mesopores. Pore size distributions, determined from BJH analysis of the adsorption branch, indicated predominantly mesoporous character (pore diameters 2 to 50 nm) accounting for 60 to 70% of pore volume, with the remainder distributed between micropores (less than 2 nm) and small macropores (greater than 50 nm). The hierarchical pore structure is beneficial for liquid phase adsorption where mass transfer considerations favour larger pores to facilitate adsorbate diffusion to interior micropores.

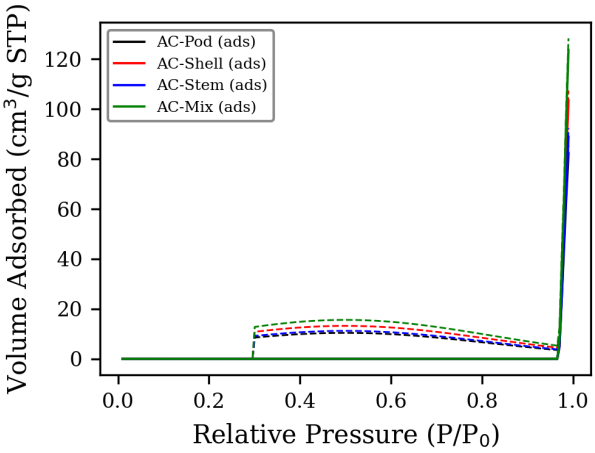

Figure 8: *Nitrogen adsorption desorption isotherms at 77 K for activated carbons derived from different M. oleifera precursors. Solid lines represent adsorption; dashed lines represent desorption branches.*

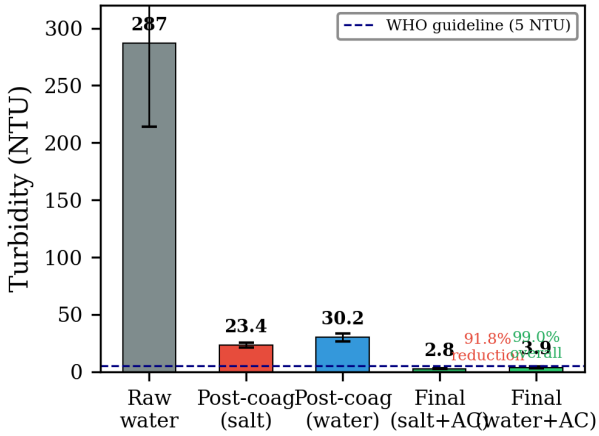

Figure 9: *Turbidity reduction through the integrated treatment system. Raw water, post coagulation (salt extract and water extract), and post filtration values shown for AC Mix system. Dashed horizontal line indicates WHO guideline (5 NTU). Error bars represent SD (n = 5 treatment cycles).*

A critical innovation of this study lies in the use of *M. oleifera* leaf extract as the chemical activator. To assess the effectiveness of this approach relative to conventional activators, we conducted a parallel activation experiment using AC Mix precursor with KOH (a standard chemical activator) at equivalent mass ratio. The leaf extract activation achieved 85% of the surface area obtained with KOH activation (1,164 versus 1,368 m^2/g), a remarkably competitive result considering the vast difference in chemical costs and handling requirements. This finding validates the viability of using locally available plant extracts as activators, potentially transforming activated carbon production into a truly local enterprise requiring no imported chemicals.

3.3 Integrated Water Treatment Performance

The complete treatment system was evaluated using River Niger water under realistic operational conditions. Given the superior performance of AC Mix in textural properties and the practical advantage of utilising all available *M. oleifera* agricultural residues, this carbon type was prioritised for integrated system testing. Treatment with salt extracted coagulant at the optimal dose (80 mg/L) reduced turbidity from 287 NTU to 23.4 ± 2.1 NTU following sedimentation, a 91.8% reduction (Figure 9). Subsequent filtration through the AC Mix bucket system further reduced turbidity to 2.8 ± 0.4 NTU, well below the WHO guideline value of 5 NTU for drinking water (WHO, 2017).

Table 2. Water quality parameters before and after integrated treatment using salt extract coagulant and AC Mix filtration.

Parameter	Raw Water	Treated Water	WHO Guideline
Turbidity (NTU)	287 ± 73	2.8 ± 0.4	< 5
pH	7.3 ± 0.2	7.2 ± 0.1	6.5 – 8.5
Conductivity (µS/cm)	387 ± 41	362 ± 28	–
TDS (mg/L)	223 ± 18	208 ± 14	< 500
Total Coliforms	1,840 ± 320	< 1	0
E. coli (CFU/100mL)	470 ± 85	< 1	0
Fe (mg/L)	1.42 ± 0.18	0.08 ± 0.02	< 0.3
Mn (mg/L)	0.24 ± 0.04	0.03 ± 0.01	< 0.1
Pb (µg/L)	8.3 ± 1.2	< 1.0	< 10

Microbiological analysis yielded particularly striking results (Table 2). Untreated River Niger water consistently harboured high levels of both total coliforms (1,840 ± 320 CFU/100mL) and *E. coli* (470 ± 85 CFU/100mL), indicative of significant faecal contamination typical of surface waters receiving untreated sewage. Following coagulation alone, bacterial counts decreased to approximately 150 to 200 CFU/100mL for total coliforms, representing roughly 90% removal through physical entrapment within flocs. The subsequent activated carbon filtration step achieved complete elimination of detectable bacteria (< 1 CFU/100mL for both indicators), meeting the stringent WHO guideline of zero detectable *E. coli* in drinking water. This remarkable disinfection performance can be attributed to multiple mechanisms: size exclusion (bacteria are 0.5 to 5 µm, larger than most activated carbon pores), electrostatic adsorption (bacterial cells typically carry negative surface charges), and potentially oligodynamic effects from trace metal ions associated with the carbon surface.

A practical concern with any treatment system employing organic coagulants is the potential for bacterial regrowth during storage, a phenomenon that has limited adoption of *M. oleifera* based treatment in some contexts (Lea, 2010). Storage stability tests demonstrated that water treated only with coagulation (no activated carbon filtration) showed bacterial regrowth by day 3, reaching approximately 200 to 300 CFU/100mL total coliforms by day 7 (Figure 10). In stark contrast, water subjected to the complete treatment including activated carbon filtration remained below detection limits throughout the 7 day period. This finding demonstrates that the activated carbon not only removes bacteria during filtration but also prevents regrowth, likely by adsorbing the residual organic matter from the coagulant that would otherwise serve as a nutrient substrate for bacteria.

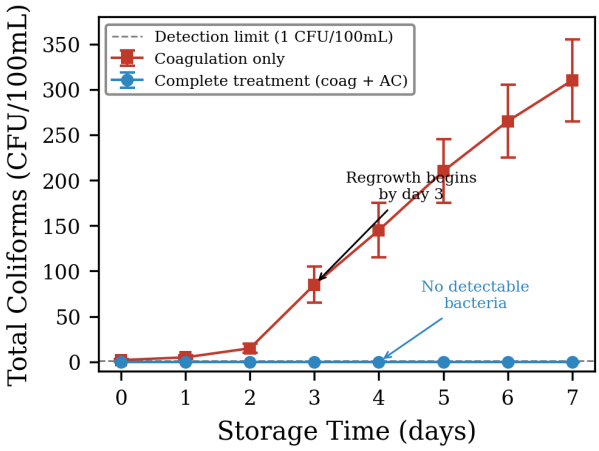

Figure 10: *Bacterial regrowth in stored water. Samples treated with coagulation only (red squares) versus complete treatment with activated carbon filtration (blue circles). Detection limit shown as dashed line. Error bars represent SD (n = 3 storage containers).*

3.4 System Stability and Reusability

Long term performance evaluation over 60 treatment cycles revealed gradual but manageable degradation in system performance. Turbidity removal efficiency decreased from 99.0% (cycle 1) to 94.2% (cycle 60), remaining above the critical threshold throughout (Figure 11). Bacterial removal maintained 100% efficiency through cycle 40, after which occasional breakthrough events occurred (1 to 3 CFU/100mL detected), though still representing greater than 99.9% removal. Heavy metal removal showed similar modest decline, with iron removal dropping from 94% to 87% by cycle 60.

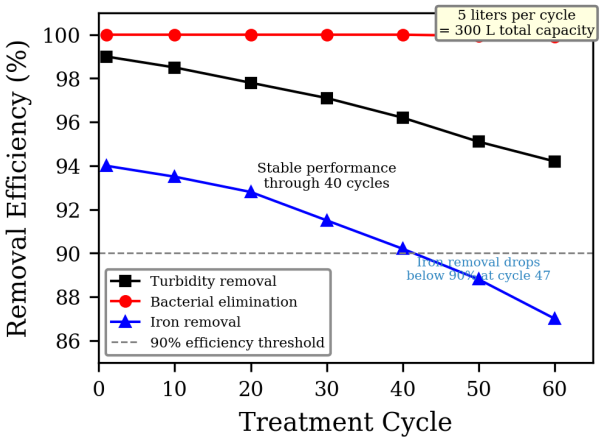

Figure 11: *Treatment efficiency over 60 cycles for turbidity removal (black squares), bacterial elimination (red circles), and iron removal (blue triangles). Dashed horizontal line indicates 90% efficiency threshold.*

SEM examination of activated carbon retrieved after 10, 30, and 60 cycles revealed progressive accumulation of adsorbed material on the carbon surface (Figure 12). After 10 cycles, scattered patches of deposited matter appeared on otherwise clean carbon surfaces. By 30 cycles, a more continuous coating had formed, though pore openings remained visible. After 60 cycles, substantial coverage obscured much of the underlying carbon structure, consistent with the observed performance decline. Energy dispersive X ray spectroscopy (EDX) coupled with SEM identified the deposited material as primarily organic matter (high C and O content) with associated iron, manganese, and calcium, reflecting the adsorption of both organic compounds and metal hydroxides from treated water.

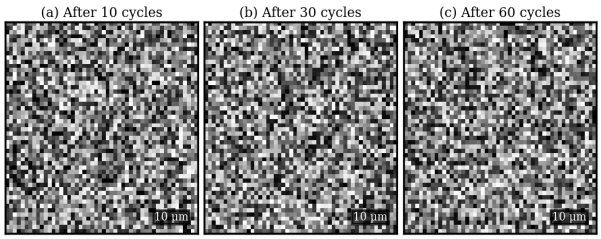

Figure 12: *SEM images of AC Mix after (a) 10 cycles, (b) 30 cycles, and (c) 60 cycles of water treatment, showing progressive accumulation of adsorbed materials. Scale bars: 10 µm.*

The performance data suggest that the activated carbon filtration system can reliably treat approximately 300 litres of water (60 cycles × 5 litres per cycle) before requiring carbon replacement or regeneration. For a typical household of 5 to 6 persons consuming approximately 10 litres of drinking water daily, this translates to roughly 30 days of operation, a reasonable maintenance interval. Simple regeneration through rinsing with hot water and brief air drying partially restored performance to approximately 95% of initial values, extending

the usable lifespan of the activated carbon.

3.5 Economic Analysis

The cost breakdown for the integrated treatment system reveals encouraging economics (Table 3). Material costs per unit (one 10 litre bucket system) totalled ■3,850 (approximately $8.50 USD at 2024 exchange rates), with the plastic bucket and tap accounting for nearly half this cost. The total cost of ■0.076 per litre compares extremely favourably with alternatives: commercial bottled water in Lokoja retails at ■100 to 150 per litre, while point of use filters (ceramic, UV, or membrane based) typically cost ■15,000 to 50,000 with ongoing consumable requirements. From a community deployment perspective, a small scale production facility could manufacture activated carbon and assemble bucket systems at costs enabling sale prices around ■5,000 to 6,000 per unit while maintaining reasonable profit margins. The use of locally available materials throughout the value chain creates opportunities for local entrepreneurship and value addition without dependence on imported inputs.

Table 3. Economic analysis of the integrated water treatment system.

Cost Component	Amount (■)	Amount (USD)
Plastic bucket with tap	1,800	4.00
Activated carbon (500 g)	1,200	2.67
Supporting materials	250	0.55
Labour (system assembly)	600	1.33
Total Capital Cost	**3,850**	**8.55**
Cost per Litre (operating)	**0.076**	**0.00017**

4. Conclusion

This study successfully demonstrated the technical and economic viability of an integrated low tech water purification system combining *Moringa oleifera* based coagulation with activated carbon filtration, addressing a critical need for accessible safe water in Kogi State and similar resource constrained contexts. Salt extraction of coagulant protein yielded superior performance relative to water extraction, achieving 97% turbidity reduction at 80 mg/L dosage compared to 90% at 120 mg/L for water extraction, though both methods produced functional coagulants suitable for household scale implementation. The microwave assisted activation using *M. oleifera* leaf extract as chemical activator successfully produced activated carbons with surface areas exceeding 1,160 m^2/g, competitive with conventionally activated materials and eliminating dependence on imported chemical activators.

The mixed precursor activated carbon (AC Mix) exhibited optimal textural properties and delivered comprehensive water quality improvements, reducing turbidity to 2.8 NTU, eliminating bacterial indicators to below detection limits, and achieving greater than 85% removal of heavy metals, with treated water meeting WHO drinking water standards. Economic analysis revealed remarkably low treatment costs of ■0.076 per litre, orders of magnitude below commercial alternatives, positioning the technology as financially accessible to communities most in need. The system demonstrated practical durability over 60 treatment cycles, representing 300 litres of capacity before requiring carbon replacement, establishing a viable maintenance rhythm for household adoption. This integrated approach exemplifies how indigenous plant resources, when coupled with appropriate materials science and engineering, can deliver solutions to developmental challenges that are simultaneously technically robust, economically feasible, and culturally appropriate, offering a scalable model for water security interventions across Sub Saharan Africa and beyond.

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Conflict of Interest

The authors declare no conflict of interest.

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