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Research Article

Integrating Moringa oleifera, Activated Charcoal, and Solar Water Disinfection (SODIS) for Improved Drinking Water Quality in Rural Communities of Kogi State, Nigeria

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Abstract: Access to safe drinking water remains a major challenge in many rural communities of Nigeria due to contamination by heavy metals and pathogenic microorganisms. This study evaluated the effectiveness of an integrated household water treatment system comprising Moringa oleifera seed powder, coconut shell activated carbon, and solar water disinfection (SODIS) for improving water quality in selected rural communities in Kogi State, Nigeria. Water samples collected from wells, boreholes, and river sources were treated with 1 g/L and 2 g/L M. oleifera seed suspensions, followed by activated carbon filtration and solar disinfection. Heavy metals (Cu, Pb, and Zn), physicochemical parameters (pH, electrical conductivity, salinity, and total dissolved solids), and microbiological indicators (total coliform and Escherichia coli) were determined using standard analytical methods. The integrated treatment significantly ($P < 0.05$) improved water quality by reducing heavy metal concentrations, salinity, electrical conductivity, total dissolved solids, and bacterial counts, while increasing pH to values within the recommended range. The 2 g/L treatment consistently achieved greater contaminant removal than the 1 g/L treatment across all sampling locations. Overall, the integrated M. oleifera–activated carbon–SODIS system represents a simple, cost-effective, and environmentally sustainable approach for improving drinking water quality in rural communities with limited access to conventional water treatment facilities.

Keywords: *Moringa oleifera; Activated carbon; Solar water disinfection (SODIS); Drinking water quality; Heavy metal removal*

1. Introduction

The importance of potable water cannot be overestimated in any human society (Khalid *et al.,* 2022). It is worth noting that 1 out of 3 people worldwide lack access to safe water (WHO,2019), posing a significant threat to human health through waterborne diseases and contributing to reduced national GDP due to inadequate water use (Okafor *et al.,* 2024). Water pollution is primarily caused by human activities that introduce physical, biological, and chemical contaminants into water bodies (Aziz *et al.,* 2023). According to the World Health Organization's recommendation, a minimum of 2–3 L of clean water should be consumed daily to support proper physiological functions. Unfortunately, about 159 million people worldwide drink unsafe water sourced from lakes and streams (Raphasha *et al.,* 2025). Due to the poor and inadequate public water distribution in rural areas particularly in developing nations, people may consider wells, streams, and rivers as alternative sources of potable water. This can lead to life-threatening and water-related disease that contributes to 19 % of the mortality among children in developing nations, including Nigeria (Yonas *et al.,* 2018). Therefore, purification of drinking water is essential for removing contaminants such as colloidal organic particles, microbes and other substances that are harmful to human health.

Despite the abundance of fresh water in developing nations, conventional water treatments involving flocculation–coagulation approaches are retarded by the cost of plant construction and synthetic coagulants in rural settlements (Moreira *et al.,* 2023). Again, the usage of synthetic coagulants poses a risk to human health and the environment due to the discharge of chemical

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residues, including chloride, fluoride, and heavy metals (Raphasha *et al.,* 2025). Cost-friendly and point-of-use treatment of contaminated water is therefore needed to mitigate the dire consequences of drinking polluted water and also improve the socio-economic condition of households of individuals who are deprived of access to pipe-borne water.

The utilization of natural organic coagulants derived from different parts of plants for water treatment dates back to time immemorial. Plant-based coagulants, such as *Moringa oleifera*, are gaining use in water treatment processes due to their biodegradable nature and affordability, particularly in resource-limited nations. *Moringa oleifera* is a fast-growing, deciduous and multipurpose plant belonging to the family Moringaceae. The tree is widely distributed globally and mainly found in Asia, South America and Africa. It is known as Zogale in the northern part of Nigeria, Odudu oyibo among the Igbos, and Adagba malero in the Yoruba land (Mishra *et al.,* 2011). *Moringa oleifera* has several uses, including medicinal, as a component of the diet, and animal feed (Milla *et al.,* 2021; Samiksha *et al.,*2023), therefore serving as a non-negligible economic resource for 3rd world nations.

The cationic proteins present in *Moringa oleifera* bind to impurities in water, causing them to aggregate and settle at the bottom of the water under the influence of gravity (Al-Jadabi *et al.,* 2022; Aziz *et al.,*2023). *Moringa oleifera* seed mechanistically aids the remediation of untreated water through adsorption and charge neutralization of the negative charge on colloidal materials (Chhikara *et al.,* 2020). Functional groups (carboxyl, hydroxyl, and amine), molecular size, and spatial conformation influence the complexation of metals to the active site of organic compounds present in *M. oleifera* (Jin and Wei, 2024). Several studies have highlighted the importance of M. oleifera in removing microbes, suspended solids, and high turbidity from water. Hendrawati et al. (2016) demonstrated the coagulating activity of *M. oleifera* for the purification of groundwater and wastewater. Tuggolou and Payus (2017) strongly observed that *Moringa Oleifera* is a cheaper and safer coagulant for purifying water for human consumption than the use of aluminum sulfate, which can harm human health. In recent times, activated carbon from coconut shell has been utilized to address the drawback of solid contaminants associated with the use of *Moringa oleifera* as a water filter. Activated carbon can be obtained by subjecting coconut shells to high temperatures under acidic conditions. Coconut shell activated carbon forms a small film on the surface of water that adsorbs residual contaminants and certain metallic elements in water due to its low ash content, high mechanical strength, and intense microporosity (Nadella and Nadella, 2024). Another way to improve the efficiency of plant-based treatment of polluted water is to integrate the system with solar disinfection, which reduces pathogenic microbes in water by applying UV light for at least 6 hours (Juvakoski *et al.,* 2022). SODIS has been considered as a relatively cheap approach for water purification, thus providing microbes-free potable water for household utilization (Dawney *et al.,* 2014). Adebiyi et al. 2021 emphasized the bactericidal effect of SODIS on diverse strains of bacteria in well water and recommended the use of other water purification methods to complement SODIS for efficient water remediation. In this study, we aimed to integrate Moringa seed, coconut shell-based activated carbon and the SODIS system to serve as a cheaper and eco-friendly approach for treating contaminated water from surface and ground water sources in Kogi State, Nigeria.

2. Materials and Methods

2.1 Study Area and Sample Collection

Water samples were obtained from rural communities in the Okene, Dekina, Kabba, and Osara Local Government Areas of Kogi State, Nigeria, where untreated groundwater and surface water remain the principal sources of drinking water and for other household activities. The selected sampling points comprised wells and boreholes in Okene, Kabba, and Osara, as well as river and borehole sources in Dekina, thereby representing the major drinking water sources available to the inhabitants of the study area. Sterile 1 L high-density polyethylene (HDPE) bottles were used for sample collection after being thoroughly washed with distilled water. Immediately before sampling, each bottle was rinsed three times with water from the respective collection point to reduce the possibility of contamination and maintain sample quality. After collection, all samples were carefully labelled, placed in an insulated cooler, and transported to the laboratory. The samples were subsequently stored at approximately 4 °C and analysed within 24 h of collection in accordance with the procedures described in the Standard Methods for the Examination of Water and Wastewater (APHA, 2023).

2.2 Preparation of *Moringa oleifera* Seed Powder

Mature *Moringa oleifera* seeds were harvested from healthy trees growing in Kogi State, Nigeria. Only fully developed seeds free from visible defects were selected for the study. The seed coats were removed manually to obtain the kernels, which were rinsed with distilled water to remove adhering debris and surface contaminants. The kernels were air-dried under ambient laboratory conditions until a constant weight was attained before being milled into a fine powder using an electric laboratory grinder. The powdered material was subsequently passed through a fine sieve to obtain a uniform particle size and stored in clean, airtight containers until required for the coagulation experiments, following a procedure comparable to that described by Ofomi et al. (2025). Two coagulant suspensions were prepared to evaluate the influence of dosage on water treatment performance. Exactly 1 g and 2 g of the prepared *M. oleifera* seed powder were separately dispersed in 1 L of distilled water, after which each suspension was thoroughly stirred to achieve a homogeneous mixture before application during the treatment process.

2.3 Preparation of Coconut Shell Activated Carbon

Discarded coconut shells were collected and thoroughly washed with clean water to remove adhering soil, dust, and other foreign materials. The cleaned shells were air-dried under ambient laboratory conditions before carbonization in a muffle furnace at 600 °C for 2 h under oxygen-limited conditions to produce charcoal. The charcoal was subsequently activated to improve its adsorption properties and then washed repeatedly with distilled water until the rinse water attained a neutral pH to remove residual activating agents and soluble impurities. The activated carbon was oven-dried at 105 °C to constant weight, crushed, and sieved to obtain a uniform particle size suitable for water treatment. The prepared activated carbon was stored in clean, airtight containers until required for the adsorption experiments. The preparation procedure was adapted from previously reported methods for coconut shell-derived activated carbon (Li *et al.,* 2008).

2.4 Integrated Water Treatment

For each treatment, 1 L of contaminated water was transferred into a clean container and treated with the prepared *Moringa oleifera* suspension at concentrations of 1 g/L or 2 g/L. The mixture was stirred thoroughly and allowed to stand until coagulation and sedimentation were completed. The clarified supernatant was carefully decanted and passed through a locally fabricated gravity filtration unit constructed from a clean polyethylene sachet-water bottle containing 100 g of coconut shell activated carbon. Sterile cotton wool was placed at the outlet of the bottle to retain the activated carbon while permitting the treated water to pass through.

2.5 Solar Water Disinfection (SODIS)

Following coagulation with *Moringa oleifera* seed powder and subsequent treatment with coconut shell activated carbon, the resulting water samples were carefully transferred into transparent polyethylene terephthalate (PET) bottles for solar water disinfection (SODIS). The bottles were filled, tightly capped, and positioned horizontally under direct sunlight for approximately 6 h during periods of favorable weather (McGuigan *et al.,* 2012).

2.6 Determination of Heavy Metals

Copper (Cu), lead (Pb), and zinc (Zn) concentrations were quantified in both untreated and treated water samples after acid digestion using the procedure recommended by APHA (2023). A measured volume of each sample was digested with concentrated nitric acid until complete mineralization was achieved. The digested solution was allowed to cool, filtered where necessary, and made up to the required volume with deionized water before analysis. Metal concentrations were determined using an Atomic Absorption Spectrophotometer (AAS), and the results were reported as milligrams per litre (mg/L). The values obtained before and after treatment were used to evaluate the performance of the integrated treatment system.

2.7 Determination of Physicochemical Parameters

The physicochemical characteristics of the untreated and treated water samples were determined in accordance with the procedures described in the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2023). Parameters including Electrical Conductivity (EC), pH, Salinity, and Total Dissolved Solids (TDS) were determined.

2.8 Microbiological Analysis

The microbiological quality of the water samples was assessed by enumerating total coliforms and *Escherichia coli* (*E. coli*) using the standard procedures outlined by APHA (2023). Appropriate volumes of each sample were inoculated onto selective culture media and incubated under recommended laboratory conditions. After incubation, the developed colonies were counted and recorded as colony-forming units per millilitre (CFU/mL). The microbial counts obtained from untreated and treated samples were subsequently compared to determine the effectiveness of the treatment process in reducing bacterial contamination.

2.9 Statistical Analysis

All experiments were performed in triplicate, and the results are presented a**s** mean ± standard deviation (SD)**.** Statistical analyses were carried out using GraphPad Prism version 10.0 (GraphPad Software Inc., San Diego, CA, USA)**.** Differences between the untreated (control) and treated water samples were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's multiple comparisons **test** to identify significant differences among treatment groups. Statistical significance was established at $P < 0.05$**.**

3. RESULT

3.1 Changes in Heavy Metal Concentrations Following Integrated Moringa–Activated Carbon–SODIS Treatment

Figure 1 presents the concentrations of copper (Cu), lead (Pb), and zinc (Zn) in water samples collected from the different sampling locations before treatment and after treatment with 1 g/L and 2 g/L of the integrated *Moringa oleifera* seed powder–activated carbon–SODIS system. Across all sampling locations, the concentrations of the three heavy metals were consistently lower after treatment than in the untreated water.

Copper concentrations (Figure 1a) varied among the sampling locations before treatment, with the highest levels observed in the Kabba well sample, while comparatively lower concentrations were recorded in the Okene borehole and Osara borehole samples. Treatment with 1 g/L resulted in a marked reduction in copper concentration at all sampling points, whereas the 2 g/L treatment produced a further decline. This pattern was consistently observed in water obtained from wells, boreholes, and the river source, indicating progressive removal of copper with the higher treatment dosage.

A similar trend was observed for lead (Figure 1b). Untreated water samples contained higher lead concentrations than the corresponding treated samples irrespective of the sampling location. Application of 1 g/L of the treatment system substantially reduced lead levels, while treatment with 2 g/L produced the lowest concentrations in all samples. Although differences in the initial lead concentrations were evident among the water sources, all locations exhibited a consistent reduction following treatment.

The zinc concentrations shown in Figure 1c also decreased after treatment. Untreated samples generally contained the highest zinc levels across the different locations. Following application of the 1 g/L treatment, zinc concentrations declined appreciably, with an additional reduction recorded after treatment with 2 g/L. This trend was evident for all well, borehole, and river samples, demonstrating a consistent decrease in zinc concentration irrespective of the sampling source.

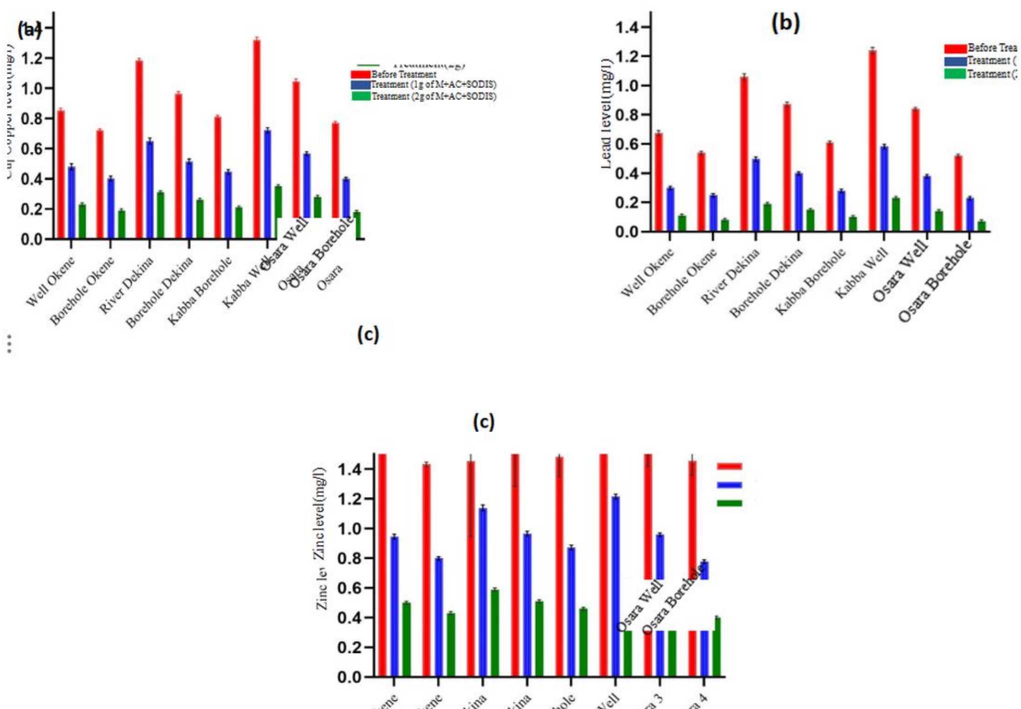

Figure 1. Concentrations of heavy metals before and after treatment: (a) Copper (Cu), (b) Lead (Pb), and (c) Zinc (Zn).

3.2 Effect of the Integrated Moringa–Activated Carbon–SODIS Treatment on Physicochemical Properties

Figure 2 illustrates the changes in electrical conductivity (EC), bicarbonate concentration, salinity, and total dissolved solids (TDS) of the water samples before treatment and after treatment with 1 g/L and 2 g/L of the integrated *Moringa oleifera*–activated carbon–SODIS system. Statistical analysis revealed significant differences among the treatment groups ($p < 0.05$).

Electrical conductivity (Figure 2a) exhibited only slight variations following treatment across the different sampling locations. In most cases, the treated samples recorded marginally higher EC values than the untreated water, with the highest values generally observed after treatment with 2 g/L. Despite these increases, the differences among the sampling locations remained relatively small, indicating a consistent response to the treatment process.

Bicarbonate concentration (Figure 2b) declined markedly after treatment in all water sources. Untreated samples consistently recorded the highest bicarbonate concentrations, whereas treatment with 1 g/L substantially reduced the values. A further decline was observed following treatment with 2 g/L, which produced the lowest bicarbonate concentrations in each of the sampling locations. This reduction was evident in the well, borehole, and river water samples.

Salinity (Figure 2c) also showed a progressive decrease after treatment. The highest salinity values were associated with the untreated water, while both treatment concentrations produced appreciable reductions. Samples treated with 2 g/L consistently recorded lower salinity than those treated with 1 g/L, demonstrating a clear improvement across all sampling sites.

A similar trend was observed for total dissolved solids (TDS) (Figure 2d). The untreated samples contained the highest TDS concentrations, followed by the 1 g/L treatment, whereas the lowest values were obtained after treatment with 2 g/L. This pattern was consistently maintained across all water sources, indicating that increasing the treatment dosage enhanced the reduction in dissolved solids.

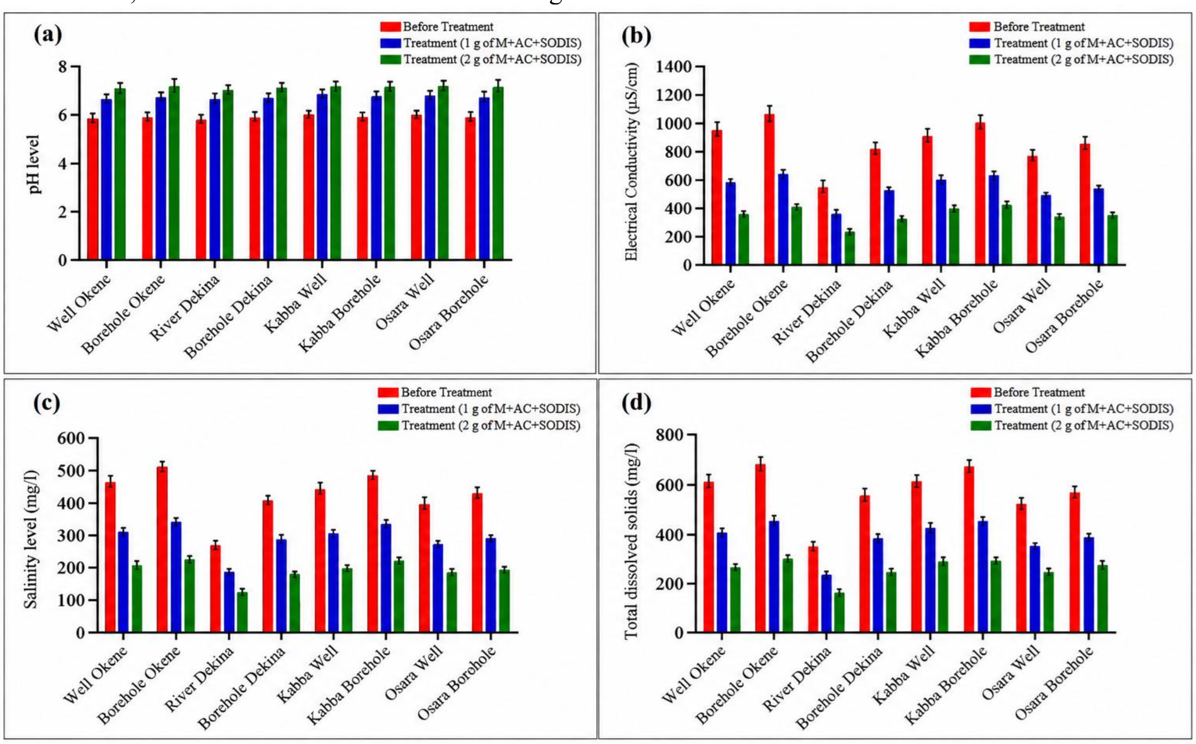

Figure X. Physicochemical parameters of water samples before and after treatment with *Moringa oleifera* (M), activated carbon (AC) and solar water disinfection (SODIS): **(a)** pH level; **(b)** Electrical conductivity; **(c)** Salinity level; **(d)** Total dissolved solids.

Figure 2: Figure 2. Effect of treatment on the physicochemical parameters:(a) pH (b) Electrical Conductivity (EC), (c) Salinity, and (d) Total Dissolved Solids (TDS).

3.3 Changes in Microbiological Characteristics Following Integrated Moringa–Activated Carbon–SODIS Treatment

Figure 3 presents the changes in total coliform and *Escherichia coli* (*E. coli*) counts in the untreated and treated water samples collected from the different sampling locations. Significant differences were observed among the treatment groups ($p < 0.05$).

The total coliform counts (Figure 3a) were highest in the untreated water samples across all sampling locations. Treatment with 1 g/L of the integrated *Moringa oleifera*–activated carbon–SODIS system resulted in a substantial reduction in bacterial counts, while further reductions were recorded following treatment with 2 g/L. This trend was consistently observed in samples obtained from wells, boreholes, and the river source. Among the sampling locations, the River Dekina and Kabba well samples exhibited the highest initial coliform counts before treatment, whereas the lowest residual counts were obtained after treatment with 2 g/L.

A similar pattern was observed for *E. coli* (Figure 3b). Untreated samples consistently recorded the highest bacterial counts, followed by samples treated with 1 g/L, while the lowest counts were obtained after treatment with 2 g/L. The reduction was evident across all sampling locations, with the most pronounced decreases occurring in samples that initially contained higher microbial loads. Regardless of the source of the water, treatment with the higher dosage consistently produced lower *E. coli* counts than the 1 g/L treatment.

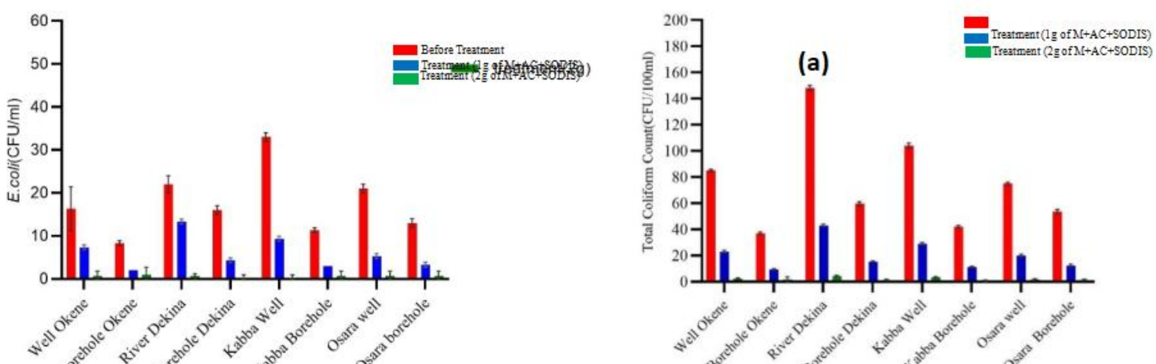

Figure 3. Effect of treatment on the microbiological parameters: (a) Total Coliform and (b) *Escherichia coli* (*E. coli*).

4. DISCUSSION

The present study demonstrated treatment system consisting of *M* powder, coconut shell activated carbon, and solar water disinfection effectively reduced the concentrations of copper (Cu), lead (Pb), and zinc (Zn) in water collected from all sampling locations. Although the initial concentrations varied among the wells, boreholes, and river water, a consistent decline in the concentrations of the three metals was observed after treatment. Moreover, the 2 g/L treatment consistently produced lower residual metal concentrations than the 1 g/L treatment, indicating that increasing the coagulant dosage improved the overall performance of the integrated treatment system.

Copper removal was evident across all sampling locations. The mean Cu concentration decreased from approximately 0.72–1.32 mg/L in the untreated water to 0.40–0.72 mg/L following treatment with 1 g/L, and was further reduced to approximately 0.19–0.35 mg/L after treatment with 2 g/L, representing an overall removal efficiency of about 70–75%. The highe concentration was recorded in th Kabba w whereas Borehole Okene contained th concentration before treatment. Despite these differences, the integrated treatment system produced substantial reductions irrespective of the water source. Similar observations were reported by Nwagbara et al. (2022), who demonstrated that *Moringa oleifera* seed biomass removed approximately 70% of Cu(II) from contaminated water under optimized conditions. Likewise, Shan et al. (2017) reported that *M. oleifera* seed substantially reduced copper concentrations in contaminated river water, confirming its effectiveness as a natural coagulant for heavy metal removal. The similarity between the present findings and previous studies indicates that *M. oleifera* remains an efficient and environmentally sustainable material for copper remediation.

Among the metals evaluated, lead exhibited the greatest reduction after treatment. Mean Pb concentrations decreased from approximately 0.52–1.24 mg/L before treatment to 0.23–0.58 mg/L following treatment with 1 g/L, and further declined to 0.07–0.23 mg/L after treatment with 2 g/L. These values correspond to removal efficiencies approaching 80–87%, with the Kabba well sample recording both the highest initial concentration and one of the greatest absolute reductions after treatment. The greater removal of lead compared with copper agrees with the adsorption behaviour reported by Nwagbara et al. (2022), who found that Pb(II) exhibited the highest biosorption efficiency among the metals investigated, with removal efficiencies approaching 90%. Earlier work by Araújo et al. (2010) similarly demonstrated that *Moringa oleifera* seeds possess a high affinity for Pb(II), owing to the abundance of functional groups capable of binding divalent metal ions. These findings suggest that lead is more readily adsorbed onto *Moringa*-based biosorbents than several other heavy metals, explaining the marked reduction observed in the present study.

Although zinc concentrations showed greater variability among the untreated samples, reflecting differences in the environmental characteristics of the sampling locations, the integrated treatment consistently reduced zinc levels after both treatment dosages. Mean Zn concentrations declined from approximately 1.43–1.93 mg/L before treatment to 0.79–1.23 mg/L after treatment with 1 g/L and further to 0.40–0.64 mg/L following treatment with 2 g/L. The broader variation observed before treatment is expected in environmental water samples because zinc concentrations are strongly influenced by local geology, runoff, and anthropogenic activities. Nevertheless, the substantial decline recorded after treatment demonstrates that the integrated system remained effective despite differences in the initial contamination levels. Previous investigations have also shown that *Moringa oleifera* is capable of removing Zn(II) from contaminated water through biosorption, although zinc generally exhibits lower adsorption efficiency than lead because of differences in metal-ion affinity for available binding sites. This trend is consistent with the comprehensive review by Gomes et al. (2022), which concluded that *M. oleifera* is an effective biosorbent for zinc and other heavy metals under a wide range of treatment conditions.

The improved performance obtained with the 2 g/L treatment demonstrates the importance of coagulant dosage during water purification. Increasing the quantity of *M. oleifera* seed powder provides additional positively charged proteins and functional groups that promote contaminant removal during coagulation and biosorption. This observation agrees with the findings of Shan et al. (2017), who reported that increasing *M. oleifera* dosage enhanced heavy metal removal until the optimum concentration was attained. Following coagulation, passage of the clarified water through coconut shell activated carbon likely provided additional adsorption sites for dissolved metal ions that remained in solution after sedimentation. The complementary action of coagulation and adsorption therefore contributed to the consistently lower residual metal concentrations obtained after the integrated treatment. Similar improvements have been reported for combined *Moringa oleifera* and activated carbon treatment systems, where activated carbon removed residual heavy metals that were not eliminated during the coagulation stage.

The integrated treatment process produced marked improvements in the physicochemical quality of the water samples, as evidenced by increases in pH and corresponding reductions in electrical conductivity (EC), total dissolved solids (TDS), and salinity. Although the untreated water exhibited varying levels of contamination depending on the sampling location, the response to treatment followed a consistent pattern across all water sources. In every case, treatment with 2 g/L of *Moringa oleifera* seed powder produced greater improvements than the 1 g/L treatment, indicating that the higher dosage enhanced the overall efficiency of the integrated treatment system.

Among the parameters evaluated, pH showed a notable improvement following treatment. The untreated water samples were slightly acidic, with mean pH values ranging from approximately 5.7 to 6.1, indicating conditions that fall below the World Health Organization (WHO) recommended range of 6.5–8.5 for drinking water. After treatment with 1 g/L of *Moringa oleifera*, pH values increased to between 6.6 and 6.9, while application of the 2 g/L treatment further increased the values to approximately 7.1–7.4. Consequently, all treated samples fell within the WHO recommended range for potable water, suggesting that the integrated treatment effectively corrected the acidic nature of the water without producing excessive alkalinity. The moderate increase in pH observed in the present study agrees with previous investigations reporting that *Moringa oleifera* treatment improves the acid–base balance of contaminated water while maintaining pH within acceptable drinking-water standards. This attribute is advantageous because water that is excessively acidic may accelerate corrosion of storage containers and distribution systems, whereas water within the recommended pH range is generally more suitable for domestic consumption.

Electrical conductivity declined considerably after treatment irrespective of the source of the water. Mean EC values decreased from approximately 538–1008 μS/cm before treatment to 372–692 μS/cm following treatment with 1 g/L and were further reduced to about 241–446 μS/cm after treatment with 2 g/L. The greatest reduction was observed in the Borehole Okene sample, where conductivity decreased by more than half following treatment. Electrical conductivity reflects the concentration of dissolved ionic species in water; therefore, the progressive reduction observed in this study indicates effective removal of dissolved ions during the sequential coagulation and adsorption processes. Although WHO does not prescribe a health-based guideline value for electrical conductivity, lower EC values generally indicate an improvement in water quality because they reflect a reduction in dissolved mineral and ionic constituents. The decrease observed in the present study is consistent with reports that natural coagulants, particularly *Moringa oleifera*, substantially reduce dissolved ionic content through coagulation and subsequent removal of suspended and colloidal materials.

A similar trend was evident for total dissolved solids. Untreated samples contained between approximately 349 and 674 mg/L TDS, whereas treatment with 1 g/L reduced the values to approximately 244–462 mg/L, and the 2 g/L treatment further lowered them to about 158–298 mg/L. These reductions indicate efficient removal of dissolved and suspended matter from the water. Importantly, all treated samples remained well below the WHO aesthetic guideline of 600 mg/L for good palatability and below the broader guideline value of 1000 mg/L for drinking water, demonstrating that the integrated treatment substantially improved the acceptability of the water for domestic use. Similar reductions in TDS have been documented in studies employing *Moringa oleifera* seed as a natural coagulant, where aggregation and sedimentation of suspended particles were accompanied by a decline in dissolved solids. The additional reduction observed in the present study is likely attributable to the adsorption capacity of coconut shell activated carbon, which effectively removed residual dissolved constituents that persisted after coagulation.

Salinity also declined consistently after treatment, with untreated samples recording values between approximately 262 and 501 mg/L compared with 119–223 mg/L after the 2 g/L treatment. The close relationship between salinity, EC, and TDS was evident throughout the study, as all three parameters decreased concurrently following treatment. This relationship is expected because dissolved salts contribute directly to both the ionic conductivity and the total dissolved solids present in water. The simultaneous reduction in these parameters therefore provides complementary evidence that the integrated treatment effectively lowered the dissolved ionic burden of the contaminated water. Although WHO has not established a health-based guideline value specifically for salinity, reducing excessive dissolved salts improves the aesthetic quality of drinking water and enhances consumer acceptability.

The consistently superior performance of the 2 g/L treatment suggests that increasing the amount of *Moringa oleifera* seed powder enhanced the coagulation process by providing a greater quantity of active cationic proteins capable of destabilizing suspended particles and associated contaminants. Following sedimentation, the passage of partially clarified water through coconut shell activated carbon likely facilitated further removal of dissolved ions and organic impurities through adsorption, while the subsequent SODIS stage ensured microbiological safety without adversely affecting the measured physicochemical properties. The sequential application of these three treatment processes therefore produced a complementary effect that yielded greater improvements than would be expected from a single treatment stage alone.

Microbiological contamination remains one of the principal causes of waterborne diseases in developing countries, particularly in rural communities where untreated surface water and shallow groundwater frequently serve as the primary sources of domestic water. In the present study, the integrated treatment system comprising *Moringa oleifera* seed powder, coconut shell activated carbon and solar water disinfection (SODIS) produced a marked reduction in both total coliform and *Escherichia coli* populations across all sampling locations. Irrespective of the water source, treatment with 2 g/L consistently yielded lower bacterial counts than the 1 g/L treatment, demonstrating that increasing the dosage of *M. oleifera* enhanced the microbiological performance of the integrated treatment process.

The untreated water samples contained considerable total coliform contamination, with mean values ranging from approximately 37 CFU/mL in Borehole Okene to about 148 CFU/mL in River Dekina. Such levels indicate substantial microbial pollution and suggest contamination arising from surface runoff, faecal inputs, poor sanitation practices or seepage into groundwater sources. Following treatment with 1 g/L, total coliform counts declined to approximately 9–43 CFU/mL, while treatment with 2 g/L further reduced the counts to between 0 and 5 CFU/mL. The reduction observed in the present study is comparable with findings reported by Andrade et al. (2021), who demonstrated that *Moringa oleifera* seed extract removed more than 99% of bacterial load during tertiary wastewater treatment while maintaining favourable physicochemical characteristics of the treated water. Similarly, Vunain et al. (2019) reported significant reductions in waterborne pathogens following treatment with *Moringa oleifera* seed powder, with microbial removal improving as treatment conditions were optimized. These studies reinforce the ability of *M. oleifera* seeds to function as effective natural coagulants capable of substantially lowering microbial contamination in polluted water.

A similar pattern was evident for *E. coli*, which is regarded as the most reliable indicator of recent faecal contamination. Mean *E. coli* counts in untreated water ranged from approximately 8 to 48 CFU/mL but declined to between 2 and 13 CFU/mL after treatment with 1 g/L and to 0–3 CFU/mL following treatment with 2 g/L. Complete elimination was achieved in several treated samples, particularly those collected from borehole sources. Although a few samples still contained very low residual counts after treatment, the overall reduction exceeded 90% in all sampling locations. Comparable observations were reported by Pritchard et al. (2010), who found that *Moringa oleifera* seed reduced *E. coli* populations by 82–93% in contaminated river water and achieved even greater removal when treatment was combined with a secondary filtration stage. Andrade et al. (2021) likewise demonstrated that *M. oleifera* seed treatment produced bacterial reductions comparable to conventional alum coagulation while offering the additional advantages of lower sludge production and minimal changes in water pH.

The pronounced reduction in microbial load observed in the present investigation can reasonably be attributed to the complementary action of the three treatment stages. During coagulation, the positively charged proteins present in *M. oleifera* seeds destabilize suspended particles and promote floc formation, allowing microorganisms attached to these particles to settle out of suspension. Passage of the clarified water through coconut shell activated carbon provides an additional polishing step by adsorbing residual suspended matter and associated microorganisms, while exposure to sunlight during SODIS further inactivates surviving bacteria through the combined effects of ultraviolet-A radiation and thermal stress. The improved microbial quality obtained in this study therefore reflects the cumulative contribution of coagulation, adsorption and solar disinfection rather than the action of a single treatment process.

The consistently better performance of the 2 g/L treatment indicates that increasing the quantity of *M. oleifera* seed powder enhanced floc formation and improved the removal of microbial contaminants before the adsorption and disinfection stages. Similar dose-dependent responses have been described in studies evaluating *M. oleifera* as a natural coagulant, where increasing the amount of seed material improved microbial removal until the optimum treatment concentration was reached. The findings of the present study therefore support the growing evidence that *M. oleifera* performs more effectively when incorporated into a multistage treatment system than when applied as a standalone treatment. According to the World Health Organization, drinking water intended for human consumption should contain no detectable *Escherichia coli* in any 100 mL sample, since its presence is regarded as evidence of faecal contamination and a potential risk of enteric disease transmission. Although a few treated samples still contained very low residual *E. coli* counts after treatment with 2 g/L, the integrated treatment reduced bacterial contamination to levels far below those recorded before treatment, indicating its potential as an effective, affordable and environmentally sustainable household water treatment option for rural communities with limited access to centralized water treatment facilities.

4 Conclusion

The findings of this study indicate that the integrated application of *Moringa oleifera* seed powder, coconut shell activated carbon, and solar water disinfection (SODIS) effectively improved the quality of water obtained from selected rural communities in Kogi State, Nigeria. The treatment process enhanced the physicochemical properties of the water, reduced the concentrations of heavy metals, and markedly lowered microbial contamination, thereby producing water of better quality than the untreated samples. The combined treatment approach therefore represents a practical, environmentally friendly, and low-cost option for improving drinking-water quality, particularly in rural communities where access to conventional water treatment systems is limited.

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Declaration

The authors declare that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere.

Conflict of Interest

The authors declare that they have no competing interests.

Reference

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