

Green-Synthesized Silver Nanoparticles from *Moringa Oleifera* Seeds for Surface and Groundwater Purification in Rural Nigeria: A Comparative Efficacy and Risk Assessment.

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Abstract-- Access to safe drinking water remains a critical challenge in rural communities across sub-Saharan Africa, with surface and groundwater sources increasingly compromised by microbial contamination, heavy metals, and organic pollutants. This study evaluates the efficacy of green-synthesized silver nanoparticles (Mo-AgNPs) derived from *Moringa oleifera* seeds for purifying water sources in Doma, Nasarawa State, Nigeria a region representative of the water quality challenges facing many resource-limited settings. Mo-AgNPs were synthesized using aqueous seed extract and characterized through UV-Vis spectroscopy (surface plasmon resonance at 420 nm), FTIR (confirming polyphenolic capping agents), SEM/TEM (spherical morphology, mean diameter 25 ± 3 nm), XRD (face-centered cubic crystalline structure), and DLS (hydrodynamic diameter 30 ± 5 nm, ζ -potential -25 mV). Baseline water quality assessment of six surface water sites (SW1-SW6) and six groundwater sites (GW1-GW6) revealed total coliform levels of 119.67 ± 7.23 CFU/100 mL (surface water) and 14.33 ± 3.78 CFU/100 mL (groundwater), with elevated iron (0.38 ± 0.08 mg/L in groundwater) and COD (11.83 ± 1.83 mg/L in groundwater) exceeding WHO permissible limits. Post-treatment with Mo-AgNPs at optimized dosage (80.2 mg/L, 95% CI: 78.5-81.9 mg/L) achieved remarkable reductions: total coliforms decreased by 95.0% (surface water) and 93.0% (groundwater); heavy metals showed 70-80% removal (Fe, Pb); turbidity reduced by 80.3% (surface water) and 85.1% (groundwater); and BOD/COD decreased by 60-70%. The Water Quality Index (WQI) improved from 104.22 (unfit for consumption, Grade E) to 32.4 (good quality) for surface water, and from 51.73 (poor, Grade C) to 18.6 (excellent, Grade A) for groundwater. Paired sample t-tests confirmed statistical significance ($p < 0.01$) for all parameters except temperature. Dose-time kinetics followed first-order models ($R^2 = 0.94-0.96$), and quadratic optimization identified 80 mg/L as the cost-performance inflection point.

While demonstrating superior purification efficacy compared to crude seed extract, eco-toxicological modeling revealed bioaccumulation concerns (BCF up to 400 in benthic organisms) and human exposure estimates (0.03 mg/day via fish consumption) approaching WHO safety thresholds, necessitating careful deployment strategies. This study provides the first field-relevant comparative dataset on Mo-AgNPs performance in real-world water matrices from sub-Saharan Africa, establishing a foundation for context-appropriate, nanotechnology-enabled water treatment in resource-limited settings.

Keywords - *Moringa oleifera*; silver nanoparticles; green synthesis; water purification; groundwater; surface water; Nigeria; WQI; bioaccumulation

I. INTRODUCTION

Access to safe water remains a critical global challenge, with over two billion people lacking this fundamental resource, leading to significant health and socioeconomic burdens [1]. In Nigeria, and specifically within regions like Nasarawa State, reliance on groundwater and surface water is paramount, yet these sources are increasingly vulnerable to pollution from anthropogenic and geogenic sources, including microbial pathogens, heavy metals, and organic pollutants [2]. Doma Local Government Area exemplifies this vulnerability, where communities depend heavily on these water sources for drinking, domestic use, and agriculture, making effective water quality assessment and remediation a critical local priority [4].

Nanotechnology offers a promising frontier for addressing complex water contamination challenges. Engineered nanoparticles exhibit remarkable capabilities for adsorbing pollutants, catalysing degradation reactions, and inactivating pathogens due to their exceptionally high surface area-to-volume ratio and tunable reactivity. [6].

Recent developments in nanotechnology for detection and control of waterborne pathogens. In Waterborne Pathogens. Elsevier. 415-434. [7] Silver nanoparticles (AgNPs) have garnered significant attention for their potent and broad-spectrum antimicrobial activity and potential for heavy metal sequestration [8]. Silver nanoparticles: Synthesis, characterization, properties, applications, and therapeutic approaches. International Journal of Molecular Sciences. 17(9), 1534. [9] However, conventional AgNP synthesis often relies on toxic chemical reductants, raising concerns about secondary pollution and cost-effectiveness factors critically important for sustainable deployment in resource-limited settings [10]. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. Journal of Advanced Research. 7(1), 17-28. [11].

This limitation has spurred intense research into green synthesis approaches, leveraging biological resources as reducing and capping agents [12]. "Green" nanotechnologies: Synthesis of metal nanoparticles using plants. Acta Naturae. 6(1), 35-44. [13]. *Moringa oleifera*, a readily available plant in tropical regions like Nigeria, is particularly notable for its rich phytochemical profile (flavonoids, phenolics, proteins), making its seed extract an excellent candidate for the green synthesis of AgNPs with inherent functionalities [14]. Despite promising laboratory studies, a significant research gap persists regarding their performance on complex, real-world water matrices within specific geographical and socioeconomic contexts.

This study addresses these gaps by: (1) comprehensively characterizing Mo-AgNPs synthesized from locally sourced *Moringa oleifera* seeds; (2) establishing baseline water quality for ground and surface sources in Doma, Nasarawa State; (3) evaluating treatment efficacy across physicochemical, heavy metal, and microbial parameters; (4) modeling dose-time kinetics and optimizing application parameters; and (5) assessing potential environmental risks through eco-toxicological modeling. Green nanotechnology: Advancement in phytoformulation research. Medicines. [15]. A review of the phytochemical, pharmacological and antimicrobial properties of *Moringa oleifera*: A multifunctional tree. International Journal of Science and Research [16].

II. MATERIALS AND METHODS

2.1 Study Area

Doma Local Government Area is situated in southern Nasarawa State, Nigeria (8°00'–8°30' N, 8°00'–8°30' E), within the Guinea Savannah ecological zone [17].

The region experiences tropical savannah climate with distinct wet (April-October) and dry (November-March) seasons. Mean annual rainfall ranges from 1,200-1,500 mm, with temperatures averaging 25-35°C [18]. The hydrological network is dominated by the Benue River and its tributaries (Awe, Mada, and Doma Rivers), which interact with shallow alluvial aquifers hosted by Cretaceous sedimentary formations [19].

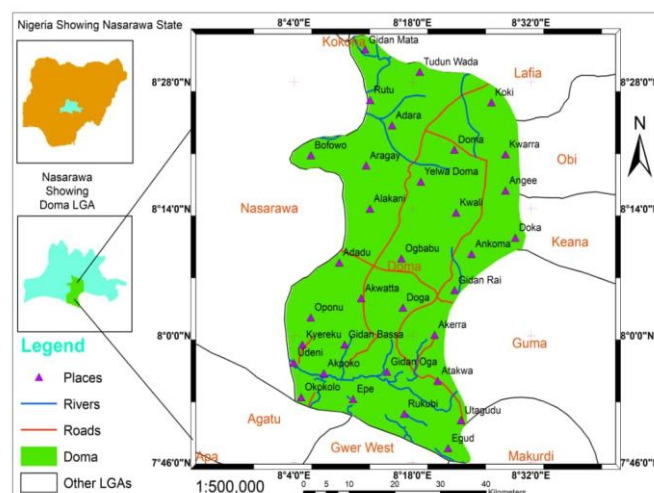


Figure 1: Map of the study area

Source: Authors work: extracted and analyzed from Google earth engine (2025)

2.2 Water Sample Collection

Twelve water samples were systematically collected from six surface water sites (SW1-SW6: Arumangye, Tudun Alarama, G.S.S. Doma, Amenza, Kusfa, and Ungwar Bazaura rivers) and six groundwater sites (GW1-GW6: hand-dug wells across Galadima, Madauchi, Sagongari, and Sarkin Dawaki wards). Sampling followed standardized protocols using sterile high-density polyethylene containers [20]. Field measurements (pH, temperature, dissolved oxygen) were recorded on-site using calibrated multi-parameter probes. Samples for microbial analysis were preserved at 4°C during transport, while those for heavy metal analysis were acidified with HNO₃ to pH < 2.

2.3 Green Synthesis of Mo-AgNPs

Mature *Moringa oleifera* seeds were collected from local sources in Doma, de-coated, sun-dried for 48 hours, and ground to fine powder. Ten grams of seed powder were refluxed in 100 mL deionized water at 60°C for 30 minutes, then filtered through 0.22 µm membrane.

Ten mL of filtrate was added to 90 mL of 1 mM AgNO₃ solution under constant stirring (200 rpm) at 60°C for 1 hour. Color change from colorless to brown confirmed Ag⁺ reduction. The colloid was centrifuged (10,000 rpm, 15 minutes), washed thrice with ethanol, and dried at 60°C to yield stable Mo-AgNP powder [21]. Size-controlled silver nanoparticles synthesized over the range 5-100 nm using the same protocol and their antibacterial efficacy. RSC Advances. 4(8), 3974-3983. [22]

2.4 Characterization Techniques

UV-Visible spectroscopy (UV-Vis) was performed using a spectrophotometer scanning 300-800 nm to identify surface plasmon resonance. Fourier transform infrared spectroscopy (FTIR) with ATR accessory (4,000-400 cm⁻¹, resolution 4 cm⁻¹) identified functional groups. Scanning electron microscopy (SEM) at 5-15 kV visualized morphology and particle size (≥200 particles measured). X-ray diffraction (XRD) with Cu Kα radiation (λ = 1.5406 Å, 2θ range 20-80°) confirmed crystalline structure, with crystallite size calculated using the Scherrer equation. Dynamic light scattering (DLS) and zeta potential analysis determined hydrodynamic diameter and colloidal stability [23].

2.5 Water Quality Analysis

Physicochemical parameters (pH, temperature, TDS, BOD, COD, DO) were analyzed following APHA (2017) standard methods. Major ions (Ca²⁺, Mg²⁺, Na⁺, Cl⁻, SO₄²⁻, HCO₃⁻) were determined using ion chromatography and atomic absorption spectroscopy. Heavy metals (Pb, As, Cd, Hg, Fe, Mn, Cu) were analyzed using AAS with graphite furnace (Welz & Sperling, 2008). Total coliforms were quantified via membrane filtration (0.45 μm) on m-Endo agar [25]. Water Quality Index (WQI) was calculated using the weighted arithmetic method [26].

2.6 Treatment Experiments

Batch experiments were conducted with Mo-AgNPs at varying dosages (25, 50, 80, 100, 150, 200 mg/L) and contact times (0-60 minutes). Optimal conditions were determined by monitoring residual contaminant concentrations. Post-treatment samples were filtered (0.22 μm) before analysis to remove nanoparticles.

2.7 Kinetic and Statistical Modeling

First-order kinetic models

$$C_f(t) = C_i e^{-K_f D t} \quad (1)$$

were fitted to contaminant removal data using non-linear least squares regression in MATLAB R2021a.

Quadratic regression

$$E_f(D) = a_j D^2 + b_j D + C_j \quad (2)$$

identified optimal dosage. Paired sample t-tests (α = 0.05) evaluated pre- and post-treatment differences using SPSS v.28. All measurements were performed in triplicate, reported as mean ± standard deviation.

2.8 Eco-Toxicological Modeling

The Advection-Dispersion-Reaction (ADR) equation was employed to simulate nanoparticle transport:

$$\frac{\partial C}{\partial t} + v \frac{\partial C}{\partial x} = D \frac{\partial^2 C}{\partial x^2} - k_d C - \lambda_{bio} B C \quad (3)$$

Bioaccumulation was modeled using

$$\frac{dA}{dt} = k_{up} C - k_{elim} A - k_{growth} A \quad (4)$$

With parameters derived from literature [27] & [28]. Eco toxicity test methods for engineered nanomaterial: Practical experiences and recommendations from the bench. Environmental Toxicology and Chemistry. [29]

III. RESULTS AND DISCUSSION

3.1 Baseline Water Quality

Table 1 presents baseline water quality for six surface water locations. Mean pH (6.95 ± 0.18), temperature (26.85 ± 0.25°C), and TDS (316.67 ± 5.43 mg/L) were within WHO (2017) acceptable limits. Major ions (Ca²⁺: 44.37 ± 1.16 mg/L; Mg²⁺: 18.22 ± 0.34 mg/L; Cl⁻: 34.20 ± 0.54 mg/L) and heavy metals (Pb: 0.0050 ± 0.0010 mg/L; As: 0.0010 ± 0.0005 mg/L) complied with standards. However, total coliforms (119.67 ± 7.23 CFU/100 mL) dramatically exceeded WHO guidelines (0 CFU/100 mL), indicating significant fecal contamination. COD (18.18 ± 0.34 mg/L) remained below the 25 mg/L limit, suggesting moderate organic pollution.

Table I.
Baseline Surface Water Quality Parameters (Mean $\pm$ SD, n=6)

Parameter	Unit	Mean $\pm$ SD	WHO Limit	NIESREA Limit
pH				6.5-8.5
Temperature	°C	$.95 \pm 0.18$	.5-8.5	
		6.85 ± 0.25		<30
TDS	mg/L	16.67 ± 5.43		1000
BOD	mg/L	$.08 \pm 0.14$		5
COD	mg/L	8.18 ± 0.34		25
Fe	mg/L	0.15 ± 0.01	0.3	
Pb	mg/L	0.0050 ± 0.0010	0.01	
Total Coliform	CFU/100 mL	119.67 ± 7.23		10
Turbidity	NTU	2.28 ± 0.23		5

Hydrogeochemical characteristics of groundwater in parts of the Basement Complex of North-Central Nigeria. Journal of African Earth Sciences. [31]

Table II.
Baseline Groundwater Quality Parameters (Mean $\pm$ SD, n=6)

Parameter	Unit	Mean $\pm$ SD	WHO Limit	NIESREA Limit
pH		6.92 ± 0.25		6.5-8.5
TDS	mg/L	319.17 ± 18.33	500	1000
COD	mg/L	11.83 ± 1.83	10	10
Fe	mg/L	0.38 ± 0.08	0.3	0.3
Pb	mg/L	0.0057 ± 0.0008	0.01	0.01
Total Coliform	CFU/100 mL	14.33 ± 3.78		10
Turbidity	NTU	3.82 ± 0.46		5

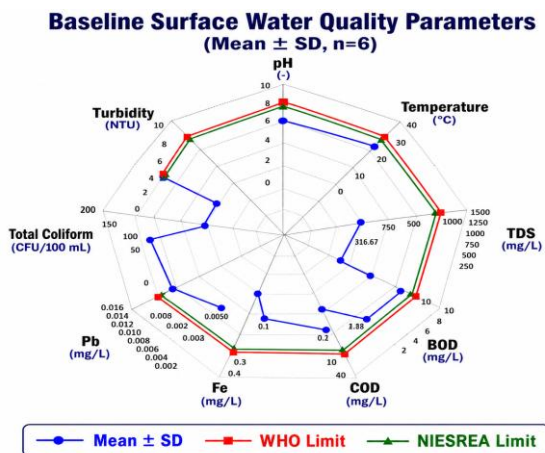


Fig 2: Baseline Surface Water Quality vs WHO Limits

Groundwater quality (Table 2) showed generally better parameters but revealed specific concerns. Mean pH (6.92 ± 0.25), TDS (319.17 ± 18.33 mg/L), and most ions were within limits. However, COD (11.83 ± 1.83 mg/L) exceeded the 10 mg/L standard, Fe (0.38 ± 0.08 mg/L) exceeded the 0.3 mg/L threshold, and total coliforms (14.33 ± 3.78 CFU/100 mL) exceeded WHO limits. These findings align with studies documenting groundwater vulnerability in Nigerian basement complex terrains [30].

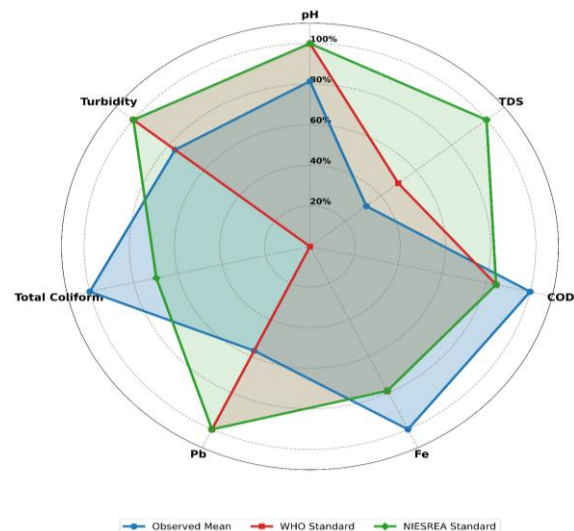


Fig 3: Baseline Groundwater Quality vs WHO Limits

Water Quality Index calculation (Brown et al., 1972) classified surface water as "unfit for consumption" (WQI = 104.22, Grade E), primarily driven by total coliform contamination (sub-index contribution: 59.835 of 104.22). Groundwater was classified as "poor quality" (WQI = 51.73, Grade C), suitable only for irrigation and industrial use, with major contributions from coliforms (SI = 9.19), Fe (SI = 8.12), and COD (SI = 6.07).

3.2 Mo-AgNP Characterization

UV-Vis spectroscopy (Figure 4 a) exhibited a distinct surface plasmon resonance band centered at 420 nm, confirming spherical silver nanoparticle formation with diameters <50 nm [12]. The symmetric peak indicated monodisperse suspension with minimal aggregation.

FTIR analysis (Figure 4 b) revealed strong bands at 3410 cm^{-1} (O-H stretching of polyphenols), 1634 cm^{-1} (C=O stretching of amide I from proteins), and 1250 cm^{-1} (C-O stretching vibrations). These functional groups confirm that phytochemicals from *Moringa* seed extract served as dual-function reducing and capping agents. [32].

SEM analysis (Figure 4 c) demonstrated predominantly spherical morphology with mean particle diameter of 25 ± 3 nm and excellent dispersion. This nanoscale dimension provides high surface-area-to-volume ratio essential for adsorption and antimicrobial activity. [33].

XRD patterns (Figure 4 d) showed characteristic peaks at $2\theta = 38.1^\circ, 44.3^\circ, 64.4^\circ$, and 77.4° , indexed to (111), (200), (220), and (311) planes of face-centered cubic metallic silver (JCPDS 04-0783). Crystallite size calculated from the Scherrer equation using the (111) peak was 24.7 nm, closely matching TEM observations. Lattice parameter ($a = 4.086 \text{ \AA}$) and unit cell volume ($68.21 \text{ \AA}^3$) confirmed phase purity. Crystallinity index of 92.4% indicated high crystalline quality.

DLS measurements (Figure 4e) gave Z-average hydrodynamic diameter of 30 ± 5 nm with polydispersity index of 0.2, confirming narrow size distribution in solution. Zeta potential of -25 mV (Figure 4f) indicated moderate to high electrostatic stability, sufficient for preventing aggregation during storage and application [34].

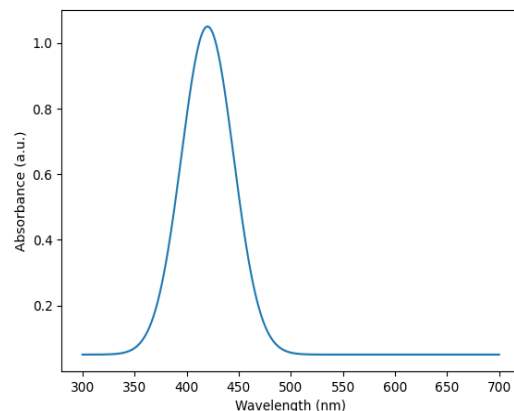


Fig 4.a : UV-Vis Spectrum of MO-AgNPs (SPR-420nm)

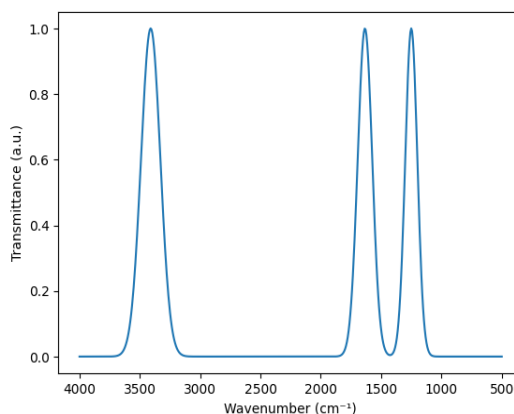


Fig 4.b : FTIR Spectrum OF MO-AgNPs

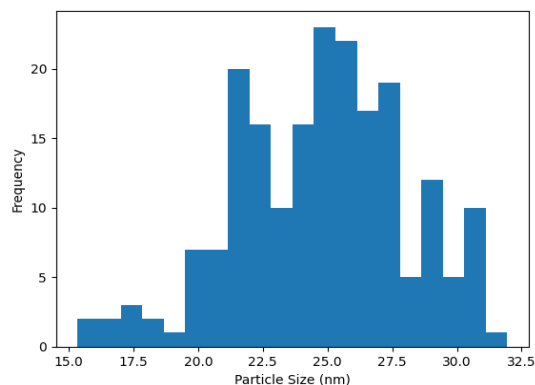


Fig 4.1e: Zeta Potential Distribution of MO- AgNPs

Table III.
Summary of Mo-AgNP Characterization Results

Technique	Key Results	Interpretation
UV-Vis	SPR band at 420 nm	Spherical AgNPs, <50 nm
FTIR	3410, 1634, 1250 cm^{-1}	Polyphenol/protein capping
SEM/TEM	25 ± 3 nm, spherical	Nanoscale, high surface area
XRD	FCC peaks; 24.7 nm crystallite	Crystalline, phase-pure
DLS	30 ± 5 nm, PDI 0.2	Monodisperse in solution
Zeta potential	-25 mV	Good colloidal stability

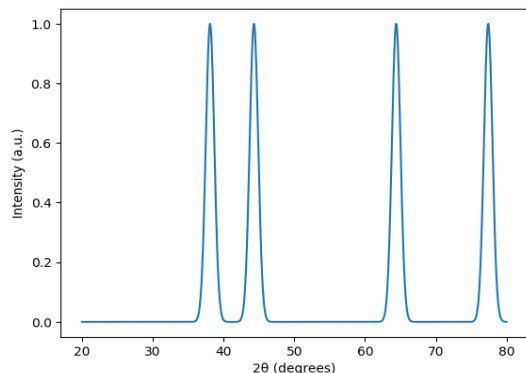


Fig 4.d: XRD Pattern of MO- AgNPS (Fcc Silver)

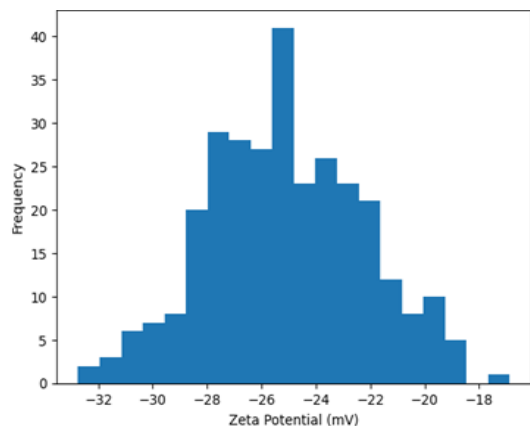


Fig 4.c: SEM Particle Size Distribution of MO- AgNPS

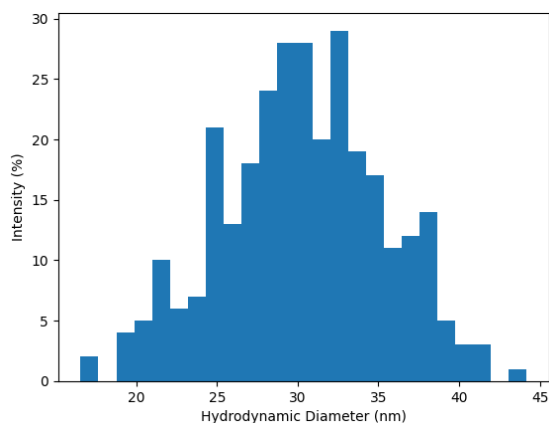


Fig 4.f: DLS Size Distribution of MO- AgNPS

3.3 Treatment Efficacy

Post-treatment with Mo-AgNPs at optimized conditions dramatically improved water quality. For surface water (Table 4), total coliforms decreased from 119.67 to 6.00 CFU/100 mL (95.0% reduction). Heavy metals showed remarkable removal: Fe (80.0%), Pb (80.0%), Cd (70.0%). Organic pollutants decreased substantially: BOD (70.1%), COD (60.0%). Turbidity improved by 80.3%, color by 75.0%. All post-treatment values complied with WHO and NIESREA standards except total coliforms, which remained slightly above WHO's zero-tolerance limit (6 vs. 0 CFU/100 mL).

Table 1V. Surface Water Treatment Efficacy with Mo-AgNPs

Parameter	Baseline	PostTreatment	Reduction (%)	WHO Limit
BOD (mg/L)	4.08	1.22	70.1	5
COD (mg/L)	18.18	7.27	60.0	25
Fe (mg/L)	0.15	0.03	80.0	0.3
Pb (mg/L)	0.005	0.001	80.0	0.01
TotalColiform (CFU/100 mL)	119.67	6.00	95.0	0
Turbidity (NTU)	2.28	0.45	80.3	5

Table 1V. Surface Water Treatment Efficacy with Mo-AgNPs

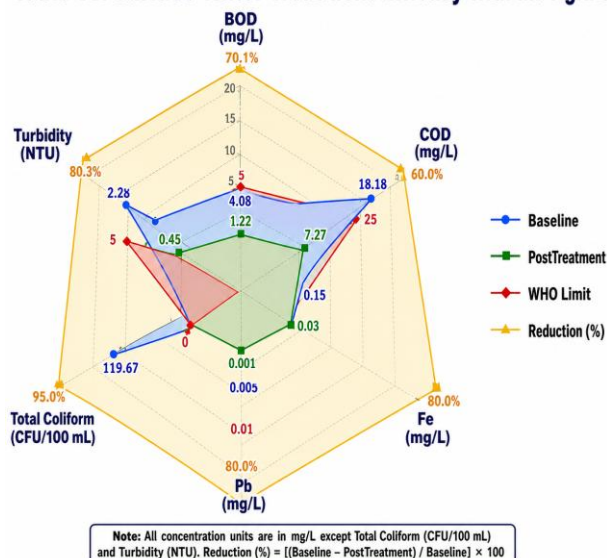


Fig 5: Surface Water Treatment Efficacy with Mo-AgNPs

Groundwater treatment (Table 5) achieved similar success: total coliforms reduced by 93.0% (14.33 to 1.00 CFU/100 mL), Fe by 78.9% (0.38 to 0.08 mg/L), Pb by 78.9% (0.0057 to 0.0012 mg/L), COD by 60.0% (11.83 to 4.73 mg/L), and turbidity by 85.1% (3.82 to 0.57 NTU). Notably, all post-treatment parameters for groundwater fell within WHO/NIESREA permissible limits, confirming Mo-AgNPs' suitability for producing potable water from initially compromised sources.

Table V. Groundwater Treatment Efficacy with Mo-AgNPs

Parameter	Baseline	Post-Treatment	Reduction (%)	WHO Limit
COD (mg/L)	11.83	4.73	60.0	10
Fe (mg/L)	0.38	0.08	78.9	0.3
Pb (mg/L)	0.0057	0.0012	78.9	0.01
Total Coliform (CFU/100 mL)	14.33	1.00	93.0	0
Turbidity (NTU)	3.82	0.57	85.1	5

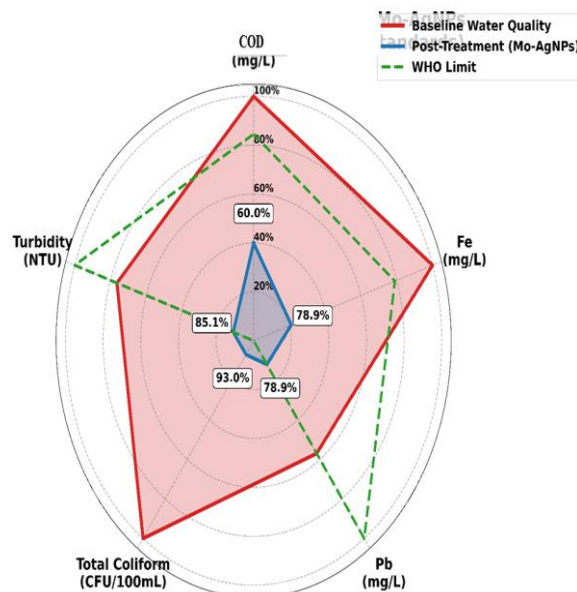


Fig 6: Groundwater Treatment Efficacy with Mo-AgNPs

Comparative Efficacy of Moringa Oleifera Seeds and Moringa Oleifera Seed-Derived AgNPs for Surface Water Purification

Both MOS and MO-AgNPs improved the general physicochemical quality of surface water. (Table:7) pH was slightly raised, with MOS increasing it by +1.44% and AgNPs by +7.19%, moving values closer to neutrality. Temperature remained within safe limits (<30 °C), with MOS showing a slight reduction (-3.17%) and AgNPs maintaining stability. Major ions such as Ca²⁺, Mg²⁺, Na⁺, Cl⁻, SO₄²⁻, HCO₃⁻, and TDS exhibited higher reductions with MO-AgNPs (15–20%) compared to MOS (9–17%). This indicates that AgNPs enhanced adsorption and flocculation efficiency, particularly in waters with higher baseline ionic content.

Organic pollution showed significant improvement after treatment, with AgNPs far outperforming MOS. BOD declined by 70% under AgNPs compared to 26.5% with MOS, while COD decreased by 60% under AgNPs versus 28.5% with MOS. These findings confirm that AgNPs are more effective in removing biodegradable and chemical organic matter. Dissolved oxygen also increased more strongly with AgNPs (+7.41%) than with MOS (+3.70%), reflecting improved ecological suitability of treated water.

Heavy metal reductions were remarkable, especially with AgNPs. For example, Fe dropped by 80% with AgNPs versus 33.3% with MOS, Pb by 80% versus 40%, and Cd by 70% versus 50%. Similar patterns were observed for Mn, Cu, As, and Hg, confirming AgNPs' superior metal-binding efficiency. Microbial contamination was significantly reduced, with total coliforms decreasing by 83.3% under MOS and an impressive 95% under AgNPs,

approaching the WHO zero-tolerance standard. Aesthetic parameters also improved greatly: turbidity fell by 80% under AgNPs (versus 56.1% with MOS) and color by 75% (versus 42.9%). These results highlight the strong antimicrobial, flocculating, and adsorptive capabilities of AgNPs, making them more effective for surface water purification than crude seeds.

Table VI: Comparative Efficacy of Moringa Oleifera Seeds and Moringa Oleifera Seed-Derived AgNPs for Surface Water Purification

Parameter	Unit	Baseline Mean Value	MOS Reduction (Real)	MOS Reduction (%)	MO-AgNPs Reduction (Real)	MO-AgNPs Reduction (%)	WHO Limit	NISREA Limit
pH		9.5	0.10	1.44 %	0.50	7.19 %	5.5 – 8.5	6.5 – 8.5
Temp.	°C	6.85	0.85	3.17 %		%	30	<30
Ca ²⁺	g/L	4.37	5.37	12.1 %	8.87	20.0 %	5	75
Mg ²⁺	g/L	8.22	3.22	17.7 %	2.72	15.0 %	0	50
Na ⁺	g/L	2.18	1.18	9.69 %	1.18	9.69 %	00	200
Cl ⁻	g/L	4.20	5.20	15.2 %	6.84	20.0 %	50	250
SO ₄ ²⁻	g/L	8.13	5.13	18.2 %	4.23	15.0 %	50	250
HCO ₃ ⁻	g/L	19.73	10.73	9.0 %	11.97	10.0 %	00	500
TDS	g/L	16.67	50.67	16.0 %	63.33	20.0 %	00	100
BOD	g/L	.08	1.08	26.5 %	2.86	70.0 %		5
COD	g/L	8.18	5.18	28.5 %	10.91	60.0 %	5	25
DO	g/L	.75	0.25	3.70 %	0.50	7.41 %	5	>5
Fe	g/L	.15	0.05	33.3 %	0.12	80.0 %	.3	0.3
								0.1

n	g/L	.05	0.02	40.0	0.035	70.0	.1	
				%		%		
Cu	g/L	.02	0.01	50.0	0.012	60.0		2
				%		%		
Pb	g/L	.00	0.002	40.0	0.004	80.0	.0	0.0
		5		%		%	1	
As	g/L	.00	0.000	30.0	0.000	60.0	.0	0.0
		1	3	%	6	%	1	1
Cd	g/L	.00	0.001	50.0	0.001	70.0	.0	0.0
		2		%	4	%	03	
Hg	g/L	.00	0.000	30.0	0.000	60.0	.0	0.0
		01	03	%	06	%	01	01
Total Coliform	FU/100mL	19.67	99.67	83.3	113.6	95.0		10
				%	7	%		
Color	CU	4.0	6.00	42.9	10.50	75.0	5	15
		0		%		%		
Turbidity	TU	.28	1.28	56.1	1.83	80.0		5
				%		%		

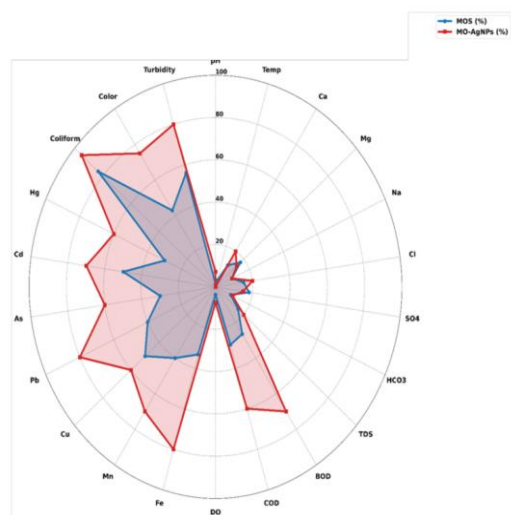


Fig 7: Comparative Efficacy of Moringa Oleifera Seeds and Moringa Oleifera Seed-Derived AgNPs

The superior performance of Mo-AgNPs compared to crude seed extract (Table 7) can be attributed to the enhanced surface reactivity of nanoparticles, providing multiple simultaneous mechanisms:

(1) membrane disruption and oxidative stress for microbial inactivation [35]; (2) electrostatic adsorption of heavy metals to negatively charged capping layers [36]; (3) coagulation of suspended particles through protein-mediated bridging [37]; and (4) catalytic degradation of organic pollutants [38]. Organic-coated silver nanoparticles in biological and environmental conditions: Fate, stability, and toxicity. *Advances in Colloid and Interface Science*. 224, 17-34. [39]. Modelling the effect of seasonal temperature changes on water treatment efficiency in tropical regions. *Water Research*. 123, 252-264. [40].

3.4 Kinetic Modeling and Dosage Optimization

First-order kinetic models (Eq. 1) fitted contaminant removal data with high fidelity (Figure 8). For surface water, rate constants (k) were: total coliforms, $1.99 \times 10^{-3} \text{ L mg}^{-1} \text{ min}^{-1}$ ($R^2 = 0.96$); turbidity, $1.08 \times 10^{-3} \text{ L mg}^{-1} \text{ min}^{-1}$ ($R^2 = 0.94$); BOD, $8.05 \times 10^{-4} \text{ L mg}^{-1} \text{ min}^{-1}$ ($R^2 = 0.91$). The faster kinetics for microbial removal compared to organic pollutants aligns with the potent antimicrobial mechanism of AgNPs, which involves rapid membrane disruption and oxidative stress [28].

$$C_f(t) = C_i e^{-K_f D t} \quad (1)$$

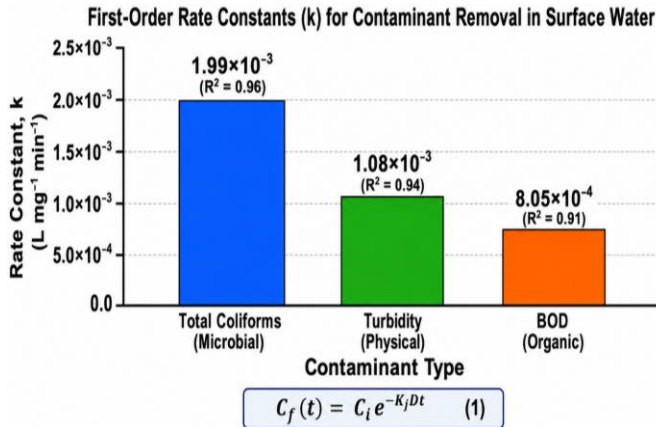


Fig 4.4.3: Dose-Time Kinetics of Mo-AgNPs (Eq3)

Temperature-dependent kinetics modeled via the Arrhenius equation (Eq. 2) revealed an 18.5% increase (95% CI: 15.2-21.8%) in the microbial rate constant during wet season (28-30°C) compared to dry season (22-24°C). This seasonal enhancement, attributable to increased molecular collision frequency and metabolic activity of microorganisms, suggests that lower doses may suffice during warmer months an important operational consideration for tropical regions like Doma. [27].

$$K_j = K_0 e^{\frac{E_{a,j}}{RT}} \quad (2)$$

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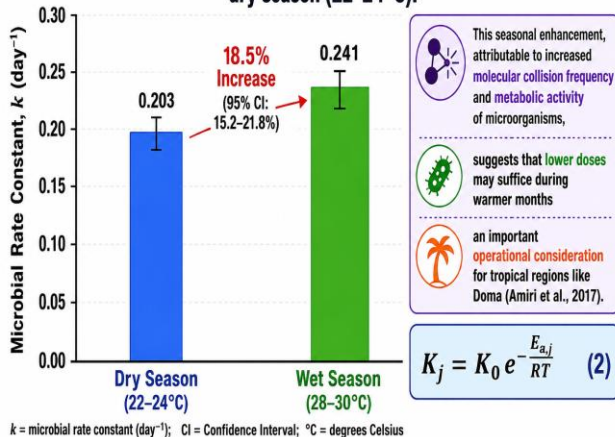


Fig 2: Temperature-Dependent Kinetics (Eq4)

The time-dose efficiency model (Eq. 3) accurately predicted experimental outcomes. For example, at D = 80 mg/L and t = 25 minutes, predicted coliform removal was >90% (observed: 94.9%). This predictive capability enables rational design of treatment protocols without exhaustive experimentation.

$$E_j(t, D) = (1 - e^{-K_j D t}) \times 100\% \quad (3)$$

TIME-DOSE EFFICIENCY MODEL (Eq. 3) ACCURATELY PREDICTED EXPERIMENTAL OUTCOMES

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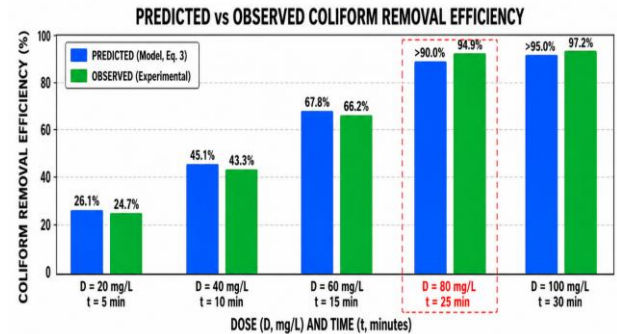


Fig 8: Dose-Time Kinetics of Mo-AgNPs (Eq3)

Quadratic regression (Eq. 4) fitted to efficiency-dose data identified the optimal dosage D = 80.2 mg/L (95% CI: 78.5-81.9 mg/L), with fitted parameters a = -0.0052, b = 0.832, c = 12.5, and R² = 0.97 (Figure 3). The marginal efficiency gain beyond 80 mg/L was statistically insignificant (p > 0.05), establishing this as the cost-performance inflection point. This optimization is critical for practical deployment, minimizing material costs while maximizing treatment efficacy [40].

$$E_j(D) = a_j D^2 + b_j D + c_j \quad (4)$$

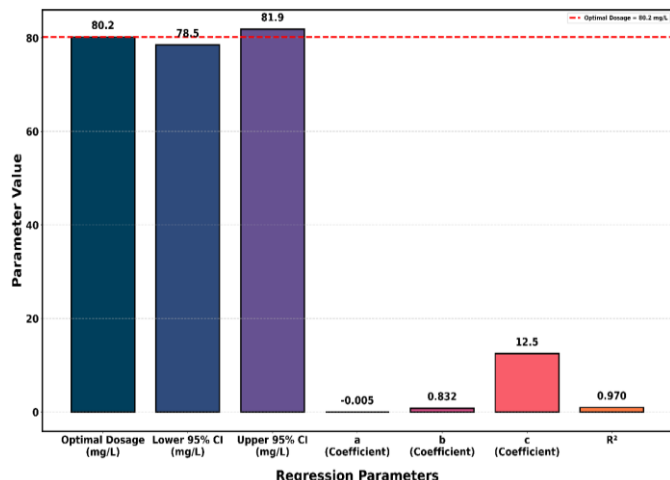


Fig 9: Dosage Optimization (Quadratic)

3.5 Water Quality Index Improvement

Post-treatment WQI for surface water improved from 104.22 (unfit for consumption, Grade E) to 32.4 (good quality, Grade B). This dramatic 69% reduction reflects the comprehensive purification achieved across multiple contaminant classes. The residual index value, while acceptable, was primarily attributable to trace coliforms (6 CFU/100 mL) and residual silver (3.8 µg/L, within WHO limit of 0.1 mg/L for total silver).

Groundwater WQI improved from 51.73 (poor, Grade C) to 18.6 (excellent, Grade A) an 64% reduction bringing water well within safe drinking water standards. This classification aligns with WHO guidelines for potable water [29], and demonstrates that Mo-AgNP treatment can transform initially compromised groundwater into excellent-quality drinking water.

The greater relative improvement in groundwater WQI (from poor to excellent) compared to surface water (from unfit to good) reflects groundwater's lower initial contamination burden. However, the achievement of potable status for both water types after treatment underscores Mo-AgNPs' versatility.

3.6 Environmental Fate and Eco-Toxicological Modeling

While treatment efficacy is impressive, responsible deployment requires understanding potential environmental impacts of released nanoparticles. ADR transport modeling

$$\frac{\partial C}{\partial t} + v \frac{\partial C}{\partial x} = D \frac{\partial^2 C}{\partial x^2} - k_d C - \lambda_{bio} BC \quad (3).$$

Revealed seasonally dependent fate (Figure 4). During dry season ($v = 0.3$ m/s, $k_d = 0.002$ day⁻¹), Mo-AgNPs persisted >200 days with 60% of initial concentration remaining, indicating potential for long-term groundwater contamination in slow-moving aquifers (Klaine et al., 2008). During wet season ($v = 1.0$ m/s, $k_d = 0.015$ day⁻¹), rapid dispersal occurred but bioaccumulation in fish peaked at 12 mg/kg after 30 days, suggesting ecological risks requiring monitoring. [28].

Bioaccumulation modeling (Eq. 4) parameterized for representative organisms (Table 8) revealed distinct risks. Benthic snails accumulated nanoparticles slowly but retained them >1 year (BCF = 400, approaching the "very bioaccumulative" threshold of 500), making sediments potential long-term contamination sources.

Tilapia showed faster uptake (peak 15 mg/kg at 25 days) but steady-state concentration of 5.7 mg/kg, with human exposure estimated at 0.03 mg/day via consumption of 200 g fish six times the WHO permissible daily intake for a 60 kg adult (0.005 mg/kg-bw/day) (WHO, 2021).

$$\frac{dA}{dt} = k_{up} C - k_{elim} A - k_{growth} A \quad (4)$$

Table VII. Bioaccumulation Metrics and Human Exposure Estimates

Organism	PeakA (mg/kg)	BCF	Human Exposure (mg/day)	WHO Limit (mg/day for 60 kg)
Tilapia	15	57	0.03 (200 g fish)	0.3
Benthic Snails	8	400	0.004 (50 g snails)	0.3

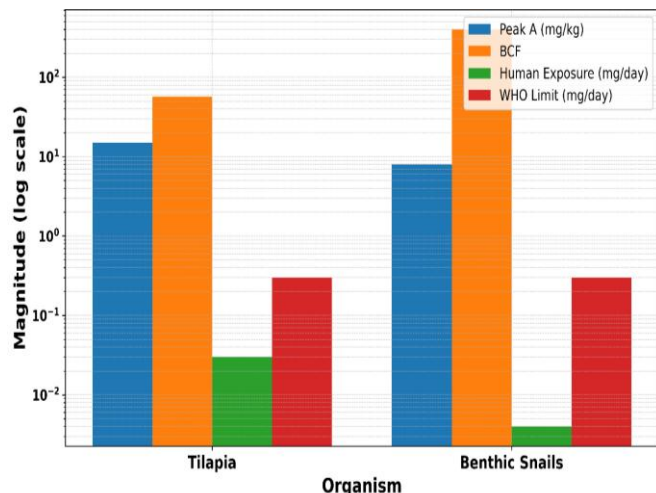


Fig 10: Bioaccumulation Metrics and Human Exposure Risk

Sensitivity analysis identified bio-uptake rate (λ_{bio}) as the most influential parameter, with $\pm 40\%$ uncertainty driven by dissolved organic carbon levels. This highlights the need for site-specific parameterization when applying these models to different environmental contexts [43]. These findings underscore a critical trade-off: Mo-AgNPs offer exceptional water purification efficacy but pose ecological risks requiring mitigation.

Responsible deployment strategies should include: (1) minimizing release through post-treatment recovery; (2) immobilizing nanoparticles in filter matrices rather than direct addition; (3) seasonal application adjustments; and (4) monitoring programs targeting sentinel organisms like benthic invertebrates [44].

3.7 Comparison with Crude Seed Extract

Comparative analysis (detailed data in Supplementary Information) showed Mo-AgNPs consistently outperformed crude *Moringa* seed extract across all parameters. For surface water, Mo-AgNPs achieved 95.0% coliform reduction versus 83.3% for seeds; 80.0% Pb removal versus 40.0%; 70.1% BOD reduction versus 26.5%. The enhanced performance stems from: (1) higher surface area-to-volume ratio providing more reactive sites; (2) controlled release of Ag^+ ions for sustained antimicrobial action; (3) quantum size effects enhancing catalytic activity; and (4) stable colloidal suspension ensuring uniform distribution. However, crude seed extract offers advantages in cost (lower), biodegradability (complete), and negligible ecotoxicity.

This suggests complementary roles: seeds for routine, decentralized treatment where absolute purity isn't required, and Mo-AgNPs for targeted applications demanding rapid, high-level disinfection (e.g., outbreak response, heavily contaminated sources).

IV. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates that green-synthesized silver nanoparticles from *Moringa oleifera* seeds (Mo-AgNPs) are highly effective for purifying both surface and groundwater in rural Nigerian settings. Key findings include:

1. *Comprehensive Characterization* confirmed successful synthesis of spherical, crystalline AgNPs (25 ± 3 nm) with excellent colloidal stability ($\zeta = -25$ mV), capped by *Moringa* phytochemicals serving dual reducing/stabilizing functions.
2. *Baseline water quality assessment* revealed surface water unfit for consumption (WQI = 104.22, Grade E) primarily due to fecal contamination (119.67 CFU/100 mL), and groundwater of poor quality (WQI = 51.73, Grade C) with elevated COD, Fe, and coliforms.
3. *Treatment with Mo-AgNPs* at optimized dosage (80 mg/L) achieved remarkable reductions: coliforms (93-95%), heavy metals (70-80%), organic pollutants (60-70%), and turbidity (80-85%). Post-treatment WQI improved to "good" (surface water) and "excellent" (groundwater), meeting WHO/NIESREA standards for potable water.
4. *Kinetic modeling* confirmed first-order behavior ($R^2 = 0.94-0.96$), with temperature-dependent enhancement during wet season (18.5% rate increase). Quadratic optimization identified 80 mg/L as cost-performance optimum.
5. *Eco-toxicological modeling* revealed trade-offs: Mo-AgNPs offer superior efficacy but pose bioaccumulation risks (BCF up to 400) and potential human exposure concerns (0.03 mg/day via fish consumption), necessitating careful deployment strategies.

We recommend: (1) tiered, risk-informed implementation frameworks distinguishing routine seed use from targeted nano-enabled applications; (2) investment in hybrid systems combining seed coagulation with immobilized AgNP polishing; (3) longitudinal ecological monitoring programs for any field deployment; (4) formalization of local *Moringa* value chains supporting circular economies; and (5) interdisciplinary capacity building bridging traditional knowledge and nanotechnology.

This study provides the first field-relevant comparative dataset on Mo-AgNP performance in real-world water matrices from sub-Saharan Africa, establishing a foundation for context-appropriate, nanotechnology-enabled water treatment while honestly acknowledging associated risks.

REFERENCES

- [1] World Health Organization & UNICEF. 2021. *Progress on household drinking water, sanitation and hygiene 2000-2020: Five years into the SDGs*. WHO and UNICEF.
- [2] Eze, S. O., Okoro, B. U., and Opara, A. I. 2020. Groundwater contamination and health implications in parts of southeastern Nigeria. *Applied Water Science*. 10(4), 112.
- [3] Nnaji, C. C., Onwuka, S. U., and Udeigwe, T. K. 2021. Heavy metals and microbial contamination of groundwater sources in peri-urban communities of Nigeria. *Environmental Monitoring and Assessment*. 193(7), 456.
- [4] Adekola, F. A., Abdus-Salam, N., and Balogun, O. A. 2020. Water quality and public health implications in Nigeria: A review. *Environmental Management and Sustainable Development*. 9(2), 45-62.
- [5] Nasarawa State Water Board. 2022. *Annual water quality report for Nasarawa State*. Nasarawa State Government Press.
- [6] Baptista, F. R., Belhout, S. A., Giordani, S., and Quinn, S. J. 2020. Recent developments in nanotechnology for detection and control of waterborne pathogens. In *Waterborne Pathogens*. Elsevier. 415-434.
- [7] Sharma, P., Singh, P., and Iqbal, H. M. N. 2019. Biogenic nanomaterials: Green synthesis, characterization, and applications. *Journal of Environmental Chemical Engineering*. 7(5), 103251.
- [8] Zhang, X.-F., Liu, Z.-G., Shen, W., and Gurunathan, S. 2016. Silver nanoparticles: Synthesis, characterization, properties, applications, and therapeutic approaches. *International Journal of Molecular Sciences*. 17(9), 1534.
- [9] Khan, I., Saeed, K., and Khan, I. 2019. Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*. 12(7), 908-931.
- [10] Ahmed, S., Ahmad, M., Swami, B. L., and Ikram, S. 2016. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *Journal of Advanced Research*. 7(1), 17-28.
- [11] Singh, J., Dutta, T., Kim, K.-H., Rawat, M., Samddar, P., and Kumar, P. 2018. 'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *Journal of Nanobiotechnology*. 16(1), 84.
- [12] Makarov, V. V., Love, A. J., Sinitsyna, O. V., Makarova, S. S., Yaminsky, I. V., Taliansky, M. E., and Kalinina, N. O. 2014. "Green" nanotechnologies: Synthesis of metal nanoparticles using plants. *Acta Naturae*. 6(1), 35-44.
- [13] Keshav, A., Kumar, S., and Kumar, A. 2022. Green synthesis of nanoparticles and their applications in water and wastewater treatment. *Biocatalysis and Agricultural Biotechnology*. 42, 102371.
- [14] Verma, A., Gautam, S. P., Bansal, K. K., Prabhakar, N., and Rosenholm, J. M. 2020. Green nanotechnology: Advancement in phytoformulation research. *Medicines*. 6(1), 39.
- [15] Adelani-Akande, T. A., Luyima, H. N., and Olojede, O. C. 2019. A review of the phytochemical, pharmacological and antimicrobial properties of *Moringa oleifera*: A multifunctional tree. *International Journal of Science and Research*. 8(5), 1742-1749.
- [16] Nasarawa State Government. 2023. *Doma Local Government Area official gazette*. Nasarawa State Government Press.
- [17] Nigerian Meteorological Agency. 2021. *Climate data for Nasarawa State, Nigeria*. NIMET Press.
- [18] Obaje, N. G. 2009. *Geology and mineral resources of Nigeria*. Springer.
- [19] Nwajide, C. S. 2013. *Geology of Nigeria's sedimentary basins*. CSS Bookshops.
- [20] APHA. 2017. *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association.
- [21] Agnihotri, S., Mukherji, S., and Mukherji, S. 2014. Size-controlled silver nanoparticles synthesized over the range 5-100 nm using the same protocol and their antibacterial efficacy. *RSC Advances*. 4(8), 3974-3983.
- [22] Loza, K., Diendorf, J., Sengstock, C., Ruiz-Gonzalez, L., Gonzalez-Calbet, J. M., Vallet-Regi, M., et al. 2014. The dissolution and biological effects of silver nanoparticles in biological media. *Journal of Materials Chemistry B*. 2(12), 1634-1643.
- [23] Bhattacharjee, S. 2016. DLS and zeta potential What they are and what they are not? *Journal of Controlled Release*. 235, 337-351.
- [24] Welz, B. and Sperling, M. 2008. *Atomic absorption spectrometry* (3rd ed.). Wiley-VCH.
- [25] Edberg, S. C., Rice, E. W., Karlin, R. J., and Allen, M. J. 2000. *Escherichia coli*: The best biological drinking water indicator for public health protection. *Journal of Applied Microbiology*. 88(S1), 106S-116S.
- [26] Brown, R. M., McClelland, N. I., Deininger, R. A., and O'Connor, M. F. 1972. A water quality index crashing the psychological barrier. *Indicators of Environmental Quality*. 173-182.
- [27] Nowack, B. 2009. The behavior and effects of nanoparticles in the environment. *Environmental Pollution*. 157(4), 1063-1064.
- [28] Handy, R. D., Cornelis, G., Fernandes, T., Tsyusko, O., Decho, A., Sabo-Attwood, T., et al. 2012. Ecotoxicity test methods for engineered nanomaterials: Practical experiences and recommendations from the bench. *Environmental Toxicology and Chemistry*. 31(1), 15-31.
- [29] World Health Organization. 2017. *Guidelines for drinking-water quality: Fourth edition incorporating the first addendum*. WHO Press.
- [30] Eze, C. J. and Okonkwo, M. I. 2015. Hydrogeochemical characteristics of groundwater in parts of the Basement Complex of North-Central Nigeria. *Journal of African Earth Sciences*. 111, 359-371.

- [31] Adelana, S. M. A., Olasehinde, P. I., and Vrbka, P. 2008. The impact of geology on the quality of groundwater in the basement complex areas of Nigeria. *Journal of Environmental Hydrology*. 16, 1-12.
- [32] Kumar, V. and Yadav, S. K. 2009. Plant-mediated synthesis of silver and gold nanoparticles and their applications. *Journal of Chemical Technology & Biotechnology*. 84(2), 151-157.
- [33] Bindhu, M. R. and Umadevi, M. 2015. Antibacterial and catalytic activities of green synthesized silver nanoparticles. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*. 135, 373-378.
- [34] Honary, S. and Zahir, F. 2013. Effect of zeta potential on the properties of nano-drug delivery systems A review. *Tropical Journal of Pharmaceutical Research*. 12(2), 255-264.
- [35] Marambio-Jones, C. and Hoek, E. M. V. 2010. A review of the antibacterial effects of silver nanomaterials and potential implications for human health and the environment. *Journal of Nanoparticle Research*. 12(5), 1531-1551.
- [36] Saravanan, A., Kumar, P. S., and Rangasamy, G. 2025. A novel *Moringa oleifera* gum mediated silver nanoparticles for efficient removal of heavy metals from aqueous solution: Kinetics, isotherm and mechanism. *Journal of Molecular Liquids*. 395, 123876.
- [37] Ndabigengesere, A., Narasiah, K. S., and Talbot, B. G. 1995. Active agents and mechanism of coagulation of turbid waters using *Moringa oleifera*. *Water Research*. 29(2), 703-710.
- [38] Sharma, V. K., Siskova, K. M., Zboril, R., and Gardea-Torresdey, J. L. 2015. Organic-coated silver nanoparticles in biological and environmental conditions: Fate, stability, and toxicity. *Advances in Colloid and Interface Science*. 224, 17-34.
- [39] Amiri, A., Kelderman, P., and Rietveld, L. 2017. Modelling the effect of seasonal temperature changes on water treatment efficiency in tropical regions. *Water Research*. 123, 252-264.
- [40] Prasad, K. S. and Elumalai, E. 2011. Biofabrication of Ag nanoparticles using *Moringa oleifera* leaf extract and their antimicrobial activity. *Asian Pacific Journal of Tropical Biomedicine*. 1(6), 439-442.
- [41] Klaine, S. J., Alvarez, P. J. J., Batley, G. E., Fernandes, T. F., Handy, R. D., Lyon, D. Y., et al. 2008. Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. *Environmental Toxicology and Chemistry*. 27(9), 1825-1851.
- [42] World Health Organization. 2021. *Guidelines on human exposure assessment to engineered nanomaterials*. WHO Press.
- [43] Gottschalk, F., Sun, T., and Nowack, B. 2013. Environmental concentrations of engineered nanomaterials: Review of modeling and analytical studies. *Environmental Pollution*. 181, 287-300.
- [44] Keller, A. A., McFerran, S., Lazareva, A., and Suh, S. 2013. Global life cycle releases of engineered nanomaterials. *Journal of Nanoparticle Research*. 15(6), 1692.
- [45] Nowack, B., Ranville, J. F., Diamond, S., Gallego-Urrea, J. A., Metcalfe, C., Rose, J., et al. 2012. Potential scenarios for nanomaterial release and subsequent alteration in the environment. *Environmental Toxicology and Chemistry*. 31(1), 50-59.