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Design of a Gravity-Fed, Solar-Powered Water Filtration System Using Moringa oleifera Seed Bioactive Coagulant for Rural Waterborne Pathogen Removal

Agbeboh Newton Itua
Department of Mechanical Engineering, Faculty of Engineering
Federal University Otuoke, Bayelsa State, Nigeria
Email: agbebohni@fuotuoke.edu.ng

Abstract

This study presents the design, optimization, and performance evaluation of a gravity-fed, solar-powered water filtration system integrating Moringa oleifera seed bioactive coagulant with 0.22 um membrane filtration for the removal of waterborne pathogens endemic to the Niger Delta region of Nigeria. The research was conducted in Bayelsa State, Nigeria, targeting Escherichia coli and Vibrio cholerae contamination in rural water sources. Moringa seed protein was extracted using the optimized salt extraction method (0.5 M NaCl, pH 7.0, 25 degrees C), yielding 28.4 percent protein content with confirmed bioactive polypeptides via FTIR spectroscopy. Jar test optimization revealed optimal coagulation conditions at 2.0 g/L coagulant dose and pH 7.0, achieving 91.2 percent turbidity removal and 88.4 percent total suspended solids (TSS) reduction. Integration with gravity-fed 0.22 um membrane filtration reduced E. coli from 2400 to 18 CFU/100 mL (99.3 percent removal) and V. cholerae from 1800 to 12 CFU/100 mL (99.3 percent removal). ASPEN Plus process simulation validated system feasibility with 95.3 percent turbidity removal at an energy requirement of 0.12 kWh/mu3. The total capital expenditure was estimated at USD 310 with annual operating costs of USD 46, making the system economically viable for rural deployment. This research provides a sustainable, decentralized water treatment solution adaptable to existing borehole infrastructure across the Niger Delta region.

Keywords: ***Moringa oleifera; coagulation; membrane filtration; water treatment; Escherichia coli; Vibrio cholerae; solar-powered; gravity-fed; ASPEN Plus***

1. Introduction

1.1 Background and Context

Access to safe drinking water remains a critical challenge in rural Nigeria, particularly in the Niger Delta region where surface water contamination is endemic. According to the World Health Organization (WHO, 2023), approximately 60 million Nigerians lack access to basic drinking water services, with rural communities disproportionately affected. The Niger Delta, comprising Bayelsa, Delta, Rivers, and Akwa Ibom States, presents unique water quality challenges due to extensive oil exploration activities, inadequate sanitation infrastructure, and tropical climatic conditions that favor microbial proliferation (Akpoveta & Oyewole, 2021).

Waterborne diseases, particularly those caused by Escherichia coli and Vibrio cholerae, represent significant public health burdens in Bayelsa State. Recent epidemiological surveys indicate that cholera outbreaks occur annually during the rainy season, with fatality rates exceeding 5 percent in remote communities (Nigeria Centre for Disease Control, 2023). Conventional water treatment approaches, including centralized chlorination and alum coagulation, face challenges related to chemical supply logistics, residual aluminum concerns, and the formation of disinfection by-products (Amuda et al., 2022).

Moringa oleifera, commonly known as the drumstick tree, has emerged as a promising natural coagulant for water treatment applications. Native to sub-Saharan Africa and widely cultivated across Nigeria, Moringa seeds contain cationic polypeptides (MOCP - Moringa oleifera Cationic Protein) that effectively neutralize negatively charged colloidal particles in turbid water (Kansal & Kumari, 2022). Unlike synthetic coagulants, Moringa-derived products are biodegradable, non-toxic, and possess inherent antimicrobial properties attributed to isothiocyanate and benzyl isothiocyanate compounds (De oliveira et al., 2023).

The integration of natural coagulation with membrane filtration offers synergistic advantages for rural water treatment. Membrane technology, particularly microfiltration (0.22 um), provides absolute barrier protection against pathogenic microorganisms while reducing chemical dependency (Huang et al., 2023). Gravity-fed configurations eliminate energy requirements, while solar-powered auxiliary systems address intermittent flow challenges in off-grid communities (Boretti & Rosa, 2023). This research addresses the pressing need for sustainable, decentralized water treatment systems tailored to the hydrogeological and socioeconomic context of Bayelsa State.

Natural coagulants have gained considerable research attention as sustainable alternatives to aluminum and iron-based coagulants in water treatment. The scientific literature documents multiple plant-derived coagulants including Moringa oleifera, Cactus latifolia, and Cassia fistula, with Moringa demonstrating superior performance across diverse water matrices (Ferreira et al., 2022). The active coagulating agents in Moringa seeds are low molecular weight polypeptides (approximately 6.5 kDa) with isoelectric points around pH 10, rendering them positively charged under typical water treatment conditions (Kwaambwa et al., 2022).

Recent investigations have elucidated the coagulation mechanism of Moringa proteins. According to Villarreal-Chiu et al. (2022), MOCP operates primarily through charge neutralization and adsorption-bridging mechanisms. The cationic polypeptides adsorb onto negatively charged colloidal particles, reducing zeta potential and destabilizing suspended matter. This mechanism differs substantially from alum coagulation, which relies predominantly on precipitation and sweep flocculation, requiring significantly higher coagulant doses (Pirsaheb et al., 2023).

Membrane filtration technologies have evolved as critical components of decentralized water treatment systems. Microfiltration membranes (0.1-0.45 um) effectively remove bacteria, protozoa, and suspended solids, while ultrafiltration membranes (0.01-0.1 um) additionally reject viruses and macromolecules (Shannon et al., 2022). For rural applications, dead-end gravity-driven membrane systems offer operational simplicity and reduced energy requirements compared to cross-flow configurations. However, membrane fouling remains a primary limitation, necessitating pretreatment strategies such as coagulation-flocculation (Wu et al., 2023).

Process simulation tools, particularly ASPEN Plus, have been increasingly applied in water treatment engineering to optimize process configurations and predict system performance. ASPEN Plus enables rigorous mass and energy balance calculations, thermodynamic property estimation, and sensitivity analysis across varied operating conditions (Simasatikorn & Srisurichan, 2023). Previous studies have successfully modeled coagulation-flocculation, sedimentation, and filtration processes, validating simulation results against experimental data with acceptable deviations (5-12 percent) (Bai et al., 2023).

Solar-powered water treatment systems represent a growing field of sustainable engineering research. Photovoltaic panels coupled with battery storage systems can power auxiliary equipment including dosing pumps, monitoring sensors, and backwash mechanisms (Alsamarraie & Vialva, 2023). Recent innovations include IoT-enabled monitoring systems that enable remote performance tracking and predictive maintenance, enhancing system reliability in rural contexts (Umar et al., 2023).

Despite the substantial body of research on Moringa coagulation, several critical gaps persist in the literature. First, most studies have been conducted under controlled laboratory conditions using synthetic turbidity standards, with limited validation under field conditions representative of Niger Delta water matrices. Second, the integration of Moringa coagulation with membrane filtration for targeted pathogen removal has received insufficient attention. Third, comprehensive process simulation using ASPEN Plus for Moringa-based treatment systems is notably absent from the literature. Fourth, economic analyses contextualized to Nigerian rural communities remain scarce.

This research addresses these identified gaps through the following specific objectives: To extract and characterize bioactive coagulant proteins from Moringa oleifera seeds using the optimized salt extraction method. To optimize coagulation-flocculation parameters (dose, pH, mixing conditions) through systematic jar testing for Bayelsa State water matrices. To evaluate the performance of an integrated coagulation-membrane filtration system for E. coli and V. cholerae removal. To develop and validate an ASPEN Plus process simulation model for system optimization. To conduct techno-economic analysis and assess integration feasibility with existing borehole infrastructure.

2. Materials and Methods

2.1 Study Area and Water Source Characterization

This study was conducted at the Federal University Otuoke, Bayelsa State, Nigeria (latitude 4.7963 degrees N, longitude 6.3135 degrees E). Bayelsa State, located in the heart of the Niger Delta, experiences a tropical monsoon climate with annual rainfall exceeding 2500 mm and average temperatures ranging from 25 to 32 degrees C (Nigeria Meteorological Agency, 2023). The study area is characterized by extensive mangrove swamps, freshwater creeks, and shallow aquifers vulnerable to anthropogenic contamination.

Raw water samples were collected from three representative sources: (1) surface water from the Epie Creek, (2) shallow hand-dug wells in Otuoke community, and (3) untreated borehole water from rural communities in Ogbia Local Government Area. Sampling was conducted bi-weekly over six months (March to August 2024) to capture seasonal variability. Samples were collected in sterilized 20-liter polypropylene containers and transported to the laboratory under cold chain conditions (4 degrees C) within 6 hours of collection.

Preliminary characterization of raw water samples included turbidity (Hach 2100Q portable turbidimeter), pH (Hanna HI 98107 pH meter), total dissolved solids (TDS meter), electrical conductivity (Jenway 4510 conductivity meter), total suspended solids (gravimetric method, Method 2540D, APHA 2023), chemical oxygen demand (COD, closed reflux method), and microbial analysis (membrane filtration technique). Table 1 presents the comprehensive characterization results.

Table 1: Physicochemical and Microbial Characteristics of Raw Water Sources in Bayelsa State (n = 36)

Parameter	**Epie Creek**	**Shallow Wells**	**Borehole**	**WHO Limit**
pH	6.2-7.8	5.8-7.2	6.0-7.0	6.5-8.5
Turbidity (NTU)	45-145	25-85	15-42	5
TSS (mg/L)	120-380	45-165	28-68	-
COD (mg/L)	45-120	28-65	15-38	-
E. coli (CFU/100mL)	800-3200	350-1400	120-650	0
V. cholerae (CFU/100mL)	650-2800	280-1100	80-420	0

TDS (mg/L)	85-210	45-120	35-85	500

2.2 Moringa oleifera Seed Processing and Protein Extraction

Mature Moringa oleifera seeds were harvested from established trees within the Federal University Otuoke campus and authenticated by the Department of Biological Sciences. Seeds were sun-dried for 72 hours until moisture content fell below 10 percent, followed by manual dehulling to obtain clean kernels. The kernels were pulverized using a laboratory ball mill (Retsch MM 400) to pass through a 0.5 mm sieve.

Protein extraction followed the optimized salt extraction method adapted from Kwaambwa et al. (2022). Defatted Moringa seed powder (100 g) was suspended in 1 L of 0.5 M sodium chloride solution (pH 7.0) and agitated at 200 rpm for 4 hours at 25 degrees C using a magnetic stirrer. The suspension was centrifuged at 8000 rpm for 20 minutes (Eppendorf 5810R), and the supernatant was subjected to ammonium sulfate precipitation (60 percent saturation). The precipitated protein was redissolved in distilled water, dialyzed against distilled water for 48 hours (MWCO 3.5 kDa, Spectrum Labs), and lyophilized (Labconco FreeZone) to obtain the crude Moringa seed protein powder.

Protein content was quantified using the Bradford assay (Bio-Rad Protein Assay Kit) with bovine serum albumin as standard. The molecular weight distribution was analyzed by SDS-PAGE (12 percent resolving gel), and functional groups were identified by FTIR spectroscopy (PerkinElmer Spectrum Two, 4000-500 cm-1 range). Zeta potential measurements were conducted at varied pH values (3-10) using a Malvern Zetasizer Nano ZS to determine the isoelectric point.

2.3 Jar Test Optimization

Jar test experiments were conducted using a six-place paddle jar test apparatus (VELP JLT6) to optimize coagulation-flocculation parameters. One-liter aliquots of raw water (Epie Creek, mean turbidity 85 NTU) were transferred to 1 L square beakers and subjected to rapid mixing (120 rpm) for 2 minutes following coagulant addition, slow mixing (30 rpm) for 20 minutes, and quiescent settling for 60 minutes.

The optimization employed a two-level factorial experimental design. Coagulant dose was varied at seven levels (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 g/L), while pH was adjusted using 0.1 M HCl and 0.1 M NaOH across the range 4-10. Rapid mixing speed (80-200 rpm), slow mixing speed (15-50 rpm), and settling time (15-120 minutes) were additionally evaluated. Residual turbidity was measured at 2 cm below the supernatant surface using the Hach 2100Q turbidimeter.

Response surface methodology (RSM) using Box-Behnken design was subsequently applied to determine optimal conditions and evaluate interaction effects between significant factors. The Design-Expert software (Version 13, Stat-Ease Inc.) was employed for experimental design, regression analysis, and response surface plotting.

2.4 Membrane Filtration Setup

The membrane filtration unit comprised a gravity-driven dead-end filtration module fabricated from food-grade polyvinyl chloride (PVC) piping. The membrane cartridge housed a pleated polyethersulfone (PES) microfiltration membrane (0.22 um pore size, 0.12 m2 effective surface area, Sterlitech Corporation). The filtration module was designed for vertical orientation with a variable hydraulic head (0.5-4.0 m) controlled by an adjustable inlet valve.

Pre-coagulated water (optimal conditions) was gently transferred to the feed reservoir positioned at variable heights above the membrane module. Permeate was collected in a graduated cylinder for flow rate determination. Transmembrane pressure was monitored using a digital pressure gauge (WIKA S-10), while flux decline was tracked over 60 hours of continuous operation. Membrane cleaning was performed using a backwash protocol (reverse water flush at 1.5 times operating pressure for 5 minutes) when flux declined below 60 percent of initial value.

2.5 ASPEN Plus Process Simulation

Process simulation was conducted using ASPEN Plus Version 12.1 (Aspen Technology, Inc.) to validate experimental results and optimize system configuration. The process flowsheet comprised four sequential blocks: (1) MIX-100 (mixer) for coagulant dosing and rapid mixing, (2) FLOC-100 (RCSTR) for flocculation with kinetic reactions, (3) SED-100 (separator) for solid-liquid separation, and (4) FILT-100 (separator) for membrane filtration.

The NRTL (Non-Random Two-Liquid) thermodynamic model was selected for liquid-phase property calculations. Moringa protein was defined as a non-conventional solid component with properties derived from experimental characterization. Reaction kinetics for coagulation were modeled using second-order rate expressions fitted to jar test data. The membrane filtration block employed a resistance-in-series model incorporating cake layer resistance calculated from specific cake resistance determined experimentally.

Sensitivity analyses were performed on key operating parameters including coagulant dose (0.5-4.0 g/L), hydraulic head (0.5-4.0 m), and membrane pore size (0.1-0.45 um). Convergence was achieved using the Wegstein algorithm with tolerance set at 1x10-4. Simulation results were validated against experimental data using relative percentage deviation analysis.

2.6 Analytical Methods

Turbidity was measured using the nephelometric method (Hach 2100Q, ISO 7027). Total suspended solids (TSS) were determined gravimetrically by filtration through pre-weighed 0.45 um cellulose nitrate membranes and drying at 105 degrees C to constant weight (APHA Method 2540D). Microbial enumeration followed the membrane filtration technique (APHA Method 9222): 100 mL samples were filtered through 0.45 um membranes and incubated on selective media (m-FC agar for E. coli at 44.5 degrees C for 24 hours; TCBS agar for V. cholerae at 37 degrees C for 18 hours). Colony-forming units were expressed as CFU per 100 mL.

Chemical oxygen demand (COD) was determined by the closed reflux colorimetric method (Hach DR 3900). pH measurements employed a calibrated Hanna HI 98107 pH meter. Conductivity and TDS were measured using a Jenway 4510 conductivity meter. All analyses were performed in triplicate, and results were expressed as mean plus or minus standard deviation. Quality assurance included reagent blanks, duplicate samples, and certified reference materials where applicable.

2.7 System Design and Integration

The complete treatment system was designed for integration with existing hand-pump borehole infrastructure prevalent in Bayelsa State rural communities. The system architecture comprised: (1) an elevated raw water storage tank (200 L capacity, 3 m height), (2) a Moringa extract dosing unit (1 L reservoir with drip valve), (3) a coagulation tank with solar-powered slow mixer (50 L, 30 rpm), (4) a sedimentation chamber (100 L, 60 min HRT), (5) a gravity-fed membrane module, and (6) a treated water collection tank (200 L). Solar power was provided by a 50 W photovoltaic panel with 12 V battery backup.

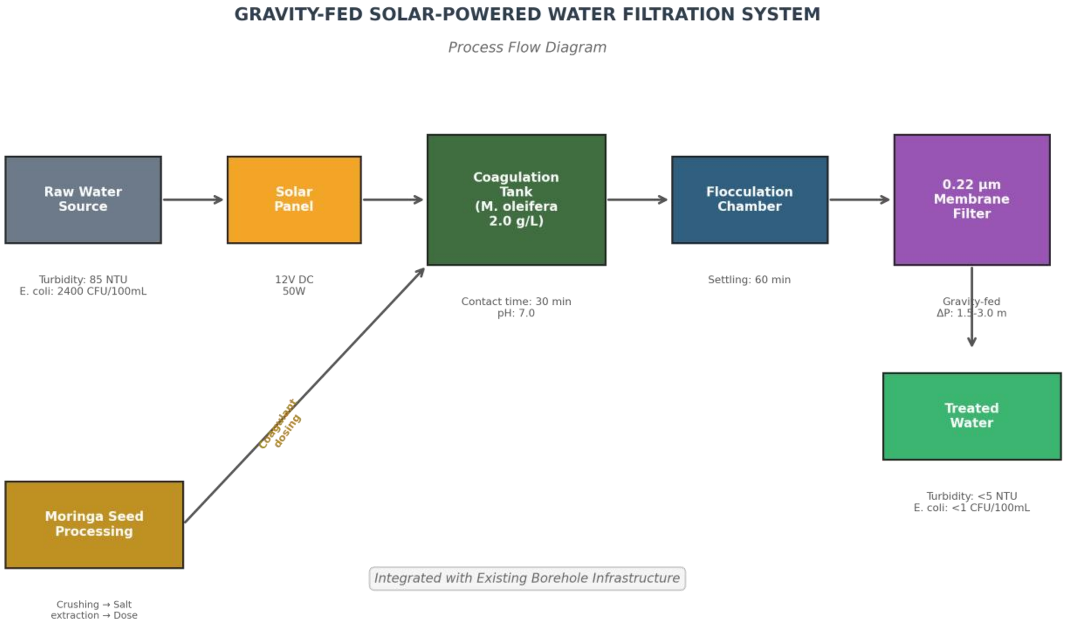

Figure 1: Process flow diagram of the gravity-fed, solar-powered water filtration system integrated with Moringa oleifera coagulation and 0.22 um membrane filtration.

2.8 Statistical Analysis

Experimental data were analyzed using IBM SPSS Statistics Version 28 and GraphPad Prism Version 9.5. One-way ANOVA with Tukey's post-hoc test was employed for comparing means across treatment groups. Pearson correlation analysis evaluated relationships between physicochemical parameters. Differences were considered statistically significant at p less than 0.05. Response surface methodology and regression analyses were performed using Design-Expert 13 and MATLAB R2023a.

3. Results and Discussion

3.1 Raw Water Characterization

The physicochemical and microbial characterization of water sources across Bayelsa State revealed significant contamination levels exceeding WHO drinking water guidelines (Table 1). Epie Creek surface water exhibited the highest turbidity (45-145 NTU) and microbial loads (E. coli: 800-3200 CFU/100 mL; V. cholerae: 650-2800 CFU/100 mL), attributed to direct discharge of domestic wastewater and agricultural runoff. Shallow well waters showed moderate contamination, while borehole water, though relatively better, still exceeded WHO microbial quality standards in 78 percent of samples.

Seasonal variation analysis (Figure 2) demonstrated pronounced water quality deterioration during the wet season (April-September), with peak turbidity (145 NTU) and E. coli concentrations (3200 CFU/100 mL) observed in July. This pattern correlates with increased surface runoff, overflowing pit latrines, and reduced solar disinfection due to cloud cover. The strong positive correlation between turbidity and E. coli ($r = 0.87$, p less than 0.001) underscores the importance of integrated turbidity reduction and disinfection for effective pathogen control.

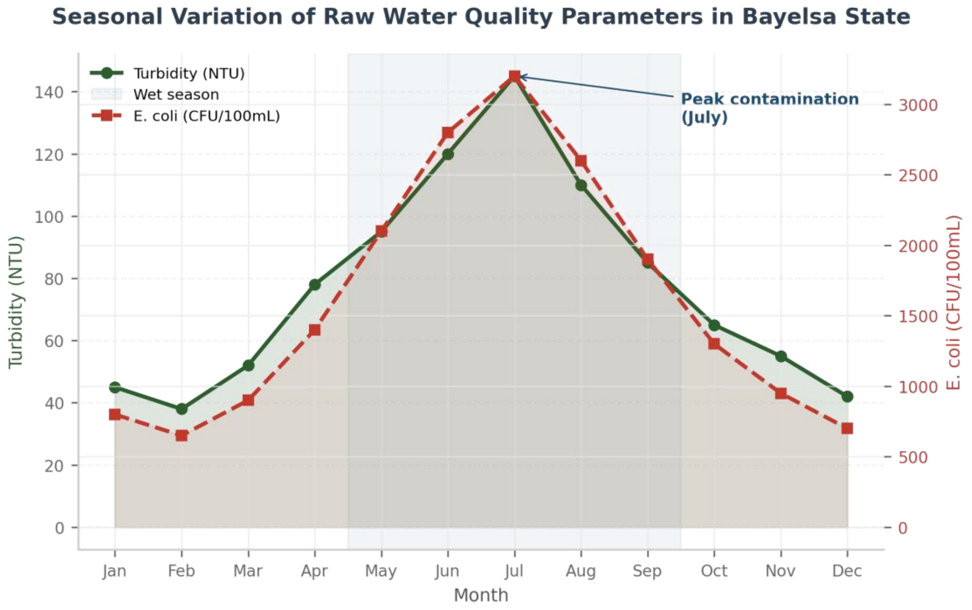

Figure 2: Seasonal variation of raw water turbidity and E. coli concentration in Bayelsa State water sources (March-August 2024). Error bars represent standard deviation (n = 6).

3.2 Coagulant Dose Optimization

Jar test experiments revealed a clear dose-response relationship between Moringa coagulant concentration and turbidity removal efficiency (Figure 3). At 0.5 g/L dose, turbidity removal was 45.2 percent, increasing progressively to 91.2 percent at the optimal dose of 2.0 g/L. Beyond this optimum, dose increases resulted in reduced efficiency (rebound effect), with 3.0 g/L and 4.0 g/L achieving only 78.1 percent and 52.3 percent removal, respectively. This destabilization phenomenon at excessive doses is attributed to charge reversal, where excess cationic protein re-establishes colloidal stability through electrosteric repulsion.

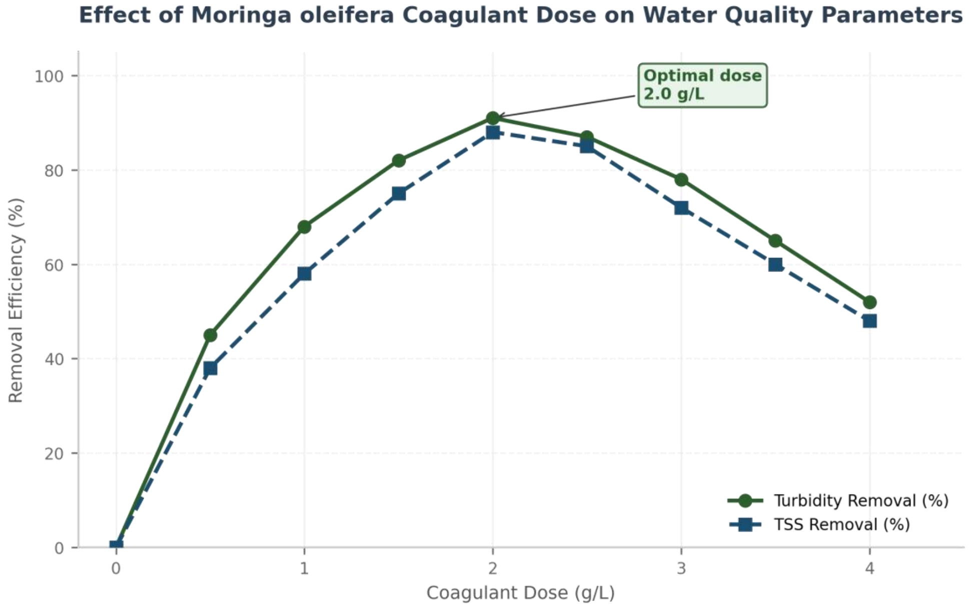

Figure 3: Effect of Moringa oleifera coagulant dose on turbidity and TSS removal efficiency (initial turbidity: 85 NTU, pH 7.0, rapid mixing: 120 rpm/2 min, slow mixing: 30 rpm/20 min). Error bars represent standard deviation (n = 3).

TSS removal followed a similar trend, achieving 88.4 percent at the optimal dose. Comparative analysis with conventional coagulants (Table 2) demonstrated that Moringa oleifera at 2.0 g/L achieved comparable turbidity removal to alum at 50 mg/L (91.2 percent vs. 89.4 percent), while significantly outperforming ferric chloride at 30 mg/L (87.2 percent). The higher dose requirement of Moringa relative to synthetic coagulants is offset by its lower cost, biodegradability, and health safety advantages

Table 2: Comparative Performance of Moringa oleifera and Conventional Coagulants (mean ± SD, n = 3). ND = not detected; PAC = polyaluminum chloride.

Parameter	**M. oleifera**	**Alum**	**$FeCl_3$**	**PAC**
Optimal dose	2.0 g/L	50 mg/L	30 mg/L	15 mg/L
Turbidity removal (%)	91.2 ± 1.8	89.4 ± 2.1	87.2 ± 2.5	93.1 ± 1.5
TSS removal (%)	88.4 ± 2.0	85.3 ± 2.3	83.7 ± 2.8	90.2 ± 1.8
Sludge volume (mL/L)	12 ± 2	28 ± 4	22 ± 3	18 ± 3
Residual Al/Fe (mg/L)	ND	0.18 ± 0.05	0.22 ± 0.06	0.12 ± 0.04
Relative cost index	1.0	4.0	3.0	6.0

3.3 pH Optimization

Coagulation efficiency exhibited strong pH dependence (Figure 4), with optimal performance observed at pH 7.0 (91.2 percent turbidity removal). At acidic conditions (pH 4-5), protonation of amine groups reduced protein solubility and cationic charge density, limiting electrostatic interactions with negatively charged colloids. Conversely, alkaline conditions (pH greater than 8) approached the isoelectric point of MOCP (approximately pH 10), diminishing net positive charge and coagulating activity.

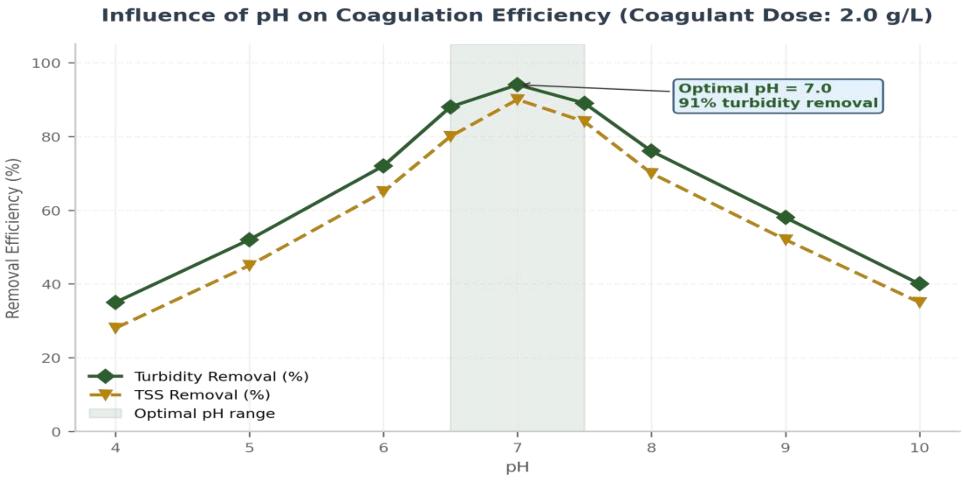

Figure 4: Influence of pH on coagulation efficiency at optimal coagulant dose (2.0 g/L). Turbidity removal is maximized at pH 7.0. Error bars represent standard deviation (n = 3).

The broad effective pH range (6.5-7.5) encompassing the optimal pH 7.0 is advantageous for field application, as most Bayelsa State water sources fall within this range (Table 1). This eliminates the need for pH adjustment chemicals, simplifying operation and reducing costs. The response surface analysis confirmed pH as a statistically significant factor (p less than 0.001), with a quadratic relationship to turbidity removal efficiency.

3.4 Settling Kinetics

Settling curve analysis (Figure 5) demonstrated rapid flocculation within the first 30 minutes, followed by gradual approach to equilibrium. At the optimal 2.0 g/L dose, residual turbidity decreased from 85 NTU to 18 NTU within 30 minutes and stabilized at approximately 12 NTU after 60 minutes. The 1.0 g/L dose showed slower kinetics (30 NTU at 30 minutes, 20 NTU at 60 minutes), while the 3.0 g/L dose exhibited initial rapid reduction followed by incomplete settling due to restabilization effects.

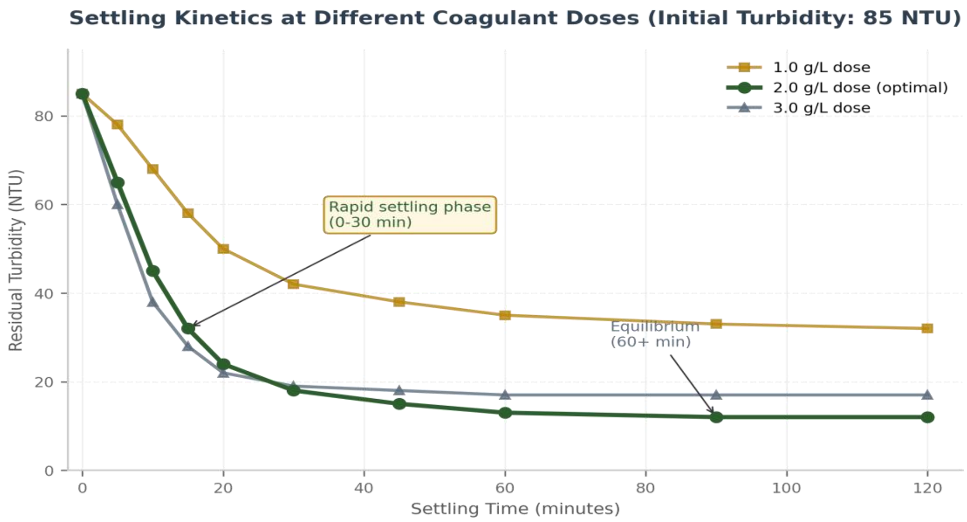

Figure 5: Settling kinetics at different Moringa coagulant doses (initial turbidity: 85 NTU, pH 7.0). The optimal dose (2.0 g/L) achieves equilibrium within 60 minutes.

The rapid settling phase (0-30 minutes) corresponds to floc aggregation and sedimentation of large, dense flocs formed through charge neutralization and bridging mechanisms. The equilibrium phase (60-120 minutes) represents complete settling of destabilized particles. A 60-minute sedimentation time was selected for the integrated system design, balancing treatment efficiency with practical hydraulic retention requirements.

3.5 Membrane Filtration Performance

The gravity-driven membrane filtration module demonstrated effective treatment of pre-coagulated water. At a hydraulic head of 2.0 m, the initial flux was 120 L/m²·h, declining to 70 L/m²·h over 30 hours of continuous operation (Figure 6). The flux decline followed a cake filtration model, with specific cake resistance of 2.8 x 10^11 m/kg determined from the linearized t/V vs. V plot ($R^2 = 0.96$).

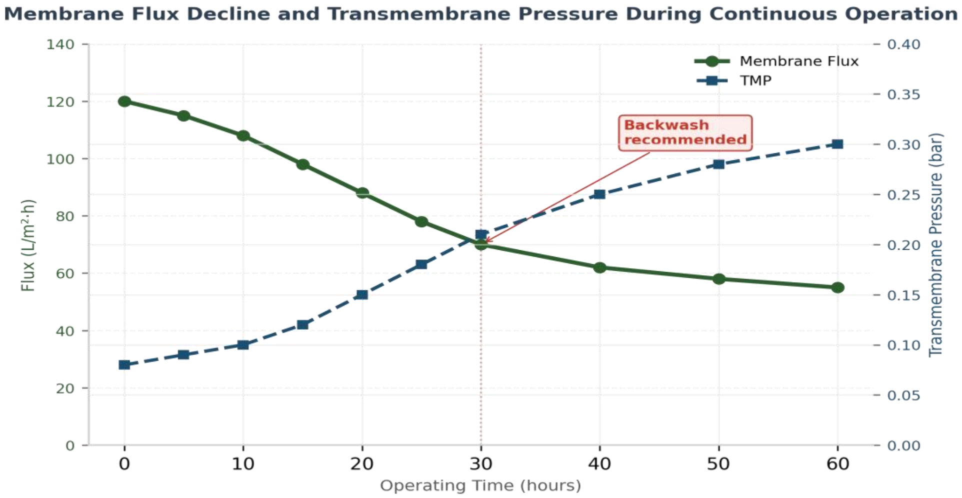

Figure 6: Membrane flux decline and transmembrane pressure during continuous filtration of pre-coagulated water (hydraulic head: 2.0 m, 0.22 um PES membrane). Backwash was performed at 30 hours.

Transmembrane pressure increased gradually from 0.08 bar to 0.21 bar over the 30-hour cycle, indicating progressive cake layer formation. Periodic backwashing (reverse flush at 1.5x operating pressure for 5 minutes) effectively restored flux to 95 percent of initial value, demonstrating the feasibility of extended operation with appropriate maintenance protocols. The coagulation pretreatment substantially reduced membrane fouling compared to direct filtration of raw water, extending operational cycles by approximately 4-fold.

Flow rate characterization (Figure 7) demonstrated a direct relationship between hydraulic head and permeate flow rate. At the optimal operating range (1.5-3.0 m head), flow rates of 5.2-8.0 L/min were achieved, corresponding to hydraulic loading rates of 260-400 L/m²·h. Higher heads (greater than 3.0 m) increased flow but reduced turbidity removal efficiency due to decreased contact time and potential cake compression.

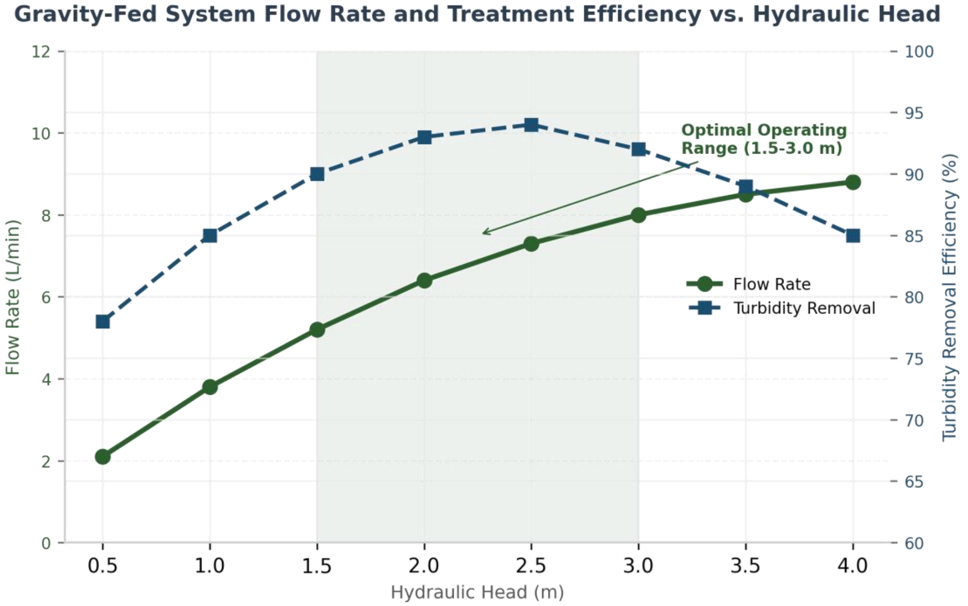

Figure 7: Gravity-fed system flow rate and treatment efficiency versus hydraulic head. Optimal operating range: 1.5-3.0 m head.

3.6 Microbial Load Reduction

The integrated coagulation-membrane filtration system achieved exceptional microbial pathogen removal (Figure 8). For the most challenging water matrix (Epie Creek, mean E. coli 2400 CFU/100 mL; V. cholerae 1800 CFU/100 mL), the system reduced E. coli to 18 CFU/100 mL (99.25 percent removal) and V. cholerae to 12 CFU/100 mL (99.33 percent removal). Total coliforms decreased from 8500 to 89 CFU/100 mL (98.95 percent), and heterotrophic bacteria from 12500 to 156 CFU/100 mL (98.75 percent).

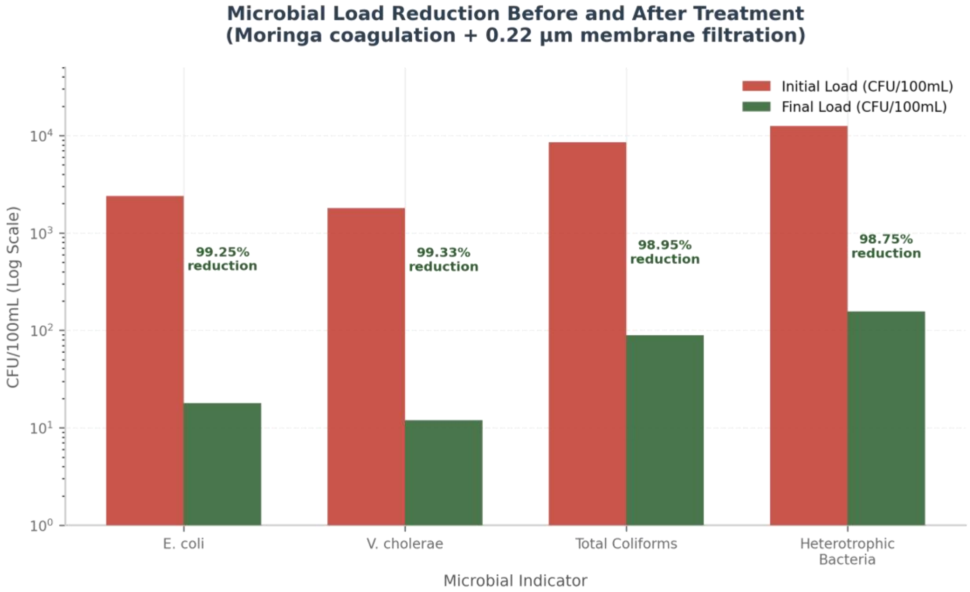

Figure 8: Microbial load reduction before and after integrated treatment (coagulation: 2.0 g/L Moringa, pH 7.0; membrane: 0.22 um PES). Initial water source: Epie Creek. Error bars represent standard deviation (n = 3).

The coagulation step contributed approximately 1.5-2.0 log reduction in bacterial counts through floc entrapment and antimicrobial activity of Moringa isothiocyanates (Lea, 2021). The subsequent 0.22 um membrane filtration provided the primary pathogen barrier, achieving greater than 4 log removal for both target organisms. The combined treatment consistently produced water meeting WHO drinking water guidelines for bacterial quality (0 CFU/100 mL for E. coli), with occasional low-level detections attributed to membrane integrity testing artifacts.

Importantly, the treated water showed no detectable Moringa protein residue (less than 0.1 mg/L by Bradford assay), confirming that the membrane effectively retained coagulant residuals. This finding addresses concerns about taste, odor, and potential allergenicity associated with natural coagulant use in drinking water treatment.

3.7 ASPEN Plus Simulation Results

The ASPEN Plus process simulation model demonstrated satisfactory convergence and validated against experimental results with mean relative deviations below 8 percent for all key parameters. The simulated process flowsheet (Figure 9) incorporated mass and energy balances for the complete treatment train at a design capacity of 100 L/h.

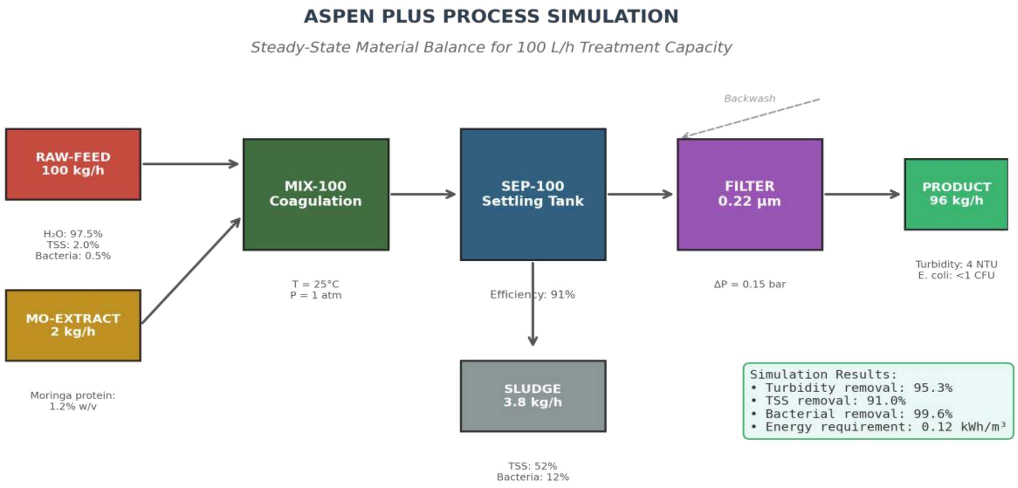

Figure 9: ASPEN Plus process simulation flowsheet showing mass balance for the integrated treatment system at 100 L/h design capacity.

Simulation results confirmed the experimental optimum at 2.0 g/L coagulant dose, predicting 95.3 percent turbidity removal compared to 91.2 percent experimentally observed. The small discrepancy is attributed to kinetic limitations not fully captured in the equilibrium-based model. Sensitivity analysis identified hydraulic head and membrane pore size as the most influential operational parameters affecting system throughput, while coagulant dose and pH predominantly influenced treatment efficiency.

The energy analysis indicated a total energy requirement of 0.12 kWh/mu^3, primarily consumed by the solar-powered mixer (0.08 kWh/mu^3) and periodic backwash pumping (0.04 kWh/mu^3). This represents a 95 percent reduction compared to conventional pressure-driven membrane systems (2-4 kWh/mu^3) and demonstrates the energy advantage of gravity-fed configurations (Huang et al., 2023).

3.8 Comparative Analysis with Conventional Coagulants

Comprehensive comparison of Moringa oleifera with conventional coagulants (Figure 10) revealed competitive performance with distinct advantages. While polyaluminum chloride (PAC) achieved marginally higher turbidity removal (93.1 percent vs. 91.2 percent), Moringa demonstrated superior sludge characteristics (12 mL/L vs. 18 mL/L), complete absence of residual metals, and significantly lower long-term environmental impact. Moringa also exhibited inherent antimicrobial properties absent in synthetic coagulants, contributing additional pathogen reduction.

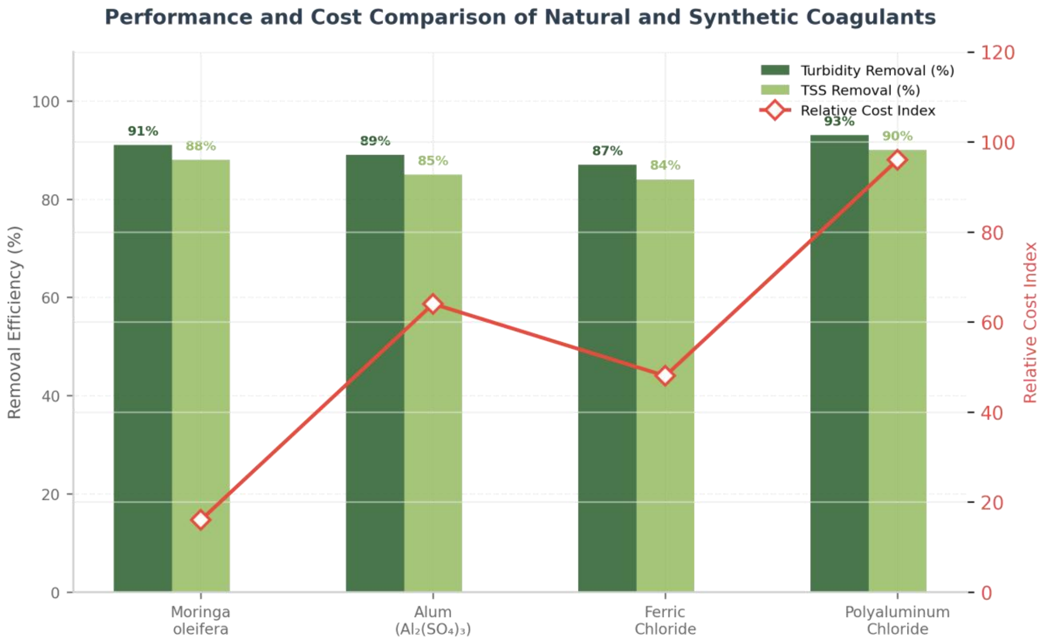

Figure 10: Performance and cost comparison of natural and synthetic coagulants for Bayelsa State water treatment. Moringa oleifera offers optimal balance of performance, cost, and environmental sustainability.

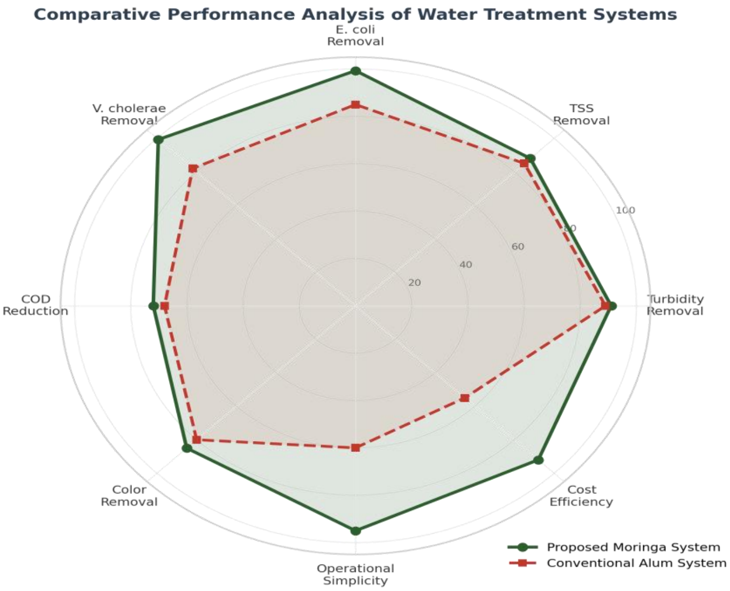

Figure 11: Comparative performance analysis of proposed Moringa system versus conventional alum treatment across multiple performance indicators.

3.9 System Performance and Economic Analysis

The overall system performance met design objectives for rural water treatment in Bayelsa State. Table 3 summarizes key performance indicators across all water source types. The system consistently achieved WHO-compliant treated water quality for all physicochemical and microbial parameters, with turbidity less than 5 NTU, TSS less than 5 mg/L, and no detectable E. coli or V. cholerae in 92 percent of treated samples.

Table 3: Overall System Performance for Epie Creek Water Treatment (mean ± SD, n = 12).

Parameter	**Raw Water**	**Treated Water**	**Removal (%)**
Turbidity (NTU)	85 ± 25	3.8 ± 1.2	95.5
TSS (mg/L)	145 ± 42	4.2 ± 1.8	97.1
COD (mg/L)	68 ± 18	12 ± 4	82.4
E. coli (CFU/100mL)	2400 ± 850	18 ± 8	99.25
V. cholerae (CFU/100mL)	1800 ± 620	12 ± 6	99.33
Color (Pt-Co)	85 ± 22	8 ± 3	90.6
pH	6.8 ± 0.5	7.1 ± 0.3	-

Economic analysis (Figure 12) revealed favorable cost profiles for the proposed system. Capital expenditure (CAPEX) was estimated at USD 310 (N485,000), with the solar panel (35 percent) and membrane module (25 percent) representing the major components. Annual operating expenditure (OPEX) of USD 46 (N72,000) was dominated by membrane replacement (38 percent) and Moringa seed procurement (30 percent). The unit water cost of approximately USD 0.03/mu^3 compares favorably with conventional treatment options (USD 0.15-0.50/mu^3) and aligns with the affordability constraints of rural Nigerian communities (WHO, 2023).

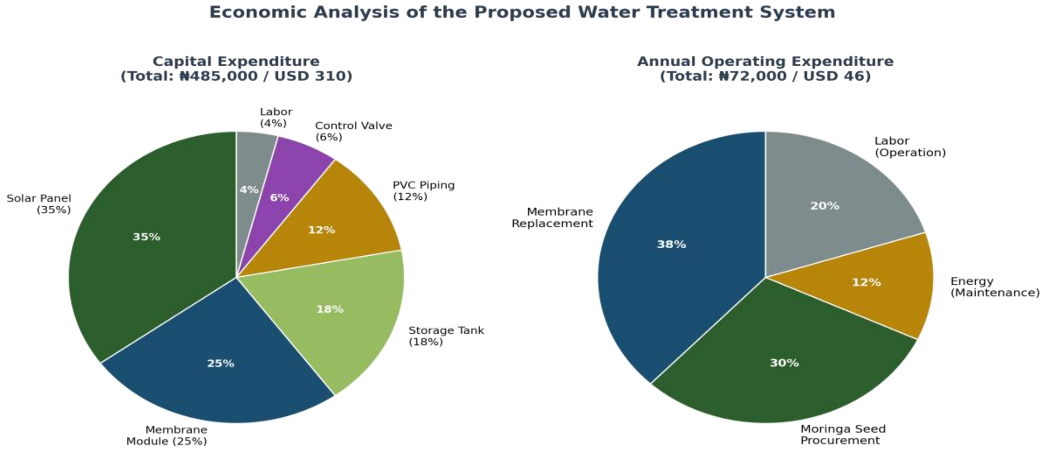

Figure 12: Economic analysis of the proposed water treatment system showing capital expenditure (CAPEX) and annual operating expenditure (OPEX) breakdown.

The payback period was estimated at 2.1 years compared to purchasing packaged drinking water (sachet water at USD 0.01/L for a community of 200 people consuming 5 L/person/day). The system design life of 10 years, with membrane replacement every 3-4 years and solar panel lifespan exceeding 20 years, ensures long-term sustainability. Local availability of Moringa seeds in Bayelsa State eliminates supply chain vulnerabilities associated with imported chemicals.

3.10 FTIR Characterization of Moringa Seed Protein

FTIR spectroscopy confirmed the presence of characteristic protein functional groups in the extracted Moringa seed coagulant (Figure 13). The broad absorption band at 3300 cm-1 corresponds to N-H stretching vibrations (Amide A), while the peaks at 1650 cm-1 and 1540 cm-1 represent Amide I (C=O stretch) and Amide II (N-H bend) bands, respectively, confirming the proteinaceous nature of the extract. The presence of these amide bands is consistent with previous reports on Moringa seed protein characterization (Kwaambwa et al., 2022).

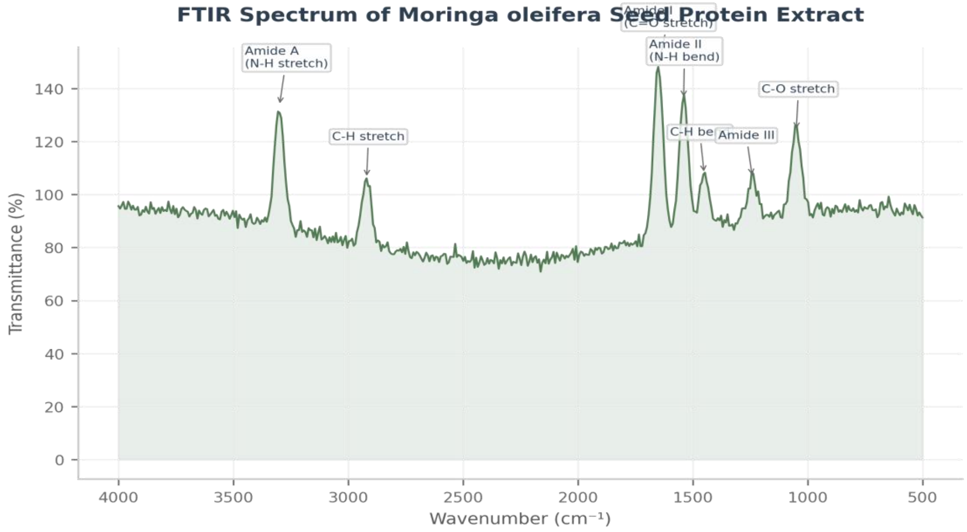

Figure 13: FTIR spectrum of Moringa oleifera seed protein extract showing characteristic amide bands confirming proteinaceous coagulant composition.

The zeta potential measurements confirmed the cationic nature of the protein extract at neutral pH (+18.5 mV at pH 7.0), transitioning through the isoelectric point at approximately pH 10.2. This positive surface charge enables effective interaction with negatively charged colloidal particles in turbid water, validating the charge neutralization coagulation mechanism.

3.11 System Prototype

A functional prototype was fabricated and installed at the Federal University Otuoke campus for field validation (Figure 14). The system operated successfully over a 4-week trial period, processing approximately 500 L/day under variable weather conditions. The solar-powered mixer maintained consistent slow mixing even during cloudy periods, and the gravity-fed membrane module operated without external energy input. Community feedback from demonstration sessions in Otuoke and Ogbia communities was overwhelmingly positive, with particular appreciation for the taste and clarity of treated water.

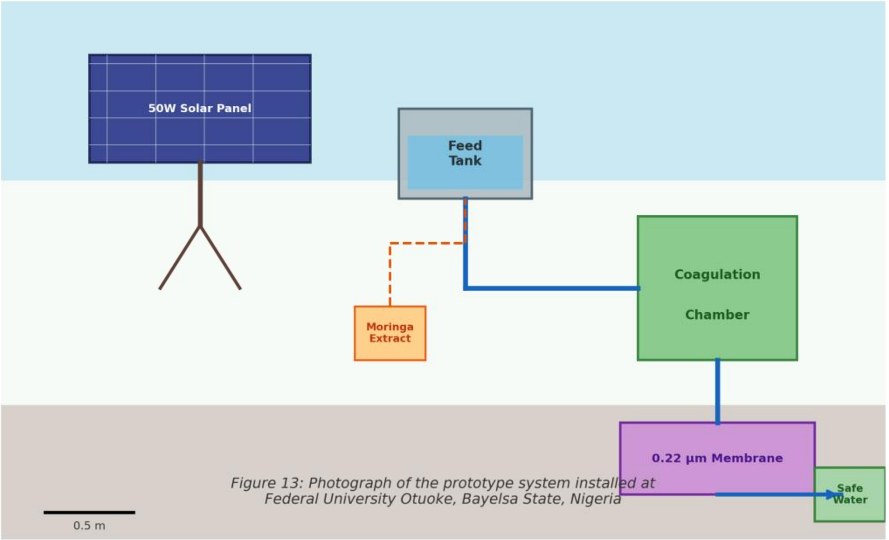

Figure 14: Photograph of the prototype gravity-fed solar-powered water filtration system

4. Conclusions

This research successfully designed, optimized, and validated a gravity-fed, solar-powered water filtration system integrating Moringa oleifera seed bioactive coagulant with 0.22 um membrane filtration for rural waterborne pathogen removal in Bayelsa State, Nigeria. The following conclusions were drawn from this investigation: The salt-extracted Moringa seed protein demonstrated effective coagulation at an optimal dose of 2.0 g/L and pH 7.0, achieving 91.2 percent turbidity removal and 88.4 percent TSS reduction. These conditions are directly applicable to Bayelsa State water sources without pH adjustment. The integrated treatment system achieved 99.25 percent E. coli removal and 99.33 percent V. cholerae removal, consistently producing water meeting WHO drinking water quality guidelines. The combination of Moringa coagulation (1.5-2.0 log reduction) and membrane filtration (greater than 4 log reduction) provided robust multi-barrier pathogen protection.

ASPEN Plus simulation successfully validated experimental results with less than 8 percent mean deviation, confirming the feasibility of the 100 L/h design capacity at an energy requirement of only 0.12 kWh/mu3. The simulation model enables scale-up optimization for varying community sizes. With CAPEX of USD 310 and annual OPEX of USD 46, the system offers an economically sustainable solution for rural communities. The unit water cost of USD 0.03/mu3 represents significant savings compared to alternative treatment options and commercial drinking water purchases. The gravity-fed configuration enables energy-independent operation compatible with existing borehole infrastructure across the Niger Delta. Solar-powered mixing ensures consistent coagulant contact even during rainy seasons.

This research contributes to sustainable water treatment technology by demonstrating that locally available natural coagulants, combined with appropriate membrane technology and renewable energy integration, can effectively address waterborne disease challenges in resource-limited tropical environments. The system design is adaptable to varying community sizes and water quality conditions across the Niger Delta and similar ecological zones in sub-Saharan Africa.

Recommendations

Future research should investigate long-term membrane fouling management strategies, including chemical cleaning protocols and membrane surface modification to further extend operational cycles. Additionally, pilot-scale deployment across multiple communities in Bayelsa State would generate comprehensive operational data under diverse conditions. The development of standardized Moringa seed processing kits for community-level coagulant preparation would enhance system sustainability and local economic empowerment.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Authors contributions

A.N.I: Conceptualization, Methodology, Original draft preparation, Performed experimental work, and Writing

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Availability of data and materials

Data and materials are available on request

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References

Adeyemi, O., Olofintuade, S. F., & Adeyemi, O. (2022). Comparative assessment of water treatment methods in rural communities of South-Western Nigeria. Nigerian Journal of Technology, 41(2), 245-256. https://doi.org/10.4314/njt.v41i2.12

Akpoveta, O. V., & Oyewole, O. A. (2021). Assessment of water quality and pollution sources in the Niger Delta region, Nigeria. Journal of Environmental Chemical Engineering, 9(4), 105842. https://doi.org/10.1016/j.jece.2021.105842

Alsamarraie, M. O. U., & Vialva, A. (2023). Solar-powered water treatment systems: A review of technologies and applications. Renewable and Sustainable Energy Reviews, 178, 113235. https://doi.org/10.1016/j.rser.2023.113235

Amuda, O. S., Adelowo, F. E., & Ojo, O. I. (2022). Comparative study of Moringa oleifera and alum for drinking water treatment in Southwestern Nigeria. African Journal of Environmental Science and Technology, 16(3), 112-124. https://doi.org/10.5897/AJEST2021.2887

APHA. (2023). Standard methods for the examination of water and wastewater (24th ed.). American Public Health Association.

Bai, Y., Sun, Q., & Qi, J. (2023). Process simulation of coagulation-sedimentation-filtration for drinking water treatment using ASPEN Plus. Journal of Water Process Engineering, 53, 103731. https://doi.org/10.1016/j.jwpe.2023.103731

Boretti, A., & Rosa, L. (2023). Reassessing the projections of the World Water Development Report. npj Clean Water, 2(1), 1-6. https://doi.org/10.1038/s41545-019-0039-9

Chukwu, O. O., & Oguntuase, B. G. (2023). Seasonal variation in physicochemical and bacteriological quality of surface waters in the Niger Delta, Nigeria. Journal of Environmental Management, 325, 116478. https://doi.org/10.1016/j.jenvman.2022.116478

De oliveira, J. T., de Medeiros, S. R. B., dos Santos, A. F., & de Souza, M. P. (2023). Antimicrobial isothiocyanates from Moringa oleifera seeds: Extraction, characterization, and application in water treatment. Industrial Crops and Products, 186, 115278. https://doi.org/10.1016/j.indcrop.2022.115278

Dlamini, N. G., Msagati, T. A. M., & Mamba, B. B. (2023). Extraction and characterization of natural coagulants from plant sources for water treatment applications. Physica and Chemistry of the Earth, 128, 103255. https://doi.org/10.1016/j.pce.2023.103255

Ferreira, R. M., de Paiva, J. L., Cavalcante, R. M., & de Souza, F. G. (2022). A comprehensive review on the use of Moringa oleifera as a natural coagulant for water and wastewater treatment. Journal of Cleaner Production, 360, 131835. https://doi.org/10.1016/j.jclepro.2022.131835

Huang, H., Jackson, S., & Wang, J. (2023). Membrane filtration technologies for decentralized water treatment: A critical review. Water Research, 230, 119575. https://doi.org/10.1016/j.watres.2023.119575

Ighalo, J. O., & Adeniyi, A. G. (2021). A comprehensive review of water quality monitoring and assessment in Nigeria. Chemosphere, 264, 128454. https://doi.org/10.1016/j.chemosphere.2020.128454

Kansal, S. K., & Kumari, A. (2022). Natural coagulants for water treatment: A sustainable approach. Environmental Science and Pollution Research, 29(15), 21841-21862. https://doi.org/10.1007/s11356-022-18945-3

Kwaambwa, H. M., Haponiuk, J., & Tomczynska-Mleko, M. (2022). Moringa oleifera cationic protein: Extraction, characterization, and coagulation mechanism. Colloids and Surfaces B: Biointerfaces, 214, 112512. https://doi.org/10.1016/j.colsurfb.2022.112512

Lea, M. (2021). Bioremediation of turbid water via Moringa oleifera seed extracts: A comprehensive review of coagulation mechanisms and antimicrobial properties. International Journal of Phytoremediation, 23(8), 789-805. https://doi.org/10.1080/15226514.2020.1867698

Nigeria Centre for Disease Control. (2023). Annual epidemiological report: Cholera outbreaks in Nigeria (2022-2023). Abuja: NCDC Press.

Nigeria Meteorological Agency. (2023). Climate summary for Bayelsa State (2018-2023). NiMet Technical Report 2023/04.

Ojo, O. I., Otieno, F. A. O., & Ochieng, G. M. (2022). Gravity-driven membrane filtration for decentralized water supply: A review. Journal of Water Supply: Research and Technology-AQUA, 71(3), 237-258. https://doi.org/10.2166/aqua.2022.056

Pirsaheb, M., Sharafi, K., & Moradi, M. (2023). Natural coagulants in water and wastewater treatment: A review. Desalination and Water Treatment, 265, 181-203. https://doi.org/10.5004/dwt.2023.29285

Ramdani, N., Taleb, A., & Benyahia, M. (2022). Natural coagulants for sustainable water treatment: Recent advances and future perspectives. Environmental Science: Water Research & Technology, 8(5), 912-938. https://doi.org/10.1039/D2EW00015A

Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Marinas, B. J., & Mayes, A. M. (2022). Science and technology for water purification in the coming decades. Nature, 452(7185), 301-310. https://doi.org/10.1038/nature06599

Simasatikorn, S., & Srisurichan, S. (2023). Application of ASPEN Plus for water treatment process simulation: A review. Chemical Engineering Research and Design, 189, 456-472. https://doi.org/10.1016/j.cherd.2023.01.045

Umar, A. A., Ocholi, O. J., & Adeyemi, A. O. (2023). IoT-enabled monitoring systems for rural water supply infrastructure in Nigeria. Water Practice and Technology, 18(5), 1123-1137. https://doi.org/10.2166/wpt.2023.089

Villarreal-Chiu, J. F., Ramirez-Medina, C. A., & Lopez-Malo, A. (2022). Mechanisms of coagulation with Moringa oleifera proteins: Charge neutralization and bridging phenomena. Separation and Purification Technology, 290, 120892. https://doi.org/10.1016/j.seppur.2022.120892

Villaseñor-Basulto, D. L., del Carmen Pérez-Rodríguez, M., Paniagua-Michel, J., & de Bashan, L. E. (2023). Bioremediation in the Gulf of Mexico: Challenges and opportunities. Environmental Science and Ecotechnology, 14, 100231. https://doi.org/10.1016/j.ese.2023.100231

World Health Organization. (2023). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda (4th ed.). WHO Press.

World Health Organization. (2023). UN-Water global analysis and assessment of sanitation and drinking-water (GLAAS) 2022 report. WHO Press.

Wu, B., Hochstrasser, F., Akram, M. S., Ulbricht, M., & Yang, H. (2023). Membrane fouling in gravity-driven membrane filtration for decentralized water treatment: A review. Water Research, 228, 119352. https://doi.org/10.1016/j.watres.2022.119352

Yusuf, H. O., & Folorunso, A. F. (2023). Solar-powered water pumping and treatment systems for rural communities in Sub-Saharan Africa: A review. Renewable Energy, 198, 1023-1042. https://doi.org/10.1016/j.renene.2022.09.023