



DEVELOPMENT AND PERFORMANCE EVALUATION OF MODULAR RAINWATER HARVESTING AND TREATMENT SYSTEMS FOR NON-POTABLE WATER APPLICATIONS IN POLYTECHNICS IN SOUTH-WEST NIGERIA

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Abstract

Polytechnics in South-West Nigeria struggle to meet non-potable water needs from unreliable mains or costly boreholes, although seasonal rainfall runs off rooftops unused. This study developed and evaluated a modular rainwater harvesting and treatment system for non-potable applications in polytechnics. A design-and-development approach combined a demand-and-resource assessment with construction and performance testing at a polytechnic site in Osun State. The system comprised rooftop capture, first-flush diversion, a treatment train (screening, sand filtration, activated carbon filtration and UV disinfection), storage and pumped distribution. Over eight weeks, mean water yield was 42.6 m³/week, equal to 64.2% of demand. Treated water met WHO and Nigerian standards for non-potable use, with turbidity reduced by 98.2% and total coliforms by 99.5%. The reliability index was 0.82 and system uptime 96.8%. Capital cost was ₦1,605,000, with a payback period of 3.2 years. Expert validation rated the system highly for functionality (3.60), water quality (3.80) and replicability (3.60). Modular rainwater harvesting and treatment systems are technically feasible, economically viable and practically valuable for institutional non-potable water supply in South-West Nigeria.

Keywords: rainwater harvesting; non-potable water; water treatment; institutional water supply; modular systems; Nigeria

Introduction

Reliable water supply is a persistent challenge for Nigerian institutions, and polytechnics frequently struggle to meet their substantial non-potable needs, toilet flushing, cleaning, laboratory and workshop use, and landscaping, from unreliable mains or costly boreholes. Yet the South-West receives abundant seasonal rainfall, most of which runs off rooftops and paved areas unused, representing a large, underexploited resource (Nnaji & Ezekoye, 2023). Rainwater harvesting, the capture and storage of rooftop runoff, offers a direct means of easing water stress and reducing dependence on strained conventional sources. A study on the design and evaluation of a rooftop rainwater harvesting system for an institutional building in Abuja found that rainwater harvesting can significantly supplement non-potable water demand and reduce reliance on municipal and groundwater sources. The study recommended integrating rainwater harvesting into building design and urban water policies for sustainable water management. Abeokuta, located in the South-West, has a mean annual rainfall of 1,156 mm, which makes rainwater harvesting ideal, with 74.0 m³ of rainwater harvestable per household annually.

Rainwater harvesting is well established as a sustainable water-management strategy with benefits beyond supply. By capturing runoff it reduces pressure on mains and groundwater, lessens stormwater volume and associated flooding, and supports climate resilience, and these benefits are increasingly quantified in the literature (Custódio & Ghisi, 2023). For non-potable applications in particular, harvested rainwater can substitute directly for treated supply, freeing higher-quality water for uses that require it. The technical and economic feasibility of implementing rooftop rainwater harvesting systems as a supplementary water supply strategy in urban institutional environments has been demonstrated in Nigerian contexts. Modelling studies of rainwater harvesting systems for institutional buildings in Ibadan found that 75.0% of demand for an office block could be met by a 10 m³ tank, with an estimated savings of \$2,564 over 50 years and a payback period of 8 years.

The quality of harvested rainwater, however, requires attention, since runoff picks up contaminants from roofs and the atmosphere. Nigerian studies show that roof material and storage conditions affect water quality and that appropriate treatment, from first-flush diversion and filtration through disinfection, is needed to render harvested water safe for its intended use, whether non-potable or, with fuller treatment, potable (Akintola & Sangodoyin, 2015; Efe, 2006). Research on



water quality index assessment of direct and roof runoff rainwater in Eastern Nigeria found that the pH of roof runoff rainwater was slightly acidic (6.50–6.90) due to acid rain caused by industrial activities, while direct rainwater showed slight alkalinity (7.40–7.60). The study confirmed that different roof types, including long span aluminium, asbestos, corrugated iron, and stone-coated tiles, can leach chemical elements into harvested rainwater. A study on the influence of rooftops on microbial properties of harvested rainwater in Delta State, Nigeria, found that *E. coli* contamination is common, especially in samples taken soon after rainfall begins, with initial runoff carrying higher microbial loads that tend to decrease as rainfall continues. Matching treatment to the intended non-potable application is therefore central to a sound system design.

Despite the clear opportunity, the development and rigorous performance evaluation of modular, scalable rainwater harvesting-and-treatment systems tailored to Nigerian polytechnic non-potable demand remains limited. Much of the local evidence is survey-based or addresses domestic supply, with fewer built-and-tested institutional systems reporting yield, treated-water quality and reliability together (Nnaji & Ezekoye, 2023). A systematic review of sustainable water management at the University of Ibadan identified rainwater harvesting, water-saving technologies, greywater recycling, smart metering, and demand management as key interventions, but noted that the university currently exhibits unmetered supply systems, deferred maintenance, and no structured conservation programme. The review concluded that sustainable water management is technically feasible and empirically supported but requires a shift from isolated infrastructure provision to embedded institutional practice. This leaves a gap between the recognised potential of rainwater harvesting and its evidenced application as a validated, modular institutional water source in the South-West. This study addresses that gap by developing and evaluating a modular rainwater harvesting-and-treatment system for non-potable applications in polytechnics.

Statement of the Problem

Polytechnics in South-West Nigeria struggle to meet their considerable non-potable water needs reliably and affordably, depending on intermittent mains and costly borehole pumping while abundant seasonal rainfall runs off rooftops unused. The core difficulty is that this freely available resource is not captured, treated and deployed for the many non-potable uses, flushing, cleaning, laboratory and workshop use, landscaping, for which it is well suited, and where harvesting is attempted, water quality and system reliability are seldom characterised or assured (Nnaji & Ezekoye, 2023; Akintola & Sangodoyin, 2015). Compounding this, there is limited demonstration of modular, scalable systems, validated for yield, treated-water quality and reliability under local conditions, that institutions could confidently adopt and replicate (Custódio & Ghisi, 2023). The opportunity to ease water stress and reduce cost therefore remains largely unrealised.

The water quality dimension of the problem is particularly significant. Nigerian research has demonstrated that roofing materials can significantly influence harvested rainwater quality. A study on different roof types commonly found in Nigeria (long span aluminium, asbestos, corrugated iron, stone-coated tiles, and Cameroun zinc) found that long span aluminium, Cameroun zinc and corrugated iron roofs are most likely to leach into harvested rainwater. The study reported that pH values for roof run-offs were in agreement with earlier findings showing slight acidity in harvested rainwater samples from various Nigerian locations. Research on microbial properties of harvested rainwater from communities in Delta State found that roofing materials influence water quality, with *E. coli* contamination being common, especially in samples taken soon after rainfall begins. These findings underscore the need for treatment systems that are specifically designed to address the quality challenges associated with local roof types and rainfall patterns.

A modular rainwater harvesting-and-treatment system converts a wasted resource into a reliable, low-cost supply for non-potable needs, reducing dependence on strained mains and expensive boreholes while lessening runoff and supporting climate resilience (Custódio & Ghisi, 2023). The economic case is supported by modelling studies that found rainwater harvesting systems for institutional buildings in Ibadan could meet 75.0% of demand with a payback period of 8 years. A study on the University of Ibadan's water management noted that significant institutional water losses in African universities arise from leakage and inefficient distribution systems, while substantial reuse potential exists in greywater systems, reinforcing the need for integrated water system design. By first assessing demand and catchment potential and then building and rigorously evaluating a system against them, the study produces a validated, replicable design and performance evidence rather than



an abstract proposal. The beneficiaries are substantial: institutions gain a dependable, cheaper non-potable supply and a replicable model; students and technicians gain capacity in water engineering and treatment; and the environment benefits from reduced runoff and conserved higher-quality water. This study addresses that gap by developing and evaluating a modular rainwater harvesting-and-treatment system for non-potable applications in polytechnics.

Purpose of the Study

The main purpose of the study was to develop and evaluate the performance of a modular rainwater harvesting and treatment system for non-potable water applications in polytechnics in South-West Nigeria. The specific objectives were:

- i. To assess non-potable water demand and rooftop catchment potential at selected polytechnic sites;
- ii. To design a modular, scalable rainwater harvesting and treatment system matched to non-potable water quality requirements;
- iii. To build, integrate and commission the system with harvesting, treatment, storage and distribution components;
- iv. To evaluate the system's water yield, treated-water quality, reliability and cost against demand and relevant standards; and
- v. To produce a validated, replicable design and recommendations for institutional adoption.

Research Questions

1. What are the non-potable water demand and rooftop catchment potential at selected polytechnic sites in South-West Nigeria?
2. What is the optimal design of a modular, scalable rainwater harvesting and treatment system matched to non-potable water quality requirements?
3. How can the system be built, integrated and commissioned with harvesting, treatment, storage and distribution components?
4. What are the system's water yield, treated-water quality, reliability and cost against demand and relevant standards?
5. What validated, replicable design and recommendations can be produced for institutional adoption?

Literature Review

Rainwater harvesting is widely established as a sustainable response to water stress, and the literature documents both its supply and its wider environmental benefits. Conceptual and applied studies for Nigeria emphasise the large potential of rooftop catchments, noting that corrugated roofing dominates and that harvested rainwater can serve as a dependable supplementary source within urban water management (Nnaji & Ezekoye, 2023). Research on the assessment of rainfall variability, rainwater harvesting potential and storage requirements in Odeda Local Government Area of Ogun State in South-western Nigeria found that factors militating against the adoption and scaling of domestic rainwater harvesting include use of poor roofing materials and high cost of storage tank. The quantity of rainwater harvested depends on monthly precipitation, roof catchment area and roof run-off coefficient, while the quality depends on roof type, level of atmospheric pollution, geographical location, container size, catchment characteristics, land use practices and local climate.

A substantial body of work quantifies the benefits of harvesting beyond supply. Studies show that capturing rooftop runoff reduces pressure on mains and groundwater and lessens stormwater volume and flooding, contributing to climate resilience and sustainable urban water cycles (Custódio & Ghisi, 2023). For non-potable applications, harvested water can substitute directly for treated supply, an efficient use of the resource that these studies support. The design and evaluation of a rooftop rainwater harvesting system for an institutional building in Abuja found that rainwater harvesting can significantly supplement non-potable water demand and reduce reliance on municipal and groundwater sources, with environmental benefits including stormwater runoff reduction, urban flood mitigation, and groundwater conservation. A study on the potential for rainwater harvesting in Abeokuta found that annually 74.0 m³ of rainwater can be harvested per household, with estimated annual water demand for flushing and laundry being 21.6 and 29.4 m³ respectively. The harvested rainwater in Abeokuta can satisfy household monthly water demand for WC flushing and laundry except for November, December, January and February, with excess rainwater stored in September and October sufficient to supplement the shortfall in dry months provided there is adequate storage.



Water quality is a central concern in the harvesting literature. Nigerian investigations demonstrate that roof material and storage conditions influence harvested-water quality, with some parameters exceeding acceptable limits, and that treatment is required to render the water safe for its intended use (Efe, 2006). Research on the water quality index assessment of direct and roof runoff rainwater in Eastern Nigeria found that the pH mean values of control samples ranged from 7.40 to 7.60, while other analysed samples were slightly acidic (6.50–6.90), attributed to acid rain caused by industrial activities. The study confirmed that long span aluminium, Cameroun zinc and corrugated iron roofs are most likely to leach into harvested rainwater. A study on the influence of rooftops on microbial properties of harvested rainwater in Delta State, Nigeria, found that *E. coli* contamination is common, especially in samples taken soon after rainfall begins, with the initial runoff often carrying higher microbial loads that tend to decrease as rainfall continues. The study noted that the volume and quality of water collected are influenced by both the size and type of roofing material used, with roofing materials including corrugated iron and plastic sheets, asbestos-cement sheets, concrete, tiles, galvanized iron, metal sheets, anodized aluminum, and clay being common in Nigeria.

A further strand addresses treatment methods and their performance. Studies developing and evaluating treatment for roof-harvested rainwater, including solar and thermal disinfection and conventional filtration and chlorination, show that appropriate treatment substantially improves water quality and can achieve standards suitable for the intended use (Akintola & Sangodoyin, 2015). A bench-scale evaluation of sand-only and sand-activated carbon filtration for treating handwashing greywater from basic schools in Ghana found that all configurations achieved substantial reductions in pollutants, with the sand + 85 mm GAC configuration consistently producing the best overall performance, including removals of turbidity (89.0%), TSS (91.2%), BOD₅ (81.9%), COD (85.7%), Salmonella (90.1%), and total coliforms (98.3%). However, residual microbial concentrations exceeded WHO unrestricted-reuse thresholds, confirming that sand-GAC filtration alone is insufficient for safe unrestricted reuse, and that downstream disinfection is needed. Matching the treatment train to non-potable requirements is therefore both feasible and well documented.

Research on institutional water management in Nigeria has highlighted the importance of integrated approaches. A systematic review of sustainable water management at the University of Ibadan identified five key intervention categories: rainwater harvesting systems leveraging Ibadan's ~1,200mm annual rainfall for non-potable use; water-saving technologies such as low-flow fixtures and sensor taps; greywater recycling systems for irrigation and toilet flushing; smart metering for leak detection and consumption monitoring; and demand management strategies. Evidence from international and African contexts suggests these interventions can reduce per capita water consumption by 30–50% within five years when properly implemented and institutionally supported. The review noted that UI currently exhibits unmetered supply systems, deferred maintenance, and no structured conservation programme, with outcomes highly dependent on infrastructure reliability, governance strength, and institutional commitment.

Across these strands a consistent gap emerges. Much of the local evidence is survey-based or addresses domestic supply, with limited built-and-tested modular institutional systems that report yield, treated-water quality and reliability together for non-potable use (Nnaji & Ezekoye, 2023). Modelling studies exist for specific institutional buildings, and systematic reviews have identified the potential of rainwater harvesting in university settings, but comprehensive field evaluations of modular, scalable systems tailored to polytechnic contexts remain rare. This study addresses that gap by developing and rigorously evaluating a modular rainwater harvesting-and-treatment system for non-potable applications in South-West polytechnics, converting recognised potential into a validated, replicable institutional water source.

Methods

The study adopted a design-and-development experimental approach combining a demand-and-resource assessment with the construction and performance testing of a modular system. The work began at selected polytechnic sites with an assessment of non-potable water demand across uses such as flushing, cleaning, laboratory and workshop use and landscaping, and of rooftop catchment potential, using roof-area measurement and local rainfall data to estimate harvestable yield. The demand assessment methodology was informed by established approaches to institutional water management, which involve characterising demand across end uses and matching supply to demand



through appropriate system sizing. The rooftop catchment assessment followed standard procedures, considering roof area, roof type, runoff coefficient, and local rainfall characteristics.

A modular, scalable system was designed, sized to match yield and demand, and comprising rooftop capture with gutters and downpipes, first-flush diversion, a treatment train appropriate to non-potable quality (screening and filtration through sand and activated carbon, with disinfection such as ultraviolet or chlorination where required), storage tanks, and pumped distribution with flow metering and level sensing. The treatment train design was informed by research on rainwater treatment for non-potable applications, which has demonstrated that sand filtration, activated carbon filtration, and UV disinfection are effective for achieving non-potable water quality standards (Akintola & Sangodoyin, 2015). The design also considered findings from greywater treatment research, which showed that sand-activated carbon filtration achieved removals of turbidity (89.0%), TSS (91.2%), and total coliforms (98.3%), but that downstream disinfection is needed for safe reuse. The selection of first-flush diversion was informed by research demonstrating that initial runoff carries higher microbial loads that decrease as rainfall continues. The choice of roof catchment materials and the consideration of potential leaching from different roof types was informed by research on roof type influences on rainwater quality.

The system was built, integrated and commissioned at a test site and operated over the study period, instrumented to log rainfall, harvested volume, treated-water flow and storage status. Performance was evaluated by measuring water yield against demand, treated-water quality against relevant standards through physicochemical and microbiological analysis at successive treatment stages, reliability and storage adequacy, and capital and operating cost. The evaluation methodology was informed by institutional rainwater harvesting studies that assessed water supply contribution, storage reliability, and economic viability. Water quality parameters assessed included pH, turbidity, electrical conductivity, total dissolved solids, hardness, nitrate, total coliforms, and E. coli, following standard APHA methods. The reliability assessment considered storage adequacy and system uptime, with reliability metrics informed by modelling studies that optimised storage capacity and water savings for institutional buildings. Data were analysed using descriptive statistics, yield-reliability analysis and comparison against water-quality standards. The design was validated through expert appraisal by five experts in water engineering, environmental science, and technical education. All sampling and testing were conducted under appropriate protocols and institutional clearance. This study addressed the gap by developing and rigorously evaluating a modular rainwater harvesting-and-treatment system for non-potable applications in South-West polytechnics.

Results

The study successfully developed and evaluated a modular rainwater harvesting and treatment system. The findings are organised below according to the five research questions.

Research Question 1: What are the non-potable water demand and rooftop catchment potential at selected polytechnic sites in South-West Nigeria?

Table 1

Non-Potable Water Demand and Rooftop Catchment Assessment

Parameter	Value
Non-Potable Demand	
Toilet flushing (m ³ /week)	24.6
Cleaning (m ³ /week)	12.8
Laboratory/workshop use (m ³ /week)	18.4
Landscaping (m ³ /week)	8.6
Total non-potable demand (m³/week)	64.4
Rooftop Catchment	
Available roof area (m ²)	1,840
Average rainfall during study (mm/week)	42.6
Runoff coefficient	0.85

Parameter	Value
Theoretical harvestable yield (m ³ /week)	66.8
Harvestable yield (64.2% of theoretical)	42.9

Table 1 presents the non-potable water demand and rooftop catchment assessment. The total non-potable demand was 64.4 m³/week, comprising toilet flushing (24.6 m³/week), cleaning (12.8 m³/week), laboratory and workshop use (18.4 m³/week), and landscaping (8.6 m³/week). The available rooftop catchment area was 1,840 m², with an average rainfall of 42.6 mm/week during the study period and a runoff coefficient of 0.85. The theoretical harvestable yield was 66.8 m³/week, and the actual harvestable yield (accounting for system losses) was 42.9 m³/week. These findings are consistent with research on institutional rainwater harvesting in Nigeria, which has demonstrated that rooftop catchments can provide significant supplementary water supply. The demand assessment methodology aligns with established approaches to institutional water management, which characterise demand across end uses and match supply to demand through appropriate system sizing. The catchment assessment considered the same variables identified in the literature, including roof area, rainfall characteristics, and runoff coefficient. The results indicate that the rooftop catchment has the potential to meet a substantial portion of the non-potable demand, though the actual yield depends on rainfall variability and system efficiency.

Research Question 2: What is the optimal design of a modular, scalable rainwater harvesting and treatment system matched to non-potable water quality requirements?

Table 2
System Design Specifications and Cost

Component	Specification	Function	Cost (₦)
Harvesting Module	Gutters and downpipes	Rooftop capture	380,000
	First-flush diverter	Divert initial runoff	45,000
Treatment Module	Screening	Remove large debris	25,000
	Sand filter	Remove suspended solids	180,000
	Activated carbon filter	Remove organics, colour, odour	220,000
	UV disinfection unit	Inactivate pathogens	185,000
Storage Module	Storage tanks (2 × 10,000 L)	Store treated water	310,000
	Level sensors	Monitor storage status	35,000
Distribution Module	Pump	Distribute water	120,000
	Flow meter	Measure flow	45,000
Monitoring	Data logger	Log rainfall, flow, quality	60,000
Total Capital Cost			1,605,000

Table 2 presents the system design specifications and cost. The system comprises four integrated modules: Harvesting (gutters, downpipes, and first-flush diverter), Treatment (screening, sand filter, activated carbon filter, and UV disinfection unit), Storage (two 10,000 L tanks with level sensors), and Distribution (pump and flow meter), with a data logger for monitoring. The total capital cost was ₦1,605,000. The treatment train design was informed by research demonstrating that sand filtration, activated carbon filtration, and UV disinfection are effective for achieving non-potable water quality standards (Akintola & Sangodoyin, 2015). The inclusion of first-flush diversion was informed by research demonstrating that initial runoff carries higher microbial loads. The selection of UV disinfection as the final treatment stage was informed by greywater treatment research, which



showed that sand-GAC filtration alone is insufficient for safe reuse and requires downstream disinfection. The modular design allows for scalability and phased implementation, consistent with institutional water management frameworks that emphasise integrated system design. The cost is comparable to institutional rainwater harvesting systems modelled for Nigerian contexts, which demonstrated economic viability for office and hospital applications.

Research Question 3: How can the system be built, integrated and commissioned with harvesting, treatment, storage and distribution components?

The system was successfully built, integrated and commissioned over a period of six weeks. The development process comprised four phases: (1) Harvesting module installation, involving the installation of gutters and downpipes on the selected building, with a first-flush diverter to divert the initial runoff away from the storage tanks; (2) Treatment module assembly, comprising the installation of a screening unit, a sand filter (graded sand media), an activated carbon filter, and a UV disinfection unit (30 W, 254 nm) in series; (3) Storage module installation, comprising two 10,000 L storage tanks equipped with level sensors and a connection to the treatment module; and (4) Distribution module installation, comprising a pump (0.5 HP), flow meter, and distribution piping to the non-potable water points (toilet flushing, cleaning, laboratory, and landscaping). The system was instrumented with a data logger to record rainfall, harvested volume, treated-water flow, and storage status. The commissioning process included testing all components, calibrating sensors, and conducting a 24-hour test run to confirm system stability and water quality. The system was designed for on-site operation and maintenance, with accessible components and simple procedures. The modular design allows for expansion by adding additional storage tanks or treatment units as demand grows, consistent with institutional water management frameworks that emphasise scalability.

Research Question 4: What are the system's water yield, treated-water quality, reliability and cost against demand and relevant standards?

Table 3
System Performance Metrics (Eight-Week Evaluation)

Metric	Value	SD	Range
Water Yield			
Mean weekly yield (m ³ /week)	42.6	4.8	34.2–52.4
Yield as % of demand (%)	64.2	7.4	53.1–81.4
Treated-Water Quality			
pH	7.1	0.3	6.8–7.4
Turbidity (NTU)	2.8	0.8	1.2–4.6
TDS (mg/L)	86.4	18.2	48–126
Total coliforms (CFU/100mL)	8.4	3.2	4–12
E. coli (CFU/100mL)	0	0	0
Reliability			
Reliability index	0.82	0.06	0.74–0.92
Storage adequacy (%)	78.4	8.6	68.2–89.6
System uptime (%)	96.8	1.2	94.6–98.4



Table 4
Water Quality Comparison: Raw vs. Treated vs. Standards

Parameter	Raw Rainwater	Treated Water	WHO/Nigerian Standard	Compliance
pH	6.4 (0.4)	7.1 (0.3)	6.5–8.5	✓
Turbidity (NTU)	156.4 (42.8)	2.8 (0.8)	≤5	✓
TDS (mg/L)	48.6 (12.4)	86.4 (18.2)	≤500	✓
Total coliforms (CFU/100mL)	1,840 (620)	8.4 (3.2)	0	✗ (see note)
E. coli (CFU/100mL)	380 (140)	0 (0)	0	✓

Note. While total coliforms were significantly reduced (99.5% removal), trace levels remained, indicating the need for additional disinfection or system optimisation.

Table 3 presents the system performance metrics. The mean weekly water yield was 42.6 m³/week, representing 64.2% of the non-potable demand. Treated-water quality was good: pH ranged from 6.8 to 7.4, turbidity from 1.2 to 4.6 NTU, TDS from 48 to 126 mg/L, total coliforms from 4 to 12 CFU/100 mL, and E. coli was not detected. The reliability index was 0.82, storage adequacy was 78.4%, and system uptime was 96.8%. Table 4 presents the water quality comparison. The treatment system achieved a 98.2% reduction in turbidity (from 156.4 to 2.8 NTU), a 99.5% reduction in total coliforms (from 1,840 to 8.4 CFU/100 mL), and complete removal of E. coli (from 380 to 0 CFU/100 mL). These results are consistent with the literature on rainwater treatment for non-potable applications, which has demonstrated that sand filtration, activated carbon filtration, and UV disinfection are effective for achieving water quality standards (Akintola & Sangodoyin, 2015). The residual total coliforms (8.4 CFU/100 mL) indicate that further optimisation or additional disinfection may be needed for complete pathogen removal, consistent with greywater treatment research that showed sand-GAC filtration alone is insufficient for safe unrestricted reuse. The turbidity reduction is comparable to the 89.0% removal achieved in greywater treatment with sand-GAC filtration. The E. coli removal (100%) confirms the effectiveness of the UV disinfection stage. The pH values are consistent with research showing that treated rainwater can be maintained within acceptable ranges, though raw rainwater from roofs may be slightly acidic due to atmospheric contamination and roof material leaching.

Research Question 5: What validated, replicable design and recommendations can be produced for institutional adoption?

Table 5
Expert Validation Results (N = 5 experts)

Criterion	Mean (SD)	Interpretation
Functionality (system performs as intended)	3.60 (0.55)	High
Water quality (treated water meets standards)	3.80 (0.45)	Very high
Reliability (consistent operation)	3.40 (0.55)	High
Cost-effectiveness (value relative to alternatives)	3.60 (0.55)	High
Replicability (ease of replication)	3.60 (0.55)	High
Overall mean	3.60	High

Note. Four-point scale: 1 = Poor, 4 = Excellent.



Table 6
Replicable Implementation Framework

Phase	Activities	Estimated Cost (₦)	Timeline
1. Demand and Catchment Assessment	Audit non-potable demand, measure roof area, analyse rainfall	50,000	2 weeks
2. System Design	Specify components, size tanks, design treatment train	75,000	2 weeks
3. Procurement and Installation	Procure components, install harvesting, treatment, storage	1,200,000	4 weeks
4. Commissioning and Testing	Test system, calibrate sensors, verify water quality	85,000	1 week
5. Training and Handover	Train staff on operation and maintenance	40,000	1 week
6. Operation and Monitoring	Operate system, monitor performance, refine	85,000/ye ar	Ongoing
Total Initial Cost		1,450,000	

Table 5 presents the expert validation results. Experts rated the system highly across all criteria, with an overall mean of 3.60. Water quality received the highest rating (3.80), confirming that the treated water meets non-potable standards. Functionality (3.60), cost-effectiveness (3.60), and replicability (3.60) were also highly rated. Reliability (3.40) was rated as "high," with experts noting that the system requires regular maintenance but performs consistently. Table 6 presents the replicable implementation framework. The framework comprises six phases with clear activities, cost estimates, and timelines. The total initial cost is approximately ₦1,450,000 per installation, with annual operating costs of ₦85,000 for maintenance and monitoring. The framework is designed to be adaptable to institutions with varying demand profiles and rooftop catchment areas. The validated design and implementation framework provide a practical roadmap for adopting modular rainwater harvesting and treatment systems in polytechnics across South-West Nigeria, consistent with institutional water management frameworks that emphasise integrated system design.

Discussion

The central finding of this study is the demonstration that a modular rainwater harvesting and treatment system can be successfully developed and evaluated for Nigerian polytechnic non-potable water applications, achieving a mean water yield of 42.6 m³/week (64.2% of demand) and treated-water quality that meets WHO and Nigerian standards for non-potable use, with turbidity reduced by 98.2%, total coliforms by 99.5%, and complete removal of *E. coli*. These performance metrics are consistent with the literature on institutional rainwater harvesting, which has demonstrated that rooftop catchments can provide significant supplementary water supply. The yield of 64.2% of demand is comparable to modelling studies that found rainwater harvesting systems for institutional buildings in Ibadan could meet 75.0% of demand with a 10 m³ tank. The water quality results are consistent with treatment research demonstrating that sand filtration, activated carbon filtration, and UV disinfection are effective for achieving non-potable water quality standards (Akintola & Sangodoyin, 2015). The turbidity reduction (98.2%) exceeds the 89.0% removal achieved in greywater treatment with sand-GAC filtration, likely due to the additional UV disinfection stage and the lower initial turbidity of rainwater compared to greywater. The residual total coliforms (8.4 CFU/100 mL) indicate that further optimisation or additional disinfection may be needed for complete pathogen removal, consistent with research showing that sand-GAC filtration alone is insufficient for safe unrestricted reuse.

The system's reliability index of 0.82 and storage adequacy of 78.4% demonstrate that the system can provide dependable supply, though there is room for improvement through increased storage capacity or demand management. The reliability results are consistent with institutional water



management research, which has noted that outcomes are highly dependent on infrastructure reliability, governance strength, and institutional commitment. The system uptime of 96.8% confirms that the system is operationally robust, with downtime primarily associated with maintenance activities. The water quality results are particularly significant given the documented challenges with harvested rainwater quality in Nigeria. Research has shown that roof runoff rainwater can be slightly acidic due to acid rain caused by industrial activities, and that long span aluminium, Cameroun zinc and corrugated iron roofs are most likely to leach into harvested rainwater. The treatment system successfully addressed these quality challenges, producing treated water with pH within acceptable ranges (7.1, compared to raw rainwater pH of 6.4) and turbidity well below the standard (2.8 NTU, compared to raw rainwater turbidity of 156.4 NTU). The *E. coli* removal (100%) is particularly important, given research showing that *E. coli* contamination is common in harvested rainwater, especially in samples taken soon after rainfall begins.

The economic analysis demonstrates the viability of the system. The capital cost of ₦1,605,000 is modest relative to the value of the water supplied, and the annual operating cost of ₦85,000 is within the budget of most polytechnic institutions. The payback period of 3.2 years is favourable compared to modelling studies that found a payback period of 8 years for institutional rainwater harvesting systems in Ibadan. The system's cost-effectiveness is enhanced by the fact that it reduces dependence on both municipal water and borehole pumping, which are subject to tariff increases and electricity costs. The replicable implementation framework provides a practical roadmap for adoption, with clear phases, cost estimates, and timelines. The framework's emphasis on demand and catchment assessment ensures that the system is tailored to the institution's specific conditions, while the training and handover phase builds local capacity for operation and maintenance. The framework is consistent with institutional water management research, which has identified rainwater harvesting as a key intervention for reducing water consumption and improving sustainability. The system's environmental benefits are also significant, as capturing rooftop runoff reduces stormwater volume and flooding, contributing to climate resilience. The research context is particularly important, as Nigerian universities and polytechnics face significant water management challenges. A systematic review of sustainable water management at the University of Ibadan noted that the university currently exhibits unmetered supply systems, deferred maintenance, and no structured conservation programme. Empirical evidence from African universities demonstrates that significant institutional water losses arise from leakage and inefficient distribution systems. The modular rainwater harvesting and treatment system developed in this study provides a technically sound and locally appropriate solution that addresses these challenges. Overall, the findings confirm that modular rainwater harvesting and treatment systems are technically feasible, economically viable, and practically valuable for institutional non-potable water supply in South-West Nigeria, and they provide a deployable design and evidence base for wider adoption in the region.

Conclusion

This study successfully developed and evaluated a modular rainwater harvesting and treatment system for non-potable water applications in polytechnics in South-West Nigeria. The system achieved a mean water yield of 42.6 m³/week (64.2% of demand) and treated-water quality that met WHO and Nigerian standards for non-potable use, with turbidity reduced by 98.2%, total coliforms by 99.5%, and complete removal of *E. coli*. The reliability index was 0.82, and the system uptime was 96.8%. The capital cost was ₦1,605,000, with a payback period of 3.2 years. The developed replicable implementation framework provides a practical roadmap for adoption across technical-education facilities in the region. The principal implication is that modular rainwater harvesting and treatment systems are technically feasible, economically viable, and practically valuable for institutional non-potable water supply in South-West Nigeria, and that the system and framework developed in this study provide the tools and guidance required to support wider adoption. Future research should extend this work in several directions: evaluating the system across a larger number of institutions and varying rainfall conditions; improving pathogen removal through enhanced disinfection; investigating the integration of rainwater harvesting with greywater recycling and other water conservation measures; and exploring the use of smart metering and monitoring for demand management and leak detection.



Funding

This research was funded through the Tertiary Education Trust Fund (TETFund) Institution-Based Research (IBR) Intervention, The Federal Polytechnic Ede, Osun State, Nigeria. The funding agency provided financial support for the execution of the study. The funder had no role in the study design; data collection, analysis, or interpretation; manuscript preparation; or the decision to publish the findings.

Conflict of Interest

The authors declare that there are no competing financial interests or personal relationships that could have influenced the work reported in this study.

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