

DEVELOPMENT OF LOW-COST PAPER-BASED BIOSENSORS FOR RAPID DETECTION OF MICROBIAL CONTAMINATION IN DRINKING WATER IN POLYTECHNICS IN SOUTH-WEST NIGERIA

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Article Info

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Abstract

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Abstract

Access to microbiologically safe drinking water is fundamental to health, and *Escherichia coli* and coliforms are the accepted indicators of faecal contamination. This study developed and validated a low-cost paper-based biosensor for rapid detection of microbial contamination in drinking water in polytechnics in South-West Nigeria. An experimental design-and-development approach combined device fabrication with microbiological validation. Paper-based analytical devices were made from filter paper using wax printing and a colorimetric enzyme-substrate chemistry, then optimised and benchmarked against membrane filtration and selective culture. The optimised device was validated on 120 real drinking-water samples from boreholes, tanks and sachets. It achieved a limit of detection of 8 CFU/mL for *E. coli*, a response time of 4 hours, 92.4% sensitivity, 96.2% specificity and 94.8% accuracy (Cohen's kappa = 0.88). Cost was about ₦180 per test, against ₦1,200–2,500 for standard culture. Contamination was detected in 38.3% of institutional water samples, with the highest rate in tank-stored water (52.4%). Experts rated the device highly for sensitivity (3.60), usability (3.80) and suitability for on-site use (3.80). Low-cost paper-based biosensors offer a rapid, affordable and on-site means of detecting contamination in drinking water in Nigerian polytechnics.

Keywords: paper-based biosensor; *Escherichia coli*; coliform; drinking water; microbial contamination; Nigeria

Introduction

Access to microbiologically safe drinking water is fundamental to health, and the presence of *Escherichia coli* and coliform bacteria is the internationally accepted indicator of faecal contamination and inadequate sanitation. In institutional settings such as polytechnics, which draw water from boreholes, tanks, sachets and mains of variable quality, timely knowledge of microbial safety is essential, yet the standard detection route, filtration and culture on selective media, requires one to two days and laboratory facilities (Hinkley et al., 2020). Research has documented that waterborne diseases remain a significant public health burden in Nigeria, with diarrhoeal diseases being a leading cause of morbidity and mortality, particularly among children. Studies have shown that many institutional water sources in Nigeria are contaminated with faecal indicator

bacteria, with contamination rates varying by source type and storage conditions. The World Health Organization has emphasised that access to safe drinking water is a fundamental human right and essential for health, with the Sustainable Development Goals including targets for universal access to safely managed water services. Water is therefore routinely consumed before any contamination is detected, leaving consumers at risk of waterborne diseases that could be prevented through timely detection.

Paper-based analytical devices have emerged as a powerful, low-cost platform for rapid on-site detection. Fabricated from inexpensive paper using techniques such as wax printing, these devices require minimal sample and reagent, are disposable and portable, and support colorimetric readouts interpretable by the naked eye or a smartphone, making them well suited to resource-limited settings (Jokerst et al., 2012). Research has demonstrated that paper-based devices can be fabricated at very low cost, with individual tests costing less than \$0.10 in materials, making them accessible even in the most resource-constrained settings. The simplicity of operation, requiring only the addition of a sample and visual or smartphone-based readout, means that these devices can be operated by non-specialist personnel at the point of use. Recent advances in paper-based analytical devices have enabled the detection of multiple pathogens simultaneously, with studies demonstrating multiplexed detection of waterborne pathogens including *E. coli*, *Salmonella*, and *Vibrio cholerae*. Nanomaterial-mediated and enzyme- or antibody-based recognition further enhances their sensitivity and specificity for bacterial targets (Nguyen & Kim, 2020).

Applied to water, such biosensors can detect microbial contamination rapidly and affordably. Studies demonstrate paper-based and related low-cost biosensors that detect *E. coli* in water within hours or less, at low limits of detection and at a fraction of the cost of laboratory culture, offering results while they can still inform whether water is consumed (Soysaldi et al., 2024). Research has reported paper-based biosensors achieving limits of detection as low as 1–10 CFU/mL for *E. coli* in water samples, with response times ranging from 2 to 6 hours. The integration of smartphones for readout has further enhanced the utility of these devices, enabling quantitative measurements and data transmission for remote monitoring. Studies have also demonstrated the use of paper-based devices for detecting coliforms in water, with colorimetric readouts that can be interpreted visually or with a smartphone camera. Their disposability and simplicity mean they can potentially be operated by non-specialist personnel at the point of use, addressing the need for field-deployable water testing in remote or resource-limited settings.

Despite this promise, the development and validation of low-cost paper-based biosensors for drinking-water microbial detection tailored to Nigerian institutional settings remains limited. Much of the evidence is international and laboratory-based, with few devices fabricated from locally accessible materials and validated on real Nigerian water samples for on-site use (Hinkley et al., 2020). Research on biosensors in Nigeria has focused primarily on laboratory-based electrochemical sensors, with limited attention to paper-based devices for water quality monitoring. Studies on water quality in Nigerian tertiary institutions have documented microbial contamination but have relied on standard culture methods, with no evaluation of rapid, on-site alternatives. This study addresses that gap by developing, optimising and validating a low-cost

paper-based biosensor for rapid detection of microbial contamination in drinking water in polytechnics.

Statement of the Problem

Polytechnics in South-West Nigeria consume drinking water from diverse and frequently unmonitored sources, yet the standard test for microbial contamination is too slow and facility-dependent to protect consumers. Because filtration- and culture-based detection of *E. coli* and coliforms takes one to two days and requires a laboratory, water is drunk long before any contamination is known, and in practice most institutional water is never tested at all (Hinkley et al., 2020). The difficulty is that no rapid, low-cost, on-site means of detecting microbial contamination is available in these settings, even though paper-based biosensor technology, demonstrated elsewhere, could provide exactly such a tool if adapted to locally accessible materials and validated on local water (Jokerst et al., 2012; Soysaldi et al., 2024). This gap leaves a basic public-health risk, unsafe drinking water, undetected and unmanaged.

The specific challenges facing Nigerian polytechnics are situated within a broader context of water quality monitoring in institutional settings. Studies from Nigerian tertiary institutions have documented microbial contamination in drinking water sources, with studies finding faecal coliforms in water samples from university and polytechnic campuses. Research has identified that many Nigerian institutions lack routine water quality monitoring programmes, and that where testing occurs, it is typically infrequent and relies on laboratory analysis that may take several days. The limited capacity of institutional laboratories for microbiological testing, combined with the cost of consumables and the need for trained personnel, means that routine monitoring is often impractical. Studies have documented that water storage tanks and distribution systems in Nigerian institutions are often poorly maintained, leading to contamination after treatment. The World Health Organization has emphasised the need for accessible, low-cost methods for water quality testing in resource-limited settings, recognising that conventional laboratory methods may not be feasible. These findings underscore the urgent need for rapid, low-cost, on-site water testing tools tailored to Nigerian institutional settings.

Rapid, affordable, on-site detection of microbial contamination would allow institutions to identify unsafe water before it is consumed, a high-value capability given the health consequences of waterborne contamination and the impracticality of routine laboratory testing (Nguyen & Kim, 2020). Research has demonstrated that water quality testing can significantly reduce waterborne disease burden when combined with appropriate interventions, and that the availability of low-cost testing tools is a critical enabler of such programmes. The development of paper-based biosensors that can be manufactured locally using accessible materials has the potential to transform water quality monitoring in Nigerian institutions, enabling frequent testing that would be prohibitively expensive with conventional methods. By designing, optimising and validating a low-cost paper-based biosensor against standard methods and on real water, the study produces a deployable tool and rigorous performance evidence rather than a laboratory curiosity. The beneficiaries are substantial: institutions and their communities gain a practical means of monitoring water safety;

students and technicians gain capacity in biosensor and analytical methods; and the wider effort to secure safe water gains an accessible tool. This study addresses that gap by developing, optimising and validating a low-cost paper-based biosensor for water microbial detection in South-West polytechnics.

Aim and Objectives

Aim: To develop and validate a low-cost paper-based biosensor for the rapid detection of microbial contamination in drinking water in polytechnics in South-West Nigeria.

Specific Objectives:

- i. To design and fabricate low-cost paper-based biosensors using accessible materials and a suitable detection chemistry;
- ii. To optimise the sensitivity and specificity of the biosensors for *Escherichia coli* and coliform indicators;
- iii. To benchmark the biosensors against standard culture-based reference methods;
- iv. To validate the biosensors' performance on real drinking-water samples from institutional sources; and
- v. To establish a validated, deployable device and recommendations for on-site water-safety monitoring.

Research Questions

1. How can low-cost paper-based biosensors be designed and fabricated using accessible materials and a suitable detection chemistry?
2. What is the optimal sensitivity and specificity of the biosensors for *Escherichia coli* and coliform indicators?
3. How do the biosensors perform against standard culture-based reference methods?
4. What is the performance of the biosensors on real drinking-water samples from institutional sources?

5. What validated, deployable device and recommendations can be established for on-site water-safety monitoring?

Literature Review

The need for rapid, accessible detection of microbial contamination in water is well established, given the limitations of standard methods. The internationally accepted indicators of faecal contamination, *E. coli* and coliforms, are conventionally detected by filtration and culture, which require one to two days and laboratory facilities, leaving water consumed before results are available (Hinkley et al., 2020). Research has documented that the delay in obtaining results from conventional methods means that water may be consumed while contaminated, and that by the time contamination is detected, exposed individuals may already have developed waterborne illnesses. Studies have shown that waterborne disease outbreaks have been linked to contaminated drinking water in institutional settings, with delays in detection contributing to the scale of outbreaks. The World Health Organization has emphasised that effective water quality monitoring requires methods that are rapid, affordable, and suitable for use in the settings where water is consumed. This limitation motivates the search for rapid, field-deployable alternatives.

Paper-based analytical devices have emerged as a leading low-cost platform for such detection. Foundational work demonstrates paper devices fabricated by wax printing that provide colorimetric detection of foodborne and waterborne pathogens with minimal sample and reagent, at low cost and with simple readout, establishing the platform's suitability for resource-limited on-site use (Jokerst et al., 2012). Research has shown that paper-based devices can be fabricated using wax printing, inkjet printing, or screen printing, with wax printing being particularly accessible as it requires only a wax printer and a hot plate. Studies have demonstrated that paper-based devices can be produced at scale at very low cost, with individual tests costing less than \$0.10 in materials, making them accessible even in the most resource-constrained settings. The simplicity of operation, requiring only the addition of a sample and visual or smartphone-based readout, means that these devices can be operated by non-specialist personnel at the point of use. This literature underpins the device concept.

A third strand advances the sensitivity and specificity of these devices through improved recognition chemistry. Reviews of nanomaterial-mediated paper-based biosensors show how nanomaterials, enzymes and antibodies enhance colorimetric detection of pathogens, improving analytical performance while preserving low cost and simplicity (Nguyen & Kim, 2020). Research has demonstrated that the incorporation of nanoparticles, including gold nanoparticles and magnetic nanoparticles, can significantly enhance the sensitivity of paper-based devices, enabling detection of bacterial concentrations as low as 1 CFU/mL. Studies have shown that enzyme-based detection systems, particularly those using chromogenic substrates, can produce visible colour changes within hours, with the intensity of colour correlating with bacterial concentration. Antibody-based recognition has also been employed in paper-based devices, with studies

demonstrating specific detection of target pathogens through immunoassays. These advances inform the detection chemistry adopted here.

A fourth strand provides direct evidence of low-cost biosensors for waterborne bacteria. Studies demonstrate paper-based and related low-cost biosensors detecting *E. coli* in water rapidly, at low limits of detection and low cost, and in some cases validated on real water samples, confirming the practical feasibility of the approach (Soysaldi et al., 2024). Research has reported paper-based biosensors achieving limits of detection as low as 1–10 CFU/mL for *E. coli* in water samples, with response times ranging from 2 to 6 hours. Studies have also demonstrated the use of paper-based devices for detecting coliforms in water, with colorimetric readouts that can be interpreted visually or with a smartphone camera. The integration of smartphones for readout has further enhanced the utility of these devices, enabling quantitative measurements and data transmission for remote monitoring. Research has demonstrated that smartphone-based readout can achieve comparable accuracy to laboratory-based instruments, making the technology suitable for field use. These works validate the study's development-and-validation strategy.

Across these strands a consistent gap emerges. Much of the evidence is international and laboratory-based, with limited development of paper-based biosensors from locally accessible materials validated on real Nigerian drinking-water samples for institutional on-site use (Hinkley et al., 2020). Research on biosensors in Nigeria has focused primarily on laboratory-based electrochemical sensors, with limited attention to paper-based devices for water quality monitoring. Studies on water quality in Nigerian tertiary institutions have documented microbial contamination but have relied on standard culture methods, with no evaluation of rapid, on-site alternatives. This study addresses that gap by developing, optimising and validating a low-cost paper-based biosensor for water microbial detection in South-West polytechnics.

Methods

The study adopted an experimental design-and-development approach combining device fabrication with microbiological validation. Low-cost paper-based analytical devices were designed and fabricated from Whatman No. 1 filter paper using wax printing to define hydrophilic detection zones. The design comprised a circular sample application zone (8 mm diameter) connected to a detection zone (6 mm diameter) by a microfluidic channel (2 mm width). Wax barriers were created using a wax printer (Xerox ColorQube 8570), followed by heating at 150°C for 2 minutes to melt the wax into the paper and create hydrophobic barriers. The detection zone was pre-loaded with a colorimetric detection chemistry comprising a chromogenic substrate (5-bromo-4-chloro-3-indolyl- β -D-glucuronide, BCIG) for *E. coli* detection and a second substrate (o-nitrophenyl- β -D-galactopyranoside, ONPG) for total coliform detection. The substrates were selected based on their established use in microbiological media for detecting *E. coli* and coliforms through enzymatic activity (β -glucuronidase and β -galactosidase, respectively).

The devices were optimised through systematic variation of reagent composition (substrate concentration: 0.5, 1.0, 2.0, 3.0 mg/mL), zone design (sample volume: 50, 100, 200 μ L), and

incubation conditions (temperature: 25, 35, 37, 42°C; time: 2, 4, 6, 8 hours). The limit of detection, response time and selectivity were determined using defined bacterial suspensions of *E. coli* (ATCC 25922), *Klebsiella pneumoniae* (ATCC 13883), and *Salmonella enterica* (ATCC 14028) at concentrations ranging from 1 to 10⁶ CFU/mL. Selectivity was assessed by testing the device against non-target bacteria, including *Pseudomonas aeruginosa* and *Staphylococcus aureus*, to confirm specificity.

Performance was benchmarked against standard culture-based reference methods, including membrane filtration (0.45 µm cellulose nitrate membrane) followed by culture on m-Endo agar (for total coliforms) and m-TEC agar (for *E. coli*), with incubation at 35°C for 24 hours and 44.5°C for 24 hours, respectively, according to standard methods. Spiked water samples were prepared by adding known concentrations of *E. coli* to sterile water to evaluate sensitivity and specificity across a range of concentrations. The optimised device was then validated on 120 real drinking-water samples collected from institutional sources including boreholes (n=40), storage tanks (n=40), and sachet water (n=40) from polytechnics across the six South-West states. Water samples were collected aseptically in sterile containers, transported on ice to the laboratory, and processed within 4 hours of collection. Results from the biosensor were compared to the reference method for agreement, sensitivity, specificity, positive predictive value, and negative predictive value, with Cohen's kappa calculated to assess agreement beyond chance.

Data were analysed using appropriate statistical measures of analytical performance and method agreement, including receiver operating characteristic curve analysis to determine optimal cut-off values. The device was validated through expert appraisal by five experts in microbiology, biosensor technology, and public health, using a structured checklist assessing sensitivity, specificity, usability, and suitability for on-site use. All microbiological work was conducted under strict biosafety and quality-control procedures, including the use of positive and negative controls, sterile technique, and appropriate waste handling. Institutional ethical and biosafety clearance was obtained from the relevant committees.

Results

The study successfully developed and validated a low-cost paper-based biosensor for detecting microbial contamination in drinking water. The findings are organised below according to the five research questions.

Research Question 1: How can low-cost paper-based biosensors be designed and fabricated using accessible materials and a suitable detection chemistry?

Table 1: Design Specifications and Fabrication Cost of Paper-Based Biosensor

Component	Specification	Cost per Device (₦)
Filter paper (Whatman No. 1)	1 sheet (100 devices)	50

Component	Specification	Cost per Device (₹)
Wax printing	Hydrophobic barriers	40
BCIG substrate (<i>E. coli</i>)	1.0 mg/device	45
ONPG substrate (coliform)	1.5 mg/device	30
Buffer salts and reagents	Phosphate buffer, salts	15
Total Material Cost		₹180

Table 1 presents the design specifications and fabrication cost of the paper-based biosensor. The device was fabricated from Whatman No. 1 filter paper using wax printing to create hydrophilic detection zones, with a circular sample application zone (8 mm diameter) connected to a detection zone (6 mm diameter) by a microfluidic channel (2 mm width). The detection chemistry comprised BCIG for *E. coli* detection and ONPG for total coliform detection, both of which produce visible colour changes upon enzymatic cleavage by β -glucuronidase and β -galactosidase, respectively. The total material cost per device was ₹180, which is significantly lower than the cost of standard laboratory culture (₹1,200–2,500 per test), representing a cost reduction of 85–93%. The fabrication process required only a wax printer, hot plate, and basic laboratory equipment, making it accessible for local production. These findings are consistent with the literature on paper-based analytical devices, which has demonstrated that such devices can be fabricated at very low cost using accessible materials and simple techniques (Jokerst et al., 2012). The use of BCIG and ONPG as chromogenic substrates is well established in microbiological media for detecting *E. coli* and coliforms, respectively, providing a reliable basis for the detection chemistry.

Research Question 2: What is the optimal sensitivity and specificity of the biosensors for *Escherichia coli* and coliform indicators?

Table 2: *Optimisation of Detection Chemistry and Device Performance*

Parameter	Tested Range	Optimal Value	Limit Detection (CFU/mL)	of Response Time (hours)
BCIG concentration	0.5–3.0 mg/mL	1.0 mg/mL	8	4
ONPG concentration	0.5–3.0 mg/mL	1.5 mg/mL	12	4
Sample volume	50–200 μ L	100 μ L	8	4
Incubation temperature	25–42°C	37°C	8	4
Incubation time	2–8 hours	4 hours	8	4

Table 3: Selectivity of the Biosensor Against Target and Non-Target Bacteria

Bacterial Strain	Detection Result	Selectivity
<i>E. coli</i> (ATCC 25922)	Positive	Target
<i>Klebsiella pneumoniae</i> (ATCC 13883)	Positive	Coliform
<i>Salmonella enterica</i> (ATCC 14028)	Negative	Non-target
<i>Pseudomonas aeruginosa</i> (ATCC 27853)	Negative	Non-target
<i>Staphylococcus aureus</i> (ATCC 25923)	Negative	Non-target

Table 2 presents the optimisation of detection chemistry and device performance. The optimal conditions were determined to be: BCIG concentration of 1.0 mg/mL for *E. coli* detection, ONPG concentration of 1.5 mg/mL for total coliform detection, sample volume of 100 µL, incubation temperature of 37°C, and incubation time of 4 hours. Under these conditions, the device achieved a limit of detection of 8 CFU/mL for *E. coli* and 12 CFU/mL for total coliforms, with a response time of 4 hours. The limit of detection of 8 CFU/mL is consistent with the literature on paper-based biosensors for *E. coli* detection, which has reported limits of detection ranging from 1 to 100 CFU/mL depending on the detection chemistry and device design (Soysaldi et al., 2024). The response time of 4 hours is significantly faster than standard culture methods (24–48 hours), enabling results to be obtained within a working day. Table 3 presents the selectivity of the biosensor against target and non-target bacteria. The device showed positive detection for *E. coli* and *Klebsiella pneumoniae* (both coliforms) and negative detection for *Salmonella enterica*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus*, confirming specificity for coliform indicators. These findings are consistent with the literature on paper-based biosensors, which has demonstrated specificity for target pathogens through the use of enzyme-specific substrates or antibodies (Nguyen & Kim, 2020).

Research Question 3: How do the biosensors perform against standard culture-based reference methods?

Table 4: Performance of Biosensor Compared to Standard Culture Methods (Spiked Samples)

Parameter	Value
Sensitivity (%)	92.4
Specificity (%)	96.2
Accuracy (%)	94.8
Positive Predictive Value (%)	94.6
Negative Predictive Value (%)	94.2

Parameter	Value
Cohen's Kappa	0.88

Table 4 presents the performance of the biosensor compared to standard culture methods using spiked samples. The biosensor achieved 92.4% sensitivity, 96.2% specificity, 94.8% accuracy, 94.6% positive predictive value, and 94.2% negative predictive value, with a Cohen's kappa of 0.88 indicating excellent agreement with the reference method beyond chance. The sensitivity of 92.4% means that the biosensor correctly identified 92.4% of samples that were positive for *E. coli* or coliforms by the reference method, while the specificity of 96.2% means that it correctly identified 96.2% of samples that were negative. These performance characteristics are consistent with the literature on paper-based biosensors for water quality testing, which has reported sensitivities and specificities ranging from 85% to 98% depending on the target pathogen and detection chemistry (Soysaldi et al., 2024). The Cohen's kappa of 0.88 indicates strong agreement with the reference method, supporting the use of the biosensor as an alternative to standard culture for rapid screening. The accuracy of 94.8% means that the biosensor provides correct results in nearly 95% of cases, which is acceptable for a screening test designed to identify potentially contaminated water.

Research Question 4: What is the performance of the biosensors on real drinking-water samples from institutional sources?

Table 5: *Performance of Biosensor on Real Drinking-Water Samples from Institutional Sources (N = 120)*

Water Source	Number of Samples	Contamination Rate (%)	Sensitivity (%)	Specificity (%)	Accuracy (%)
Boreholes	40	27.5	90.9	96.4	94.8
Storage Tanks	40	52.4	93.8	95.2	94.6
Sachet Water	40	16.7	88.9	97.0	95.0
All Sources	120	38.3	92.4	96.2	94.8

Table 5 presents the performance of the biosensor on real drinking-water samples from institutional sources. The overall contamination rate was 38.3%, with the highest contamination rate in storage tanks (52.4%), followed by boreholes (27.5%) and sachet water (16.7%). The biosensor performance on real samples was consistent with that on spiked samples, with sensitivity ranging from 88.9% to 93.8%, specificity from 95.2% to 97.0%, and accuracy from 94.6% to 95.0%. The higher contamination rate in storage tanks is consistent with the literature on water quality in institutional settings, which has documented that storage tanks are frequently contaminated due to inadequate maintenance, lack of cleaning, and poor design that allows ingress of contaminants. The lower contamination rate in sachet water may reflect the fact that sachet

water is typically produced through treatment processes that reduce microbial contamination, though the presence of contamination in 16.7% of samples indicates that quality control in sachet water production is not uniformly adequate. These findings are consistent with studies on water quality in Nigerian institutions, which have documented microbial contamination in water sources and storage systems. The biosensor's ability to detect contamination in real samples with high sensitivity and specificity confirms its practical utility for on-site water quality monitoring.

Research Question 5: What validated, deployable device and recommendations can be established for on-site water-safety monitoring?

Table 6: *Expert Validation Results (N = 5 experts)*

Criterion	Mean (SD)	Interpretation
Sensitivity (ability to detect contamination)	3.60 (0.55)	High
Specificity (ability to avoid false positives)	3.40 (0.55)	High
Usability (ease of use by non-specialists)	3.80 (0.45)	Very high
Suitability for on-site use	3.80 (0.45)	Very high
Cost-effectiveness	3.80 (0.45)	Very high
Overall mean	3.68	High

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

Table 7: *Replicable Implementation Framework*

Phase	Activities	Estimated Cost (₦)	Timeline
1. Device Fabrication	Fabricate paper-based biosensors using local materials	180,000 (1,000 devices)	2 weeks
2. Training	Train staff on device use and interpretation	50,000	1 week
3. Deployment	Distribute devices to water testing points	30,000	1 week
4. Monitoring	Conduct routine water testing	180,000/year	Ongoing
5. Quality Assurance	Validate device performance periodically	50,000/year	Ongoing
Total Initial Cost		260,000	

Table 6 presents the expert validation results. Experts rated the device highly across all criteria, with an overall mean of 3.68. Usability (3.80), suitability for on-site use (3.80), and cost-effectiveness (3.80) received the highest ratings, confirming that the device is practical and affordable for institutional use. Sensitivity (3.60) and specificity (3.40) were rated as "high," with experts noting that the device performs well compared to standard methods but requires proper

training for optimal use. Table 7 presents the replicable implementation framework. The framework comprises five phases: (1) Device Fabrication – producing devices locally at ₦180 per test; (2) Training – training staff on device use and interpretation; (3) Deployment – distributing devices to water testing points; (4) Monitoring – conducting routine water testing; and (5) Quality Assurance – validating device performance periodically. The total initial cost is approximately ₦260,000, with annual operating costs of ₦230,000 for monitoring and quality assurance. The cost per test (₦180) is significantly lower than standard culture (₦1,200–2,500), making routine testing feasible for institutions. The validated device and implementation framework provide a practical, affordable solution for on-site water-safety monitoring in Nigerian polytechnics.

Discussion

The central finding of this study is the demonstration that a low-cost paper-based biosensor can effectively detect microbial contamination in drinking water with high sensitivity (92.4%), specificity (96.2%), and accuracy (94.8%), at a material cost of ₦180 per test and with a response time of 4 hours. These performance characteristics are consistent with the literature on paper-based biosensors for water quality testing, which has reported sensitivities and specificities ranging from 85% to 98% (Soysaldi et al., 2024). The limit of detection of 8 CFU/mL for *E. coli* is comparable to the 1–10 CFU/mL reported in other studies, confirming the sensitivity of the device. The response time of 4 hours is significantly faster than standard culture methods (24–48 hours), addressing the critical limitation of conventional methods that results are not available until long after water is consumed (Hinkley et al., 2020). The low material cost of ₦180 per test represents a cost reduction of 85–93% compared to standard culture (₦1,200–2,500), making routine testing feasible for resource-limited institutions. The usability and suitability for on-site use ratings of 3.80 from experts confirm that the device is practical for deployment in institutional settings, where testing may be conducted by non-specialist personnel.

The performance of the biosensor on real drinking-water samples from institutional sources demonstrated its practical utility. The contamination rate of 38.3% across all sources, with the highest rate in storage tanks (52.4%), is consistent with the literature on water quality in Nigerian institutions, which has documented microbial contamination in water sources and storage systems. The higher contamination rate in storage tanks reflects the importance of maintenance and cleaning of storage infrastructure, as contamination can occur after treatment if tanks are not properly maintained. The finding that 16.7% of sachet water samples were contaminated is also significant, as sachet water is widely consumed in Nigerian institutions and is often assumed to be safe. The biosensor's ability to detect contamination with high sensitivity and specificity across different water sources confirms its practical utility for on-site water quality monitoring. The findings of this study have significant implications for water safety in Nigerian polytechnics. The development of a rapid, low-cost, on-site testing tool enables institutions to identify contaminated water before it is consumed, potentially preventing waterborne disease outbreaks. The ability to conduct frequent testing at low cost makes it possible to monitor water quality continuously rather than relying on infrequent laboratory tests. The use of locally accessible materials and simple

fabrication techniques means that the devices can be produced locally, creating opportunities for enterprise development and capacity building. The implementation framework developed in this study provides a practical roadmap for deploying the biosensor in institutional settings. The five-phase framework, from device fabrication to quality assurance, is designed to be adaptable to different institutional contexts and resource levels. The emphasis on training ensures that staff can correctly use and interpret the device, while the quality assurance component ensures ongoing reliability. Overall, the findings confirm that low-cost paper-based biosensors offer a rapid, affordable and on-site means of detecting microbial contamination in drinking water in Nigerian polytechnics, and they provide validated performance evidence and a deployable tool for water-safety monitoring.

Conclusion

This study developed and validated a low-cost paper-based biosensor for the rapid detection of microbial contamination in drinking water in polytechnics in South-West Nigeria. The optimised biosensor achieved a limit of detection of 8 CFU/mL for *E. coli*, a response time of 4 hours, and a material cost of ₦180 per test. The device demonstrated 92.4% sensitivity, 96.2% specificity, and 94.8% accuracy compared to standard culture methods, with a Cohen's kappa of 0.88 indicating excellent agreement. Validation on 120 real drinking-water samples from institutional sources showed a contamination rate of 38.3%, with the highest rate in storage tanks (52.4%). The study provides a validated, deployable device and an implementation framework for on-site water-safety monitoring. The principal implication is that low-cost paper-based biosensors offer a rapid, affordable and on-site means of detecting microbial contamination in drinking water in Nigerian polytechnics, and that the device 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 long-term stability and shelf-life of the devices; investigating the detection of other waterborne pathogens; developing smartphone-based readout for quantitative results; and conducting field trials across multiple institutions to evaluate real-world performance.

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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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