



Research Article

Microbial Safety and Physicochemical Integrity of Houseboat Water in a Petroleum-Impacted Creek System of the Niger Delta

*Ogunkeyede, A. O., Urhibo, V. O., and Okorhi-Damisa, F. B.

Department of Environmental Management, Federal University of Petroleum Resources, Effurun, Nigeria

*Corresponding Author's email: ogunkeyede.akinyemi@fupre.edu.ng; Phone: +23409030223041

ABSTRACT

Potable water is a deceptively fragile part of public health, especially around aquatic environments that have been contaminated but remain clear hiding chemical and microbial dangers. This study evaluated the physicochemical integrity and microbiological safety of potable water stored aboard houseboats operating within the Jones Creek petroleum corridor of the Niger Delta over a three-month sampling period. A cross-sectional design was adopted, and triplicate samples were collected from multiple operational locations, including Amalgamated Marine and Technical Services Limited (AMAT), Nigerian Exploration and Production Limited (NEPL), and a treated reference source (Well Workover Node). Physicochemical parameters were determined using standard methods, while microbial quality was evaluated using membrane filtration, biochemical identification, and phenotypic virulence screening. Results showed that measured parameters were within recommended limits; however, bacterial isolates with detectable virulence traits were present, indicating *Escherichia coli*, *Enterobacter cloacae*, *Serratia marcescens*, *Pseudomonas aeruginosa* and *Bacillus subtilis*. Virulence screening demonstrated haemolytic activity in 40% of isolates and lipase expression in 60%, suggesting heterogeneous but tangible pathogenic potential. The contrast between chemical compliance and detectable virulence traits indicates that physicochemical conformity does not equate to microbiological security. These findings demonstrate that physicochemical compliance does not guarantee microbiological safety, highlighting the need for integrated water quality monitoring in petroleum-influenced aquatic systems.

Keywords: Bacterial isolates; Houseboat water; Physicochemical quality; Virulence factors; Water safety

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INTRODUCTION

Safe drinking water remains one of the most fragile assumptions in public health because aesthetic acceptability and physicochemical compliance do not necessarily guarantee microbiological safety. This remains a major global health concern, particularly in settings where water is stored for prolonged periods or handled through multiple points before use. According to the World Health Organization, faecal contamination presents the greatest risk to drinking-water safety, and an estimated 1.7 billion people globally used a drinking-water source contaminated

with faeces in 2022 (World Health Organisation [WHO], 2023). In addition, unsafe water, sanitation, and hygiene contribute substantially to preventable disease burden worldwide, particularly in low- and middle-income countries (WHO, 2023). These realities suggest that water safety should not be judged solely at the point of treatment or source abstraction, but rather across the entire chain of storage, handling, distribution, and consumption. In recent times, it has been reported that microbiological deterioration may occur even in water systems that initially meet physicochemical or

treatment standards. Drinking-water systems are increasingly recognized as ecological environments capable of supporting opportunistic and environmentally persistent microorganisms, especially where conditions favour stagnation, low disinfectant residuals, and biofilm formation (LeChevallier *et al.*, 2024). In practical terms, this means that apparently acceptable water may still pose health risks if microbial contamination occurs during storage or within the distribution pathway. This concern has become more important in recent years as studies have also shown that drinking water can serve as a reservoir for antimicrobial-resistant bacteria, thereby extending its significance beyond conventional faecal contamination alone (Alawi *et al.*, 2024). In operational environments characterized by high occupancy, repeated handling, and restricted infrastructure control, these concerns reinforce the need for integrated water quality surveillance.

Within this context, physicochemical conformity is necessary but not sufficient as a standalone indicator of potable water safety. Parameters such as pH, temperature, turbidity, electrical conductivity, alkalinity, hardness, and suspended solids remain essential for evaluating treatment performance, storage stability, infrastructure integrity, and conditions that may favour microbial persistence or regrowth. Such measurements provide important information about the physical and chemical state of water, but they do not directly indicate whether the water is biologically safe for human consumption. This is particularly relevant in stored water systems where intermittent use, material interfaces, enclosed tanks, and variable retention times can create favourable conditions for microbial colonization and survival. Biofilm development in storage and distribution systems further complicates this relationship by allowing microorganisms to persist even when the bulk water appears compliant with regulatory thresholds (LeChevallier *et al.*, 2024).

From a microbiological perspective, indicator organisms remain central to water quality surveillance. *Escherichia coli* is widely used as a marker of faecal contamination and remains one of the most important microbiological indicators of drinking-water safety. However, growing evidence suggests that reliance on indicator organisms alone may not fully capture the diversity of microbial hazards that can occur in stored and engineered water systems. As a result, increasing attention has shifted toward opportunistic bacteria associated with aquatic infrastructure, storage environments, and premise plumbing. Among these, *Pseudomonas*

aeruginosa is of particular concern because of its ability to survive under nutrient-limited conditions, colonize surfaces, and form resilient biofilms that enhance persistence within water systems. Similarly, *Serratia marcescens* has gained attention because of its ecological versatility, environmental persistence, and clinical relevance as an opportunistic pathogen (LeChevallier *et al.*, 2024; Alawi *et al.*, 2024). The detection of such organisms in potable water systems is important not only because of their presence, but because they may indicate broader weaknesses in storage hygiene and microbial control.

Beyond simple isolation and identification, the evaluation of phenotypic virulence traits can provide a more meaningful interpretation of potential public health significance. The production of extracellular enzymes such as haemolysins, DNase, gelatinase, and lipase has been associated with bacterial colonization, persistence, tissue invasion, and ecological fitness in several opportunistic species. In environmental microbiology, these traits are useful because they offer practical insight into the possible pathogenic potential of isolates recovered from non-clinical settings. Their assessment therefore strengthens microbiological interpretation beyond taxonomic detection alone and may provide a more realistic indication of the biological relevance of bacterial contaminants recovered from potable water.

The Niger Delta provides a particularly important context for this kind of investigation. The region is characterized by intense petroleum exploration and production activities, frequent marine transportation, dredging operations, equipment movement, and prolonged human presence in aquatic operational corridors. These conditions create multiple opportunities for secondary contamination of treated water during transport, storage, and use. In addition, the tropical climate and the operational dependence on enclosed or mobile water systems may favour microbial persistence in stored supplies. Although water quality monitoring in petroleum-linked environments often emphasizes chemical contamination and environmental pollution, microbiological safety within potable water systems used in these settings remains relatively underexplored. This is especially true for water stored aboard houseboats and other mobile support platforms, where supply systems are often exposed to repeated handling, storage stress, and irregular turnover.

Against this background, the present study examined the physicochemical integrity and microbial safety of

potable water stored aboard houseboats operating within the Jones Creek petroleum corridor, Warri South, Niger Delta. Specifically, the study aimed to: **(i)** determine key physicochemical indicators using triplicate determinations expressed as mean \pm standard deviation; **(ii)** isolate and identify culturable bacteria through morphological and biochemical characterization; and **(iii)** assess selected phenotypic virulence determinants as a screening tool for evaluating potential public health significance. By integrating physicochemical assessment with microbiological and virulence-based profiling, this study provides a more comprehensive understanding of potable water safety under real operational conditions.

MATERIALS AND METHODS

Study area

The investigation was undertaken within the Jones Creek corridor in Warri South Local Government Area

of the western Niger Delta, Nigeria. The creek is part of an interconnected tidal network linking the Warri River with the Forcados and Escravos waterways prior to discharge into the Atlantic system. The region represents an active petroleum-production landscape characterised by flow stations, marine logistics operations and numerous houseboats serving residential and industrial functions.

Geographically, the area lies approximately between longitudes 4°15'E–4°50'E and latitudes 7°45'N–7°50'N. The environment is low-lying, tidally influenced and receives substantial rainfall, with subsurface materials dominated by unconsolidated sands, silts and clays typical of deltaic formations. Such conditions favour contaminant redistribution and microbial persistence, providing a suitable framework for evaluating potable water integrity under operational pressure (Figure 1).

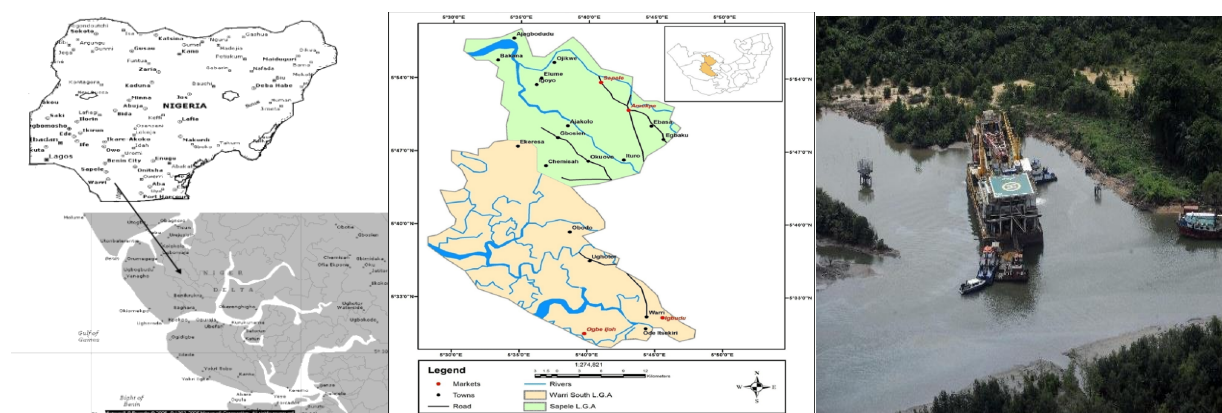


Figure 1: Maps showing the Location and Activities at the Study Area

Study design and sampling strategy

A cross-sectional monitoring design was adopted to assess physicochemical condition and microbial safety of potable water stored aboard houseboats. Sampling points comprised vessels distributed across Amalgamated Marine and Technical Services Limited (AMAT) and Nigerian Exploration and Production Limited (NEPL) operational clusters, while treated supply water in Well Workover Node (WWN) served as the reference. Triplicate samples were collected at each location to enhance representativeness and reduce analytical uncertainty. The study was conducted over a three-month period (June–August 2025).

Sample collection and preservation

Samples for physicochemical determinations were collected in pre-cleaned high-density polyethylene

containers. Microbiological samples were obtained aseptically using sterile bottles. Containers were rinsed with source water prior to final filling and transported in insulated coolers maintained at approximately 4 °C. Laboratory analysis commenced within six hours of collection to minimise alteration of chemical and microbiological characteristics.

Physicochemical measurements

Temperature, pH and electrical conductivity were measured in situ using calibrated multiparameter probes. Turbidity was determined by nephelometric method.

Total suspended solids were quantified gravimetrically following filtration and drying at 105 °C to constant weight. Alkalinity and hardness were analysed by standard titrimetric procedures. Instrument calibration and verification were performed using appropriate standards prior to

measurement. Analytical procedures followed established guidance for drinking-water examination (WHO, 2022). Results from triplicate determinations were expressed as **mean \pm standard deviation**.

Enumeration of culturable bacteria

Microbial density was evaluated using membrane filtration. A 100 mL aliquot of each sample was filtered through sterile 0.45 μ m membranes, which were incubated on selective media at 37 °C for 24 h. Colonies were enumerated and expressed as colony forming units per 100 mL (CFU/100 mL).

Isolation and purification

Distinct colonies were sub-cultured repeatedly to obtain pure isolates. Cultures were maintained on nutrient agar at 4 °C pending further analyses.

Morphological characterization

Colony characteristics including pigmentation, elevation, margin, and form were recorded. Gram reaction, cellular morphology and spore formation were examined microscopically following standard staining techniques.

Biochemical identification section

Isolates were subjected to catalase, oxidase, indole production, citrate utilisation, urease activity, motility, and carbohydrate fermentation tests. Triple Sugar Iron reactions were interpreted after incubation. Identification was achieved through comparison with established diagnostic schemes (Janda and Abbott, 2021), and results were cross validated using combined morphological and biochemical profiles.

Assessment of phenotypic virulence determinants

Virulence-associated traits were evaluated using haemolysin production on blood agar, DNase activity, gelatin hydrolysis and lipase expression. These extracellular enzymes serve as practical indicators of potential pathogenic capability among environmental isolates.

Quality assurance and control

All analyses were performed in triplicate. Media sterility, reagent performance and instrument calibration were routinely verified. Where applicable, control strains were included to validate biochemical reactions in accordance with laboratory quality management principles.

Data Analysis

Data were treated using descriptive statistics and reported as arithmetic mean \pm standard

RESULTS

Physicochemical integrity of houseboat water

The physicochemical properties of potable water sourced from houseboats in the Jones Creek operational corridor (Table 1) indicate a system that is chemically compliant but spatially heterogeneous in nuanced ways.

The pH level, which is a measure of the amount of hydrogen ions in the water, ranged from 6.06 \pm 0.23 (NEPL4) to 7.59 \pm 0.15 (AMAT1). This means that the water was slightly acidic to almost neutral. Most of the sampling points were within the recommended range of 6.5 to 8.5, but there were some small differences at NEPL4 (6.06) and NEPL3 (6.18 \pm 0.35). This could be due to local factors, such as how the samples were stored or how the source changed. The fact that the standard deviations across stations are generally less than 0.55 shows that the results can be repeated and that there isn't much variability within samples.

The temperature ranged from 25.3 \pm 1.50°C (AMAT1, AMAT2, WWN) to 29.40 \pm 1.90°C (AMAT3), which is well below the recommended limit of <35°C. This moderate change in space shows that the environmental conditions are typical of tropical creek systems and that the stored water quality is not likely to be affected by thermal stress.

Electrical conductivity varied significantly, with a 12-fold increase from 13.00 μ S/cm (AMAT4) to 159.00 μ S/cm (AMAT3). Even though AMAT3 (159 μ S/cm) and NEPL4 (110.00 \pm 10.00 μ S/cm) had higher readings, all of the measurements were still well below the guideline threshold of 1000 μ S/cm, which shows that mineralisation is low overall. The variability we saw is probably due to differences in the composition of the source water and possible interactions with the storage containers.

The turbidity values were always low, between 0.21 and 1.83 NTU (AMAT4) and 1.83 and 0.25 NTU (AMAT2), which is well below the recommended limit of 5 NTU. Total suspended solids (TSS) were also very low at all stations, ranging from 0.23 \pm 0.02 mg/L (WWN) to 0.98 \pm 0.25 mg/L (NEPL1). This shows that the water was very clear and had very little particulate matter. These results indicate that the water consistently exhibited high aesthetic quality across the sampling network.

The alkalinity values were all low, between 0.12 \pm 0.00 mg/L (AMAT4) and 0.50 \pm 0.05 mg/L (AMAT3), which is much lower than the guideline value of <50 mg/L. This means that the water does not have a lot of buffering capacity. Total hardness also stayed very low at all stations, with values ranging from 1.05 \pm 0.00 mg/L (AMAT3) to 2.95 \pm 0.23 mg/L (NEPL2). This is well below the recommended range of 100–500

mg/L. These results show that the water is very soft. This isn't a direct health risk, but it could affect how easily the storage system corrode.

Morphological and biochemical identity of isolates

The results showed that the stored water kept its stable physicochemical properties across the operational environment, with low variability (standard deviations usually less than 10% of mean values) and met established drinking-water standards. But the fact that there is a little acidity in some places and that conductivity changes show how local operational factors can affect things. This shows that even water systems that meet chemical standards need to be constantly monitored in these complicated, busy places.

The phenotypic assessment of the isolates identified five bacterial taxa: *Enterobacter cloacae*, *Escherichia coli*, *Bacillus subtilis*, *Serratia marcescens*, and *Pseudomonas aeruginosa* (Table 2). All of the isolates were shaped like rods. The Gram reaction indicated that four isolates (*E. cloacae*, *E. coli*, *S. marcescens*, and *P. aeruginosa*) were Gram-negative, whereas *B. subtilis* was Gram-positive. Only *B. subtilis* was seen to make spores.

The shape of the colonies was different for each isolate. *E. cloacae*, *E. coli*, and *B. subtilis* displayed flat elevations with undulating margins and colonies of a cream hue. *S. marcescens* and *P. aeruginosa*, on the other hand, had colonies that were raised and had whole edges. *P. aeruginosa* had a lemon-colored pigmentation.

Phenotypic virulence determinants

Biochemical characteristics showed that all isolates had positive catalase activity. Only *P. aeruginosa* had oxidase activity; the other isolates did not. Indole production occurred solely in *E. coli*, whereas citrate utilisation was confirmed in *E. cloacae*, *B. subtilis*, *S. marcescens*, and *P. aeruginosa*, but not in *E. coli*.

All of the isolates were able to move. The isolates could be consistently identified because their colony morphology, Gram reaction, and biochemical characteristics all matched up.

As shown in Table 3, the bacterial isolates showed different levels of extracellular virulence-associated enzymes. Different species had different types of haemolytic activity. For example, *Bacillus subtilis* and *Serratia marcescens* had β -haemolysis, *Enterobacter cloacae* had α -haemolysis, and *Escherichia coli* and *Pseudomonas aeruginosa* had γ -haemolysis.

Three isolates (*B. subtilis*, *S. marcescens*, and *P. aeruginosa*) had DNase activity, but *E. cloacae* and *E. coli* did not. The production of gelatinase followed a similar pattern, as it was found in *B. subtilis*, *S. marcescens*, and *P. aeruginosa*, but not in *E. cloacae* and *E. coli*.

Lipase activity was detected in three isolates: *B. subtilis*, *E. cloacae*, and *E. coli*, while *S. marcescens* and *P. aeruginosa* exhibited negative results for this enzyme. *B. subtilis* exhibited all four virulence-associated traits (β -haemolysis, DNase, gelatinase, and lipase), whereas *E. cloacae* and *E. coli* demonstrated restricted enzyme expression. *S. marcescens* and *P. aeruginosa* exhibited partial expression, as both generated DNase and gelatinase while lacking lipase activity.

Table 1: Physicochemical properties of houseboat water samples from Jones Creek (mean ± SD)

| Parameter | AMAT1 | NEPL1 | AMAT2 | NEPL2 | AMAT3 | NEPL3 | AMAT4 | NEPL4 | WWN | Guideline |
|---------------------------------|------------|------------|------------|------------|-------------|------------|------------|--------------|------------|-----------|
| pH | 7.59±0.15 | 6.71±0.55 | 6.66±0.25 | 6.33±0.25 | 6.72±0.12 | 6.18±0.35 | 6.69±0.55 | 6.06±0.23 | 6.63±0.35 | 6.5–8.5 |
| Temperature (°C) | 25.3±1.50 | 28.30±1.50 | 25.3±1.50 | 26.30±2.15 | 29.40±1.90 | 28.3±2.15 | 26.30±2.50 | 29.30±2.00 | 25.30±1.85 | <35 |
| Electrical conductivity (µS/cm) | 46.00±3.50 | 37.00±3.90 | 48.00±3.00 | 33.00±3.11 | 159.00±8.11 | 26.00±1.25 | 13.00±2.00 | 110.00±10.00 | 16.00±1.55 | 1000 |
| Turbidity (NTU) | 0.63±0.15 | 0.27±0.04 | 1.83±0.25 | 1.11±0.19 | 0.90±0.04 | 0.74±0.04 | 0.21±0.12 | 0.84±0.06 | 1.45±0.70 | 5 |
| Total suspended solids (mg/L) | 0.78±0.25 | 0.98±0.25 | 0.90±0.02 | 0.59±0.14 | 0.65±0.02 | 0.72±0.03 | 0.69±0.24 | 0.87±0.04 | 0.23±0.02 | <10 |
| Alkalinity (mg/L) | 0.21±0.01 | 0.41±0.11 | 0.43±0.03 | 0.40±0.05 | 0.50±0.05 | 0.24±0.01 | 0.12±0.00 | 0.20±0.00 | 0.12±0.01 | <50 |
| Hardness (mg/L) | 1.99±0.22 | 2.15±0.15 | 2.67±0.95 | 2.95±0.23 | 1.05±0.00 | 2.50±0.05 | 2.57±0.09 | 1.66±0.09 | 2.54±0.32 | 100–500 |

Table 2. Cultural, morphological and biochemical characteristics of bacterial isolates

| Characteristic | <i>Enterobacter cloacae</i> | <i>Escherichia coli</i> | <i>Bacillus subtilis</i> | <i>Serratia marcescens</i> | <i>Pseudomonas aeruginosa</i> |
|---------------------|-----------------------------|-------------------------|--------------------------|----------------------------|-------------------------------|
| Elevation | Flat | Flat | Flat | Raised | Raised |
| Margin | Undulate | Undulate | Undulate | Entire | Entire |
| Colony colour | Cream | Cream | Cream | Cream | Lemon |
| Gram reaction | – | – | + | – | – |
| Cell type | Rod | Rod | Rod | Rod | Rod |
| Spore formation | – | – | + | – | – |
| Catalase | + | + | + | + | + |
| Oxidase | – | – | – | – | + |
| Indole | – | + | – | – | – |
| Citrate utilisation | + | – | + | + | + |
| Motility | + | + | + | + | + |

Table 3: Phenotypic virulence determinants of bacterial isolates

| Isolate | Haemolysin type | DNase | Gelatinase | Lipase |
|-------------------------------|-----------------|-------|------------|--------|
| <i>Bacillus subtilis</i> | B | + | + | + |
| <i>Enterobacter cloacae</i> | A | – | – | + |
| <i>Escherichia coli</i> | Γ | – | – | + |
| <i>Serratia marcescens</i> | B | + | + | – |
| <i>Pseudomonas aeruginosa</i> | γ | + | + | – |

DISCUSSION

This investigation examined potable water stored aboard operational houseboats within a petroleum-influenced creek environment, integrating physicochemical evaluation with bacterial identification and virulence profiling. The combined dataset provides a systems-level perspective on water quality performance, while simultaneously revealing latent microbiological vulnerabilities that may persist despite apparent chemical compliance. Contemporary water safety literature increasingly emphasises this disconnect, noting that physicochemical conformity does not inherently equate to microbiological security, particularly in complex operational environments (Pluym *et al.*, 2024; WHO, 2022).

Physicochemical observations indicated broad conformity with recognised drinking-water standards. The relatively narrow pH range (6.06–7.59) and low variability across replicates suggest effective buffering and minimal chemical perturbation during storage. Similarly, the low electrical conductivity values (13–159 $\mu\text{S}/\text{cm}$) indicate limited dissolved ionic content, reflecting low mineralisation and reduced risk of salinity-driven deterioration. These findings are consistent with reports from controlled water supply systems in petroleum and offshore environments, where enclosed transport and storage infrastructure help preserve baseline water chemistry and limit external contamination (Rahman *et al.*, 2022; Basse *et al.*, 2021).

Turbidity and total suspended solids remained consistently low across all sampling points (0.21–1.83 NTU and 0.23–0.98 mg/L, respectively), indicating minimal particulate loading. Low turbidity is often interpreted as an indicator of good water clarity; however, recent studies caution that while reduced particulate matter may limit microbial attachment sites, it does not eliminate the presence or persistence of planktonic microorganisms or biofilm-associated cells within storage systems (Pluym *et al.*, 2024; LeChevallier *et al.*, 2024). Thus, although the observed turbidity levels fall well within recommended limits, they should not be interpreted as definitive evidence of microbiological safety.

Temperature variability (25.3–29.4°C) appeared consistent with ambient environmental equilibration typical of tropical aquatic systems, rather than indicative of internal degradation processes. Similar temperature profiles have been reported in surface-connected and semi-enclosed water systems in the Niger Delta and comparable tropical regions, where

ambient conditions exert a dominant influence on stored water temperature (Akinola *et al.*, 2023). Importantly, this temperature range remains within conditions that can support microbial survival and, in some cases, proliferation, particularly for opportunistic waterborne bacteria (LeChevallier *et al.*, 2024).

In contrast, microbiological findings demonstrated that biological integrity did not mirror chemical stability. The recovery of *Escherichia coli* and *Enterobacter cloacae* points toward episodic contamination events, most plausibly linked to handling practices, storage interfaces, or distribution pathways. These organisms are widely recognised indicators of sanitary compromise in potable water systems, and their presence—even at low frequency—signals potential faecal ingress or post-treatment contamination (Suleiman *et al.*, 2024; WHO, 2022). In high-occupancy operational environments, such as houseboats, even intermittent detection becomes significant due to repeated exposure pathways and cumulative risk.

The presence of *Pseudomonas aeruginosa* is particularly important from an operational perspective. This organism is well known for its ability to form biofilms, tolerate disinfectants, and persist within plumbing and storage systems. Such traits enable survival and proliferation even when bulk-water physicochemical parameters remain within acceptable limits (LeChevallier *et al.*, 2024; Wang *et al.*, 2023). This reflects a broader phenomenon in engineered water systems, where environmental conditions selectively favour resilient opportunistic pathogens capable of exploiting low-nutrient and intermittently disinfected environments.

The isolation of the spore-forming *Bacillus subtilis* further supports the persistence of stress-tolerant microbial populations within stored water systems. Spore formation provides resistance to environmental stressors, including temperature variation, nutrient limitation, and sanitation measures, allowing long-term survival independent of short-term water quality conditions (Wang *et al.*, 2022). This highlights the capacity of storage systems to harbour dormant microbial reservoirs that may become active under favourable conditions.

Virulence screening added an additional dimension to risk interpretation. The detection of β -haemolytic activity in selected isolates suggests the presence of cytotoxic potential, while the frequent expression of lipase indicates metabolic adaptability and potential interaction with host tissues. In contrast, the more limited occurrence of DNase and gelatinase reflects

heterogeneity in virulence expression across isolates rather than uniform pathogenicity. Similar patterns have been reported in environmental and treated water systems, where microbial communities often exhibit survival-oriented traits alongside variable virulence potential (Okafor *et al.*, 2023; Zhang *et al.*, 2024).

Collectively, these findings reinforce a critical principle in contemporary water safety science: physicochemical compliance does not guarantee microbiological security. The divergence between chemical indicators and biological behaviour is increasingly recognised in modern drinking-water risk assessment, particularly in systems involving storage, transport, and intermittent use (Pluym *et al.*, 2024; WHO, 2022).

In petroleum-linked operational environments, this challenge is amplified. Continuous vessel movement, high personnel turnover, maintenance activities, and complex water transfer pathways introduce multiple opportunities for post-treatment contamination. Under such conditions, reliance on physicochemical monitoring alone may underestimate actual exposure risks. Integrated surveillance frameworks that incorporate microbial indicators, pathogen profiling, and functional traits are therefore essential for a more accurate and protective assessment of water safety (Wolf *et al.*, 2023; Zhang *et al.*, 2024).

The study integrated replicated measurements, multi-site coverage, and phenotypic evaluation, allowing cross-validation between environmental conditions and biological responses. This combined approach aligns with contemporary water quality assessment frameworks that emphasise the integration of physicochemical and microbiological indicators to achieve a more comprehensive understanding of system performance (Pluym *et al.*, 2024; WHO, 2022). The consistency observed across replicate measurements strengthens data reliability, while the multi-location design captures spatial variability typical of operational water systems.

The findings indicate that treatment and storage infrastructure were effective in maintaining physicochemical standards across the sampling network. Similar performance has been reported in managed water systems where controlled treatment processes and enclosed storage conditions help preserve baseline chemical quality during distribution (Rahman *et al.*, 2022; Bassey *et al.*, 2021). However, recent literature highlights that such chemical stability does not necessarily extend to microbiological integrity, particularly in systems

involving intermediate storage and repeated handling (Wolf *et al.*, 2023; LeChevallier *et al.*, 2024).

The persistence of microbial indicators despite physicochemical compliance suggests that post-treatment factors may play a critical role in shaping water quality. Hygienic handling practices, storage tank conditions, and distribution pathways have been identified as key control points where contamination can be introduced or amplified, especially in high-activity environments (Zhang *et al.*, 2024). In such systems, inadequate sanitation of storage vessels, intermittent water use, and human contact can facilitate microbial survival and regrowth even when source water is initially of acceptable quality.

Consequently, while the existing infrastructure demonstrates competence in maintaining chemical parameters, targeted improvements in hygienic handling, tank maintenance, and distribution oversight are necessary to minimise microbial persistence. Current water safety approaches increasingly advocate for system-wide risk management strategies that extend beyond treatment to include operational controls at all stages from storage to point-of-use (WHO, 2022; Pluym *et al.*, 2024).

Identification in this study was based on classical phenotypic approaches, including cultural, morphological, and biochemical characterisation. Such methods remain widely applied in routine operational surveillance due to their practicality, cost-effectiveness, and ability to provide rapid preliminary identification of clinically and environmentally relevant bacteria (Pluym *et al.*, 2024). However, phenotypic techniques are inherently limited in taxonomic resolution and may not reliably distinguish closely related species or detect cryptic diversity within microbial communities (Zhang *et al.*, 2024).

Recent advances in water microbiology emphasise the value of molecular-based approaches for improving accuracy and depth of analysis. Techniques such as 16S rRNA gene sequencing, whole-genome sequencing, and metagenomic profiling enable precise taxonomic identification, detection of non-culturable organisms, and characterisation of functional genes associated with virulence and antimicrobial resistance (Wang *et al.*, 2023; Zhang *et al.*, 2024). These tools also support source tracking by linking microbial signatures to specific contamination pathways, thereby strengthening risk assessment and control strategies.

In addition, biofilm mapping has emerged as a critical component of modern water system evaluation.

Biofilms provide protective niches for microbial persistence and can act as reservoirs for opportunistic pathogens within storage and distribution systems (LeChevallier *et al.*, 2024). Mapping their spatial distribution and composition would therefore offer valuable insight into system-level contamination dynamics. Similarly, profiling disinfectant resistance is increasingly important, as certain waterborne bacteria exhibit tolerance to commonly used disinfectants, enabling survival under standard treatment conditions (Wang *et al.*, 2023).

Future investigations should therefore integrate molecular characterisation, biofilm assessment, and disinfectant-resistance profiling to complement phenotypic observations. Such an approach would enhance taxonomic resolution, improve understanding of microbial ecology within operational water systems, and provide a more robust basis for targeted intervention and water safety management.

CONCLUSION

This investigation evaluated potable water stored aboard houseboats operating within the petroleum-influenced Jones Creek corridor of the Niger Delta through integrated physicochemical assessment, bacterial identification and phenotypic virulence screening. The evidence indicates that, from a chemical perspective, supplied water largely retained stability during storage. Parameters including pH, conductivity, turbidity, suspended solids, alkalinity and hardness remained within recognised drinking-water limits, suggesting effective upstream treatment and minimal structural deterioration of storage conditions.

Despite this favourable physicochemical status, microbiological findings revealed the occurrence of opportunistic organisms of public health relevance. The recovery of taxa commonly associated with sanitary vulnerability, alongside detection of haemolytic and enzymatic activities, demonstrates that chemical compliance alone cannot be interpreted as proof of biological safety. The coexistence of acceptable chemistry with measurable virulence potential underscores the importance of incorporating routine microbiological surveillance into operational water management within industrial aquatic environments.

The study therefore reinforces a central principle of contemporary water safety: numbers may reassure, but microbes decide. Sustained monitoring, strengthened hygiene practices, and proactive infrastructure maintenance are recommended to

minimise post-treatment contamination risks. Future investigations incorporating molecular confirmation and biofilm analysis would provide deeper resolution of transmission pathways and persistence mechanisms.

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