HARNESSING ARTIFICIAL INTELLIGENCE FOR ENHANCING WATER, SANITATION, AND HYGIENE (WASH) SYSTEMS IN NIGERIAN HOSPITALS: PATHWAYS TO SAFER AND SMARTER HEALTHCARE DELIVERY

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ABSTRACT

Background

Water, sanitation, and hygiene (WASH) systems are critical for infection prevention and safe hospital environments. In Nigeria, persistent deficiencies in WASH infrastructure and practices contribute to healthcare-associated infections, maternal and neonatal morbidity, and poor patient outcomes. With healthcare increasingly adopting digital innovations, artificial intelligence (AI) offers opportunities to enhance WASH service delivery through real-time monitoring, predictive analytics, and automated feedback mechanisms. However, AI adoption in fragile health systems requires careful consideration of infrastructure limitations, ethical implications, and local contextual realities.

Materials and Methods

A structured narrative literature search was conducted across major academic databases (PubMed, Google Scholar, Scopus) and grey literature sources (government reports, programme evaluations, policy documents). The search covered publications between 2019 and 2025, focusing on WASH systems in healthcare facilities, AI and IoT applications in healthcare and water quality monitoring, and infection prevention in low-resource settings.

Due to the narrative design, formal quality appraisal was not applied; findings are synthesised thematically rather than quantitatively.

Findings

Findings revealed widespread infrastructural and behavioural gaps in Nigerian hospital WASH systems, including unreliable water supply, poor sanitation infrastructure, and low hand hygiene compliance. Evidence from predominantly high-income and non-African settings supports AI-enabled solutions including real-time water quality monitoring, AI-driven hand hygiene surveillance, predictive maintenance of sanitation infrastructure, behavioural analytics, and centralised WASH dashboards. The generalisability of these findings to Nigeria requires cautious interpretation given significant differences in infrastructure and health system capacity.

Conclusion

AI presents practical solutions to strengthen WASH systems in Nigerian hospitals by addressing infrastructural, behavioural, and managerial weaknesses. However, successful implementation will depend on supportive policies, ethical governance, sustained investment in infrastructure and human capacity, and rigorous local evaluation to establish real-world feasibility and cost-effectiveness within the Nigerian health system.

Keywords: water sanitation hygiene, artificial intelligence, healthcare-associated infections, Nigeria, infection prevention and control

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INTRODUCTION

Water, sanitation, and hygiene systems form the foundation of infection prevention and control in healthcare settings, particularly in low-resource environments such as Nigeria. Inadequate WASH infrastructure enables the transmission of infectious agents, compromises patient safety, and increases occupational risk for healthcare workers. Strengthening WASH systems has been identified as a primary prevention strategy for infectious disease control in Nigerian hospitals.[1,2] Despite increased awareness and international advocacy, many healthcare facilities in Nigeria continue to experience unreliable water supply, poor sanitation infrastructure, and low hand hygiene compliance.[3] These challenges are not limited to physical infrastructure alone but also reflect behavioral, managerial, and policy-level weaknesses that require systemic responses.

As healthcare delivery becomes increasingly digitized, artificial intelligence (AI) offers new possibilities for optimizing WASH systems through data-driven decision making, automation, and continuous monitoring. However, it is equally important to examine the limitations of AI in low-resource settings, including algorithmic bias, data quality constraints, and the risks of techno-solutionism—the assumption that technological solutions can substitute for fundamental systemic and infrastructure investment. This review critically examines the evidence for AI-enabled WASH interventions and their applicability to Nigerian hospitals, with explicit attention to both opportunities and contextual constraints.

METHODOLOGY

This narrative review synthesizes evidence on WASH challenges in Nigerian hospitals and examines applications of artificial intelligence in healthcare and environmental monitoring systems. A structured literature search was conducted across major academic databases including PubMed, Google Scholar, and Scopus, supplemented by grey literature sources including government reports, programme evaluations, and policy documents. The search covered publications and reports from 2019 to 2025, with emphasis on studies addressing WASH systems in healthcare facilities, AI and IoT applications in healthcare and water quality monitoring, and infection prevention and control in low-resource settings.

Key search terms included combinations of —WASH,‖ —water sanitation hygiene,‖ —healthcare facilities,‖ —Nigeria,‖ —artificial intelligence,‖ —machine learning,‖ —IoT,‖ —hand hygiene,‖ —water quality monitoring,‖ and —infection prevention.‖ Inclusion criteria encompassed peer-reviewed articles, evaluation reports, and grey literature documenting WASH challenges, digital health interventions, or AI applications relevant to healthcare settings in low-resource contexts. Given the narrative design, formal quality appraisal of included studies was not conducted and a structured study selection process was not applied; evidence was synthesised thematically.

For clarity throughout this review, key terms are defined as follows: —artificial intelligence‖ (AI) refers broadly to computational systems that perform tasks typically requiring human-like intelligence; —machine learning‖ (ML) refers specifically to AI systems that improve their performance from data without explicit programming; and —Internet of Things‖ (IoT) refers to networks of physical devices equipped with sensors that collect and transmit data, which may feed into AI or ML systems. These terms are distinct and are not used interchangeably.

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FINDINGS FROM LITERATURE REVIEW

<u>WASH Challenges in Nigerian Hospitals</u>

Evidence consistently demonstrates persistent WASH deficiencies across Nigerian healthcare facilities. Common challenges include inadequate access to potable water, malfunctioning or absent handwashing stations, poor waste management systems, and suboptimal hygiene practices among healthcare workers. An observational study of surgical staff in a Nigerian teaching hospital reported hand hygiene compliance of only 29.1 percent, despite ongoing awareness campaigns.[1] Factors contributing to poor compliance included heavy workloads, insufficient training, and limited access to hygiene resources.

Beyond individual practices, systemic failures continue to undermine WASH performance. Healthcare facilities in Bayelsa State have been shown to lack consistent water supply, often relying on water tankers and other unreliable sources.[3] Assessments conducted under the I-WASH programme in Kebbi State revealed inadequate sanitation facilities and dependence on manual reporting systems, resulting in delayed responses to hygiene breaches.[4] These Nigerian-specific findings highlight a pattern of structural underfunding and institutional fragility that any technological intervention must address. It is also important to note that the available Nigerian WASH evidence is primarily descriptive and cross-sectional; longitudinal or intervention studies examining the effectiveness of WASH improvement strategies in Nigerian hospitals are limited, which constrains the certainty of recommendations.

AI Applications in Health and WASH: Global Evidence and Its Limitations

Artificial intelligence has been increasingly applied across healthcare domains, including diagnostics, disease surveillance, and environmental monitoring. AI-enabled water quality monitoring systems use sensors to detect microbial contamination, chemical residues, and turbidity, transmitting alerts in real time. Studies have demonstrated the effectiveness of AI-driven monitoring systems in detecting contaminants and triggering automated disinfection processes.[5,7] However, it is critical to note that these studies were primarily conducted in high-income urban water systems with reliable electricity, internet connectivity, and technical maintenance infrastructure—conditions that differ substantially from most Nigerian public hospitals.

Hand hygiene monitoring using AI innovations has shown promise in low-resource hospital settings,[8] but these contexts still differed from Nigerian public hospitals in terms of power

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reliability and data infrastructure. IoT-based systems using machine learning models have also been shown to enhance water safety in tourist and aquaculture environments though the generalizability of these findings to healthcare settings is uncertain. [9,10] Contradictory findings and implementation failures are rarely reported in the literature due to publication bias, which likely overstates the feasibility and effectiveness of AI-WASH interventions. Evidence reviews must therefore account for the possibility that real-world implementation challenges are significantly underrepresented in the published literature.

PATHWAYS FOR AI-ENABLED WASH IMPROVEMENT IN NIGERIAN HEALTHCARE FACILITIES

1. Real-Time Water Quality Monitoring

AI-integrated IoT systems can enable continuous monitoring of water quality parameters such as pH, chlorine concentration, turbidity, and bacterial load, allowing early detection of contamination and rapid corrective action.[5,7,9] Their applicability to Nigerian hospitals depends critically on reliable power supply, internet connectivity, and maintenance capacity—factors that remain significant constraints in many public health facilities. Solar-powered or low-bandwidth solutions should be explored as contextually appropriate adaptations, and pilot implementations must assess actual performance under Nigerian infrastructure conditions rather than assuming transferability from high-income settings.

2. Hand Hygiene Surveillance and Feedback

Automated hand hygiene monitoring systems using AI algorithms and visual analytics can assess compliance and provide timely feedback to healthcare workers.[1,8] Evidence from low-resource settings supports the potential of real-time feedback to improve practices. However, camera-based surveillance systems raise significant ethical concerns regarding healthcare worker consent, the psychological impact of continuous monitoring, and data ownership that must be addressed before deployment. Any implementation framework must include participatory design processes involving frontline staff, clear governance structures for data management, and culturally appropriate communication strategies.

3. Predictive Maintenance of Sanitation Infrastructure

AI models can analyze usage patterns and environmental data to predict maintenance needs for sanitation infrastructure, including latrines, handwashing stations, and waste disposal systems.10 In the Nigerian context, where maintenance systems are often reactive and under-

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resourced, predictive maintenance could offer significant efficiency gains—provided that supply chains for spare parts and technically trained maintenance personnel are available to act on AI-generated alerts. Without this accompanying capacity, predictive systems will generate alerts that cannot be acted upon, reducing their practical value.

4. Behavioural Analysis and Digital Nudging

AI-based behavioural analytics can identify trends in hygiene practices and support targeted behaviour change interventions. Digital nudging tools such as reminders, alerts, and adaptive training modules can address behavioural barriers to hand hygiene compliance.[2] These interventions must be grounded in an understanding of local cultural norms, language contexts, and existing behavioural drivers. Digital nudging tools designed for high-income contexts may be ineffective or inappropriate if not contextually adapted. Formative research involving Nigerian healthcare workers should precede any deployment of AI-based behaviour change tools.

5. Data Integration for WASH Decision Making

Centralized dashboards powered by AI can integrate data from multiple sources, including sensor outputs, compliance records, and maintenance logs, supporting evidence-based decision making and resource prioritisation.[11,12] Nigeria's health information systems are fragmented and inconsistently maintained; any AI-powered dashboard would therefore require prior investment in data infrastructure and standardization. The quality of AI-generated insights is entirely dependent on the quality and completeness of input data, and this fundamental dependency must be addressed before dashboard solutions can be deployed meaningfully.

BARRIERS AND ENABLERS

The implementation of AI-enabled WASH systems in Nigerian hospitals is constrained by multiple intersecting barriers. Infrastructural deficits, particularly unreliable electricity supply and limited internet connectivity, represent foundational obstacles that AI solutions alone cannot overcome. Financial barriers are significant: initial investment required for sensors, data infrastructure, and workforce training may exceed available funding in most public hospital settings, and the absence of published cost-effectiveness analyses for AI-WASH interventions in African contexts makes prioritisation difficult for health administrators.

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Human resource capacity is severely limited, with insufficient numbers of skilled personnel capable of managing AI systems or interpreting complex data outputs.

There is also a genuine risk of algorithmic bias: AI systems trained predominantly on data from high-income settings may perform poorly or inequitably when deployed in Nigerian hospitals. Ethical concerns related to healthcare worker surveillance, data privacy, algorithmic transparency, and consent must be proactively addressed. The risk of techno-solutionism is particularly relevant: deploying AI systems without addressing fundamental infrastructure, staffing, and governance deficits is unlikely to produce sustainable WASH improvements.

Despite these challenges, several enabling factors exist. Nigeria's establishment of an AI Scaling Hub in collaboration with the Gates Foundation demonstrates national commitment to advancing AI applications in health and development.[6] The growing availability of affordable IoT components and open-source AI tools lowers technical barriers for motivated institutions. Nigeria's National Digital Health Strategy and existing programmes such as I-WASH provide institutional frameworks that could accommodate AI integration.[4] These enabling conditions are encouraging, but they do not eliminate the need for rigorous, locally-grounded feasibility assessment before scale-up.

ECONOMIC FEASIBILITY AND COST CONSIDERATIONS

Despite the compelling theoretical case for AI-enabled WASH systems, economic considerations remain substantially underdeveloped in the existing literature. Globally, healthcare-associated infections are costly: they prolong hospital stays, increase antibiotic consumption, and impose significant financial burdens on already strained health systems. If AI-driven WASH interventions can demonstrably reduce HAI rates, the return on investment could be considerable over the medium to long term.

However, no cost-effectiveness analysis of AI-WASH interventions specifically conducted in Nigerian or comparable sub-Saharan African settings were identified in the reviewed literature. In high-income settings, sensor-based hand hygiene monitoring systems have been shown to potentially achieve cost neutrality through reductions in hospital-acquired infection costs, but these figures cannot be uncritically extrapolated to Nigeria given differences in hardware costs, labour costs, infection burden data quality, and health financing systems. Economic models for low-resource settings must account for the full cost of implementation, including infrastructure upgrades, staff training, ongoing maintenance, and data management.

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Pilot programmes with rigorous economic evaluation components are therefore a necessary precondition for evidence-based investment decisions in this domain.

ETHICAL CONSIDERATIONS

Ethical issues related to AI deployment in WASH systems require substantially more attention prior to implementation in Nigerian hospitals. Continuous surveillance of healthcare workers using AI-powered cameras or sensor systems raises concerns of consent, dignity, and workplace trust. Healthcare workers must be meaningfully involved in the design and governance of any surveillance system, and opt-out mechanisms must be clearly defined. The psychological burden of constant observation—even automated observation—may negatively affect staff morale and must be weighed against compliance benefits.

Data ownership and governance in AI-WASH systems are contested. Health data collected from hospital environments may include information about patient movements, staff behaviour, and institutional performance. Clear legal and institutional frameworks must define who owns this data, how it may be accessed, and how it is protected from commercial exploitation. Nigeria's Data Protection Act (2023) provides a legislative basis, but implementation guidance for health AI systems remains underdeveloped and must be strengthened.[13]

Algorithmic accountability is a critical concern. AI systems that generate recommendations for resource allocation or maintenance prioritisation may embed biases that disadvantage lower-capacity facilities or marginalised populations. Mechanisms for auditing algorithmic outputs and appealing automated decisions must be built into governance frameworks from the outset. Finally, equity implications must be carefully considered: if AI-WASH systems are preferentially implemented in well-resourced urban hospitals, they risk deepening existing inequalities between public and private facilities and between urban and rural settings. National deployment strategies must include explicit equity commitments and monitoring frameworks.

POLICY AND RESEARCH DIRECTIONS

1. Policy Integration

AI-enabled WASH monitoring systems should be incorporated into national and subnational healthcare policies and standards, including Nigeria's National Digital Health Strategy and

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National Health Policy frameworks.[14] Clear guidelines are required to define acceptable use cases, data governance protocols, infrastructure requirements, and ethical standards for AI deployment in healthcare environments.

2. Pilot Programmes with Rigorous Evaluation

Demonstration projects across diverse healthcare settings—including urban tertiary facilities and rural primary healthcare centres—are necessary to generate evidence on feasibility, scalability, sustainability, and cost-effectiveness. Pilot programmes must incorporate robust monitoring, evaluation, and economic assessment frameworks to build the evidence base required for policy-level investment decisions.

3. Capacity Building

Investment in workforce development is essential, including training healthcare managers, biomedical engineers, and information technology personnel in the use and maintenance of AI-driven WASH systems. Capacity building should be embedded in broader health systems strengthening efforts and supported by sustainable financing mechanisms.

4. Ethical Oversight

Robust ethical frameworks must guide data collection, ensure privacy protection, define accountability mechanisms for system failures or misuse, and address surveillance and consent concerns specific to AI-health deployments. Ethics review processes for AI-health interventions in Nigeria should be strengthened, standardized, and adequately resourced.

5. Research Investment

Future research should prioritize: (a) cost-effectiveness evaluations of AI-enabled WASH interventions in Nigerian and comparable African settings; (b) assessment of AI system performance and potential biases in low-resource deployments; (c) contextual adaptation studies to ensure cultural and operational relevance; and (d) integration studies examining how AI-WASH tools can interface with existing health information systems.

LIMITATIONS

This study has several limitations that should be considered when interpreting its findings. First, as a narrative review, the methodology lacks the rigor and reproducibility of a systematic review. The absence of a formal quality appraisal of included studies and a structured study selection process may introduce selection bias and limit the reliability of the evidence synthesis.

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Second, the evidence base for artificial intelligence applications in WASH systems within Nigerian healthcare settings remains limited. Much of the literature informing this review is derived from studies conducted in high-income or non-African contexts, which may reduce the generalizability of findings to Nigeria due to differences in infrastructure, resource availability, and health system organization.

Third, the rapidly evolving nature of AI technology means that some cited studies may reflect capabilities or implementations that have since been updated or superseded. Readers should interpret evidence from specific AI tools or platforms with awareness of this temporal limitation.

CONCLUSION

Water, sanitation, and hygiene systems in Nigerian hospitals remain critically underdeveloped, posing ongoing risks to patient safety and healthcare quality. Artificial intelligence offers practical pathways to address infrastructural, behavioural, and managerial weaknesses in WASH service delivery through real-time monitoring, predictive maintenance, and integrated decision support. However, the optimistic framing that often characterizes AI-health literature must be tempered by honest engagement with implementation realities: most AI evidence is derived from high-income settings, economic feasibility in Nigerian hospitals remains unproven, and ethical risks around surveillance, data governance, and equity require robust governance frameworks before deployment at scale.

Successful AI-WASH integration in Nigeria will depend on supportive national policies, ethical oversight, sustained investment in underlying infrastructure, rigorous local evaluation, and meaningful engagement with healthcare workers and communities. Coordinated, evidence-based adoption of AI-driven WASH interventions, grounded in Nigerian health system realities, can contribute meaningfully to safer and smarter healthcare delivery—but only if implemented with appropriate caution, equity commitments, and long-term institutional support.

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