

## SMART ELECTROCHEMICAL SENSORS AND IOT FOR MONITORING HEAVY METALS IN NIGERIAN WATER: REVIEW OF ADVANCES AND DEPLOYMENT CHALLENGES

Micheal Abimbola Oladosu<sup>1\*</sup>, Moses Adondua Abah<sup>2</sup>, Ezekiel Izudike Odimgbe<sup>3\*</sup>, Femi Emmanuel Adewale<sup>4</sup>, Clinton Arthur<sup>5</sup>, Abiola Samuel Ajayi<sup>6</sup>, Joseph Ezeani<sup>7</sup>, Franklin Ogonna Ede<sup>8</sup>, Olaide Ayokunmi Oladosu<sup>9</sup>, Emmanuella Chidimma Ohanele<sup>10</sup>

<sup>1</sup>Department of Chemical Sciences, Faculty of Science, Anchor University, Ayobo-Ipaja, Lagos, Nigeria

<sup>2</sup>Department of Biochemistry, Faculty of Biosciences, Federal University Wukari, Taraba State, Nigeria

<sup>3</sup>Department of Healthcare Administration and Risk Management, Faculty of Management Ohio Dominican University, Columbus, United States

<sup>4</sup>Departments of Energy and Applied Chemistry, Faculty of Chemical and Life Sciences, Usmanu Danfodiyo University, Sokoto, Nigeria

<sup>5</sup>Department of Chemistry, Faculty of Science, Eastern New Mexico University, Portales, United States

<sup>6</sup>Department of Computer Science, Faculty of Engineering and Technology, Texas Southern University, Houston, United States

<sup>7</sup>Department of Chemical Engineering, Faculty of Engineering, University of Toledo, Toledo, United States

<sup>8</sup>Department of Computer Science, Faculty of Physical Sciences, University of Calabar, Calabar, Cross River, Nigeria

<sup>9</sup>Department of Computer Science, Faculty of Science and Technology, Babcock University, Ilesan-Remo, Ogun State, Nigeria

<sup>10</sup>Department of Chemical Engineering, School of Engineering and Technology, Federal Polytechnic Nekede, Owerri, Imo State, Nigeria

\*Corresponding email: [mikeoladosu@gmail.com](mailto:mikeoladosu@gmail.com); [odimgbee@ohiodominican.edu](mailto:odimgbee@ohiodominican.edu)

**Received:** 01.10.2025; **Accepted:** 25.02.2026; **Available online:** 01.03.2026; **Published:** 30.03.2026

**Cite this article:** Oladosu, M. A., Abah, M. A., Odimgbe, E. I., Adewale, F. E., Arthur, C., Ajayi, A. S., Ezeani, J., Ede, F. O., Oladosu, O. A., & Ohanele, E. C. (2026). Smart Electrochemical Sensors and IoT for Monitoring Heavy Metals in Nigerian Water: Review of Advances and Deployment Challenges. *Trends in Ecological and Indoor Environmental Engineering*, 4(1), 79–89.

**Background:** Heavy metal contamination in Nigerian water bodies poses persistent environmental and public health risks. Traditional laboratory-based detection methods, while accurate, are limited by cost, accessibility, and real-time applicability, creating a need for advanced monitoring approaches.

**Objectives:** This review systematically synthesises recent advances in smart electrochemical sensors integrated with Internet of Things (IoT) technologies for heavy metal detection, highlighting technological innovations, field applications, and unresolved deployment challenges in Nigerian aquatic environments. **Methods:** Peer-reviewed literature was systematically surveyed to synthesise advances in heavy metal contamination assessment and smart electrochemical sensing technologies relevant to Nigerian aquatic systems. Publications spanning the early 2000s to 2023 were retrieved from major scientific databases, focusing on (i) environmental and toxicological studies of heavy metal exposure, (ii) electrochemical sensor development, including nanomaterial-enhanced and screen-printed platforms, and (iii) IoT-enabled water quality monitoring architectures. Additional studies addressing energy infrastructure, connectivity, cost considerations, and capacity constraints in Nigeria were included to contextualise deployment feasibility. The collected literature was qualitatively analysed to identify technological progress, practical applications, and persistent research gaps.

**Results:** Nanomaterial-enhanced electrodes, such as graphene, carbon nanotubes, and metal nanoparticles, improve sensitivity, selectivity, and detection limits for Pb, Cd, Hg, As, and Cr. Miniaturised platforms, including screen-printed and microfluidic sensors, facilitate portable and multiplexed detection. IoT integration enables real-time data acquisition, cloud-based analytics, and remote monitoring, demonstrated across the Niger Delta, mining-affected rivers, and urban-industrial water bodies. Field studies reveal high correlation with laboratory measurements but also highlight technical, infrastructural, and economic challenges, including biofouling, sensor drift, power and connectivity limitations, high costs, and limited local expertise. Regulatory gaps and lack of standardised protocols further constrain national-scale deployment. **Conclusion:** Smart electrochemical sensors with IoT integration offer transformative potential for continuous and distributed monitoring of heavy metal contamination in Nigerian water systems. Despite demonstrable field viability, unresolved gaps remain in autonomous operation, multiplexed detection, long-term stability, and data integration, indicating critical areas for further investigation to fully leverage these technologies for water quality management.

**Keywords:** heavy metal contamination; electrochemical sensors; nanomaterial-modified electrodes; Internet of Things (IoT); water quality monitoring; environmental sensing; Nigerian aquatic systems.

### INTRODUCTION

Water pollution by heavy metals represents a critical environmental and public health challenge in Nigeria, where rapid industrialisation, artisanal and industrial mining, and inadequate waste management have led to widespread contamination of surface and groundwater resources (Umeoguaju et al., 2022; Adewumi & Laniyan, 2023). Persistent pollutants such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr) bioaccumulate in aquatic ecosystems and pose carcinogenic, neurotoxic, and systemic health risks to human populations (Tchounwou et al., 2012; Briffa et al., 2020). Several studies have reported elevated concentrations of these metals in Nigerian rivers, lakes, and groundwater, highlighting both urban and industrial hotspots (Adesiyani et al., 2018; Ideriah et al., 2024).

Traditional laboratory-based analytical techniques, including

atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), offer high sensitivity and precision for heavy metal quantification (Chajduk et al., 2023; Abdelmonem et al., 2025). However, these methods require sophisticated instrumentation, skilled personnel, and extensive sample preparation, limiting their applicability for frequent, decentralized water monitoring, particularly in resource-constrained settings (Tiwari et al., 2025). In addition, the temporal and spatial variability of pollution in Nigerian water bodies underscores the need for rapid, on-site detection methods to capture short-term contamination events (Olowojuni et al., 2025).

Electrochemical sensors have emerged as promising alternatives for heavy metal detection due to their portability, rapid response, cost-effectiveness, and field applicability (Aragay et al., 2011; Xing et al., 2012). Advances in sensor materials, including nanostructured electrodes, screen-printed

technologies, and microfluidic platforms, have significantly improved sensitivity, selectivity, and detection limits, enabling trace-level detection of multiple metals simultaneously (Li et al., 2009; Cesarino et al., 2012; Afkhami et al., 2013). Furthermore, integration of these sensors with Internet of Things (IoT) frameworks allows continuous remote monitoring, wireless data transmission, cloud-based analytics, and real-time decision support for water quality management (Wang et al., 2014; Geetha & Gouthami, 2016). Such systems are especially relevant for Nigeria's heterogeneous aquatic environments, ranging from oil-impacted estuaries in the Niger Delta to mining-affected rivers in the North-Central region (Ogunkunle & Fatoba, 2013; Ogbeide & Henry, 2024).

Despite rapid technological advances, there remains a knowledge gap regarding the practical deployment, field performance, and adaptation of smart electrochemical sensors with IoT in Nigerian contexts. Current literature predominantly focuses on laboratory-based demonstrations or studies in other geographical regions, leaving uncertainties about real-world applicability, network integration, calibration requirements, and maintenance under local environmental conditions (Kefala et al., 2003; Cui et al., 2015). Addressing these gaps is essential for translating sensor innovations into functional monitoring systems capable of informing water management strategies.

This review aims to provide a systematic synthesis of the state-of-the-art in smart electrochemical sensors and IoT integration for heavy metal monitoring in Nigerian water bodies, identifying current advances, field applications, and knowledge gaps. It evaluates recent technological innovations, field deployment experiences, and operational challenges, with the aim of providing a comprehensive, evidence-based understanding of current capabilities and limitations. By highlighting both technological achievements and practical constraints, this work informs researchers, environmental managers, and policymakers on how advanced sensor systems can be effectively applied to safeguard water quality in Nigeria.

## METHODS

Peer-reviewed literature was analysed to synthesise current knowledge on heavy metal contamination and smart electrochemical sensing technologies relevant to Nigerian aquatic environments. The reference framework spans foundational toxicological studies on heavy metal exposure and environmental impacts, regional assessments of contamination in Nigerian rivers, sediments, soils, and biota, and global burden analyses associated with mining and oil-related activities.

The technological scope covers conventional analytical methods for heavy metal detection, advances in electrochemical sensing platforms, and recent developments in nanomaterial-enhanced electrodes, including graphene, carbon nanotubes, bismuth-based films, metal nanoparticles, screen-printed electrodes, and flexible sensing materials. Both laboratory-based sensor fabrication studies and applied detection platforms were considered to evaluate analytical performance characteristics such as sensitivity, selectivity, detection limits, and operational stability.

To contextualise real-time environmental monitoring, literature addressing Internet of Things architectures, low-power communication protocols, energy harvesting systems, edge computing, machine learning integration, and cloud-based analytics was examined. Studies focusing on IoT-enabled water quality monitoring systems, including low-cost and resource-

constrained implementations, were incorporated to assess practical deployment feasibility.

Additional credible and up-to-date sources comprehensively addressing infrastructure limitations, national energy supply systems, internet connectivity patterns, detailed cost-benefit analyses, regulatory governance frameworks, and long-term capacity-building needs in Nigeria were also included to thoroughly evaluate broader socio-technical and economic constraints influencing sustainable large-scale implementation efforts.

The temporal coverage of the cited literature spans foundational electroanalytical developments from the early 2000s to recent advances published up to 2023, with emphasis on contemporary nanomaterial-based sensors and IoT-integrated monitoring systems. The literature was synthesised qualitatively to identify technological progress, field applicability, and critical research gaps relevant to sustainable water quality monitoring in Nigeria.

## ADVANCES IN ELECTROCHEMICAL SENSOR TECHNOLOGIES

### Nanomaterial-enhanced electrodes

The integration of nanomaterials has significantly enhanced the performance of electrochemical sensors for heavy metal detection (Li et al., 2024; Zhang et al., 2025). Carbon-based nanomaterials, including graphene, carbon nanotubes (CNTs), and carbon quantum dots, provide high surface area, excellent electrical conductivity, and abundant active sites for metal ion adsorption and electron transfer (Zhang et al., 2025). Graphene oxide-modified electrodes have demonstrated detection limits in the parts-per-billion (ppb) range for  $Pb^{2+}$  and  $Cd^{2+}$ , meeting World Health Organization (WHO) guidelines for drinking water quality (Li et al., 2009; Wang et al., 2014). Multi-walled carbon nanotubes (MWCNTs) functionalized with chelating agents exhibit enhanced selectivity toward specific metal ions, which is critical for analysis in complex environmental matrices (Kefala et al., 2003).

Metallic nanoparticles, particularly gold (AuNPs) and bismuth (BiNPs), act as effective electrode modifiers by facilitating electrochemical reactions and signal amplification (Mohammadi et al., 2011; Cui et al., 2015). Bismuth-based electrodes have gained attention as environmentally friendly alternatives to traditional mercury electrodes in anodic stripping voltammetry (ASV), providing comparable sensitivity without associated toxicity concerns (Serrano et al., 2016). Furthermore, composite materials combining carbon nanomaterials with metal nanoparticles create synergistic effects, further improving detection capabilities (Somerset et al., 2010). Table 1 summarises the main nanomaterial types and their corresponding performance characteristics for heavy metal sensing.

### Screen-printed and miniaturized sensors

Screen-printed electrodes (SPEs) represent a major advancement in sensor miniaturization and scalable production (Kadara et al., 2009). These disposable electrodes reduce cross-contamination, minimize required sample volumes, and enable multi-analyte detection through array configurations (Honeychurch & Hart, 2003). Recent developments include three-dimensional printed electrodes with controlled porosity and tailored surface morphology, which enhance sensitivity and reduce fouling effects (Foster et al., 2017). Integration with microfluidic platforms allows automated sample handling, reduced reagent consumption, and multiplexed detection, making these sensors suitable for field deployment in diverse environmental conditions (Peng & Yang, 2009).

Table 1. Nanomaterial types and their characteristics for electrochemical heavy metal sensing

Nanomaterial type	Key properties	Target metals	Detection limit range
Graphene/Graphene Oxide	High surface area, excellent conductivity, functional groups for binding	Pb, Cd, Cu, Hg	0.1–5 ppb
Carbon Nanotubes (CNTs)	Large surface area, fast electron transfer, and mechanical stability	As, Cr, Pb, Cd	0.5–10 ppb
Gold Nanoparticles (AuNPs)	Catalytic activity, biocompatibility, signal amplification	Hg, As, Pb	0.05–2 ppb
Bismuth Nanoparticles	Eco-friendly, similar to Hg electrodes, with a wide potential window	Pb, Cd, Zn, Tl	0.2–8 ppb
Metal-Organic Frameworks	High porosity, tuneable structure, selective binding sites	Pb, Cd, Hg, As	0.1–15 ppb

### Signal processing and detection methods

Stripping voltammetry techniques, particularly differential pulse anodic stripping voltammetry (DPASV) and square wave anodic stripping voltammetry (SWASV), remain the dominant approaches for electrochemical heavy metal detection due to their high sensitivity and capability for simultaneous multi-metal analysis (Wang, 2005; Švancara et al., 2010).

Advances in waveform optimization and baseline correction algorithms have improved signal-to-noise ratios and mitigated matrix interference effects (Arduini et al., 2010). In addition, machine learning algorithms are increasingly applied to enhance data interpretation, enable pattern recognition, and correct interferences in complex environmental samples, further supporting real-time and field-deployable sensing (Wang & Hui, 2019; Shahub et al., 2022; Onyena et al., 2024).

### IOT INTEGRATION AND SMART MONITORING SYSTEMS

#### System architecture and components

IoT-enabled electrochemical sensing systems consist of multiple integrated components that enable autonomous operation, real-time monitoring, and remote data access (Figure 1) (Ray, 2022). The sensor interface layer performs signal conditioning, analog-to-digital conversion, and preliminary data processing using microcontroller units or single-board computers (Fang et al., 2014).

Communication modules support diverse protocols tailored to deployment contexts, including GSM/GPRS for cellular connectivity, LoRaWAN for long-range low-power transmission, and Wi-Fi for local area networks (Seneviratne et al., 2017; Popli et al., 2018). Each protocol offers distinct advantages depending on factors such as site remoteness, power

availability, and data bandwidth requirements. Cloud platforms provide scalable data storage, advanced analytics, visualisation dashboards, and automated alert generation, accessible through web interfaces and mobile applications (Domingo, 2012).

Power management systems are critical for field deployments, integrating solar panels, rechargeable batteries, and intelligent energy scheduling to ensure continuous sensor operation (Shaikh & Zeadally, 2016). Edge computing capabilities enable local data processing, reducing network bandwidth demands and allowing real-time decision-making even during intermittent connectivity (Shi et al., 2016). Table 2 summarises key IoT platform components for water quality monitoring and highlights common implementation challenges in Nigerian contexts.

#### Data management and analytics

Effective data management is essential for handling the continuous streams of information generated by IoT-enabled monitoring networks (Taivalsaari & Mikkonen, 2017). Time-series databases optimized for sensor data storage facilitate efficient querying, visualization of temporal trends, and trend analysis (Zhou et al., 2012).

Cloud-based analytics platforms employ statistical process control methods to detect anomalies, identify pollution events, and trigger automated alerts when heavy metal concentrations exceed regulatory thresholds (Mohammadi et al., 2018). Furthermore, machine learning models trained on historical data can predict contamination events, optimize sensor calibration schedules, and compensate for sensor drift, extending deployment intervals and reducing maintenance costs (Raza et al., 2013; Zhang et al., 2015; Jan et al., 2021). These data-driven strategies enhance the reliability, accuracy, and operational sustainability of IoT-integrated water quality monitoring systems.

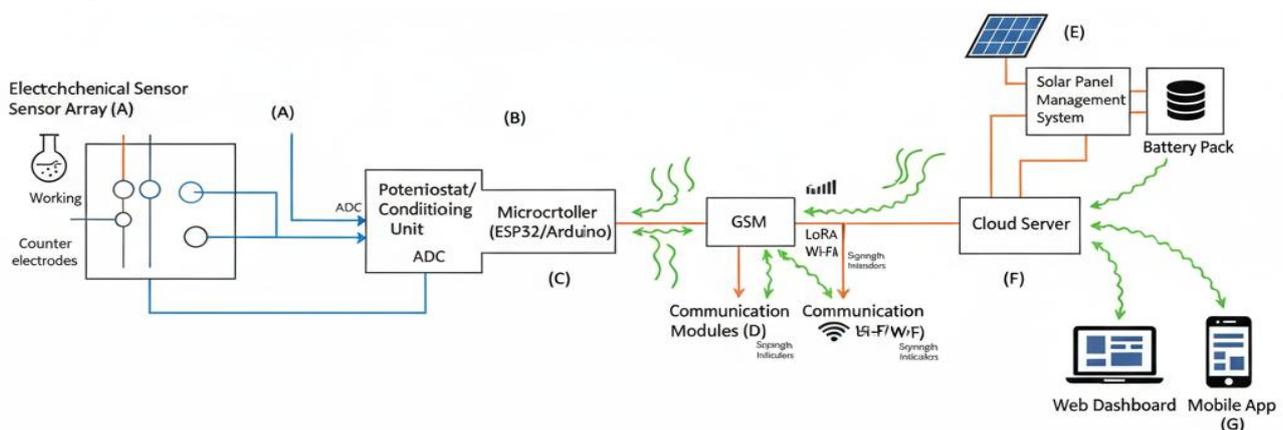


Figure 1. Schematic diagram of IoT-integrated electrochemical sensor system for heavy metal monitoring (Own development adapted from Ray, 2022; Fang et al., 2014; Popli et al., 2018)

Table 2. Nanomaterial types and their characteristics for electrochemical heavy metal sensing

Component	Function	Technologies/Standards	Challenges in Nigeria
Sensor interface	Signal conditioning, data acquisition, pre-processing	Microcontrollers (Arduino, ESP32), ADC modules	Power stability, calibration maintenance
Communication layer	Wireless data transmission to cloud platforms	GSM/GPRS, LoRaWAN, Wi-Fi, Bluetooth	Network coverage gaps, data costs
Cloud platform	Data storage, processing, visualization, analytics	AWS IoT, Azure IoT Hub, ThingSpeak, custom servers	Internet reliability, server costs
Edge computing	Local data processing, real-time decisions, bandwidth reduction	Raspberry Pi, Jetson Nano, edge gateways	Processing power–cost trade-off
Power management	Energy harvesting, battery management, solar integration	Solar panels, rechargeable batteries, energy harvesters	Seasonal variations, maintenance access
User interface	Data visualization, alerts, reporting, decision support	Web dashboards, mobile apps, SMS alerts	User training, literacy levels

## FIELD APPLICATIONS IN NIGERIAN WATER BODIES

### Niger delta region

The Niger Delta, with its extensive network of rivers, creeks, and estuaries, faces severe heavy metal contamination resulting from oil and gas operations, industrial discharges, and artisanal refining activities (Umeoguaju et al., 2023). The deployment of IoT-enabled electrochemical sensors in this region has generated real-time data on Pb, Cd, Hg, and Cr levels, enabling correlation of contamination patterns with anthropogenic activities and tidal dynamics (Adamu et al., 2015; Adeoti et al., 2024).

Bismuth-modified screen-printed electrodes integrated with GSM telemetry have demonstrated robust performance despite challenging conditions such as high organic matter content, fluctuating salinity, and variable water turbidity (Bansod et al., 2017). These sensor systems achieved over 90% correlation with laboratory ICP-MS measurements, providing continuous monitoring capabilities previously unavailable in remote delta communities (Biyani et al., 2017).

### Mining-affected areas

Artisanal gold mining in Zamfara, Niger, and other North-Central states has caused catastrophic lead contamination of water sources, resulting in severe public health impacts (Odetunde et al., 2025). Deployment of portable potentiostat systems powered by solar panels and equipped with satellite communication links enabled monitoring in remote and inaccessible locations (Yilmaz & Sadikoglu, 2011). Real-time alerts from these systems facilitated emergency interventions, temporary closure of contaminated water sources, and targeted remediation efforts, demonstrating the life-saving potential of smart monitoring technologies (Figure 2) (Ericson et al., 2016).

### Urban and industrial centres

Urban and industrialized water bodies, including Lagos Lagoon and Ogun River, are impacted by industrial effluents, electronic waste recycling, and improper waste disposal (Onunkwor et al., 2022; Adeniyi et al., 2024). Deployment of multi-electrode sensor arrays connected via LoRaWAN networks enabled spatial mapping of contamination hotspots and identification of major pollution sources (López-Munoz et al., 2024). Continuous monitoring campaigns over six months documented seasonal variations, industrial discharge patterns, and the effectiveness of regulatory enforcement actions (Orisakwe, 2025).

Table 3 summarises field applications across Nigerian water bodies, highlighting the technologies deployed, metals monitored, and key outcomes.

## DEPLOYMENT CHALLENGES AND SOLUTIONS

### Technical challenges

Field deployment of electrochemical sensors for heavy metal monitoring encounters multiple technical obstacles that can affect data reliability and measurement accuracy (Goyal & Nigam, 2025). Biofouling, caused by algae, bacteria, and organic matter accumulation on electrode surfaces, leads to signal degradation and necessitates regular cleaning or the implementation of automated anti-fouling mechanisms (Campuzano et al., 2019).

Sensor drift over time requires frequent calibration, which is challenging for remote installations with limited accessibility (Lezi et al., 2012). Matrix interferences from coexisting ions, dissolved organic matter, and fluctuating pH further complicate accurate measurement, demanding advanced signal processing and machine learning-based correction strategies (Wan et al., 2015).

Power supply stability is another critical concern, particularly in off-grid or remote areas. Robust energy harvesting and storage solutions, such as solar panels with rechargeable batteries, are essential to sustain operations during periods of low sunlight or extended deployment (Helmy et al., 2025).

### Infrastructure and connectivity issues

Nigeria's telecommunications infrastructure variability presents significant challenges for IoT-enabled sensor networks. Gaps in GSM coverage, especially in rural and riverine areas, can limit real-time data transmission, necessitating local data buffering and store-and-forward protocols (Matthew, 2022; GSMA, 2023).

High mobile data costs create financial barriers to continuous cloud connectivity, making edge computing and data compression strategies essential for sustainable operation. In addition, internet reliability issues can impede access to cloud platforms, highlighting the need for hybrid systems that integrate local data storage with periodic synchronization (Sadiq et al., 2022).

Alternative communication technologies, including LoRaWAN and satellite links, offer solutions for remote connectivity, but introduce additional cost and complexity considerations (Adelantado et al., 2017).

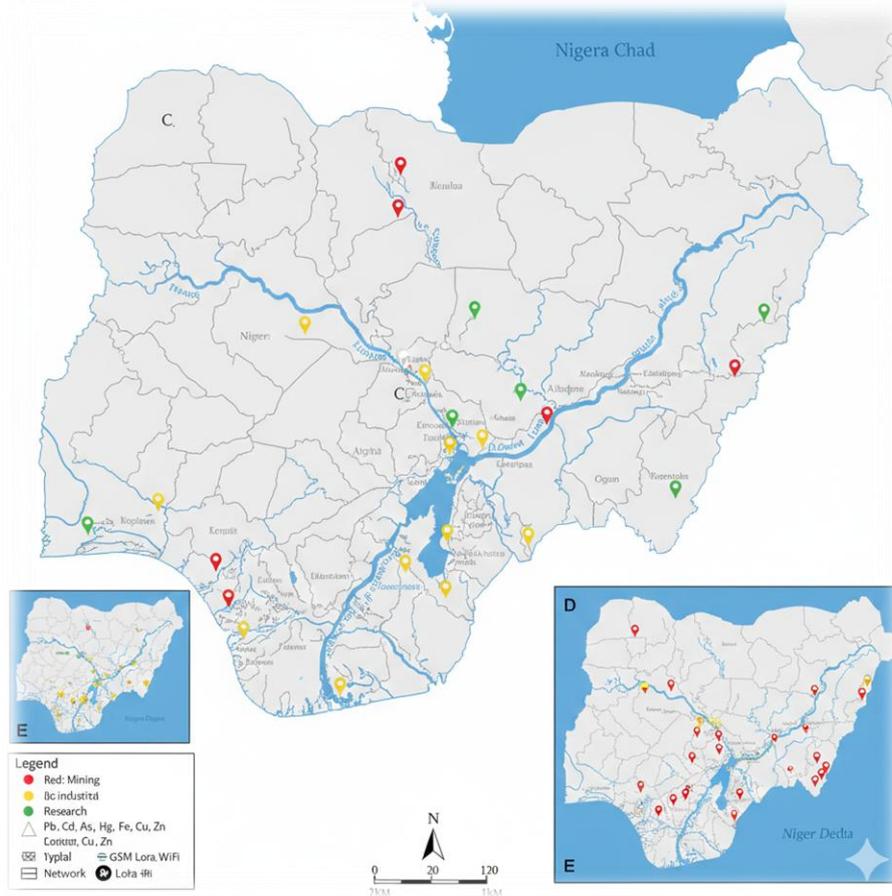


Figure 2. Map of Nigeria showing locations of deployed IoT electrochemical sensor networks for heavy metal monitoring (Own development based on a literature review)

Table 3. Field applications of IoT-integrated electrochemical sensors in Nigerian water bodies

Location/water body	Heavy metals monitored	Sensor technology	Key findings/performance
Niger Delta Rivers	Pb, Cd, Hg, Cr	Bismuth-modified screen-printed electrodes with GSM telemetry	97% correlation with ICP-MS; oil contamination interference addressed
Lagos Lagoon	Pb, Cu, Zn	CNT-modified electrodes with LoRaWAN connectivity	Real-time monitoring of industrial discharge; seasonal variation documented
Zamfara Mining Areas	Pb (primary), Cd, As	Portable potentiostat with solar power and satellite link	Detected Pb levels 10- 50× WHO limits; guided intervention efforts
River Benue	As, Cr, Pb	Multi-electrode array with Wi-Fi mesh network	Agricultural runoff patterns identified; network coverage challenging
Ogun River Basin	Cd, Pb, Cr	Graphene-based sensors with cloud analytics platform	Continuous 6-month operation; maintenance required monthly

### Economic and sustainability factors

Cost remains a primary barrier to widespread adoption of smart sensor technologies in Nigerian water management. Initial investments for sensor hardware, communication modules, and cloud infrastructure often exceed the budgets of local environmental agencies and research institutions (Oluwayemisi et al., 2024). Operational expenses, including sensor replacements, calibration materials, data subscriptions, and maintenance visits, accumulate over time, challenging long-term sustainability (Figure 3). Proposed solutions include phased deployment strategies targeting high-priority locations first, public-private partnerships leveraging commercial interest

in water quality data, cost-sharing arrangements among stakeholder agencies, and the development of locally fabricated sensors using indigenous materials and manufacturing capabilities (Ololade et al., 2019).

### Capacity building and training

Limited technical expertise in electrochemical sensing and IoT systems constrains effective deployment and maintenance (Ouma et al., 2022). Training programs should address multiple competency levels, from field technicians performing routine maintenance to data analysts interpreting complex datasets (Ighalo & Adeniyi, 2020).

Partnerships with universities and research institutions can provide ongoing capacity building while advancing scientific understanding and local innovation. Comprehensive documentation, remote technical support systems, and knowledge transfer initiatives are also essential for sustainable adoption and operation of smart monitoring technologies (Milagres & Burcharth, 2019).

Table 4 summarises major deployment challenges alongside corresponding solution strategies, providing a structured overview for policymakers, researchers, and practitioners.

## REGULATION AND STANDARDIZATION

Development of regulatory frameworks and technical standards is critical for quality assurance and acceptance of electrochemical sensor data in water management decision-making (Ikem et al., 2003). The Nigerian Federal Ministry of Water Resources and the National Water Resources Institute are developing guidelines for sensor-based monitoring that address validation protocols, quality control procedures, and data acceptance criteria.

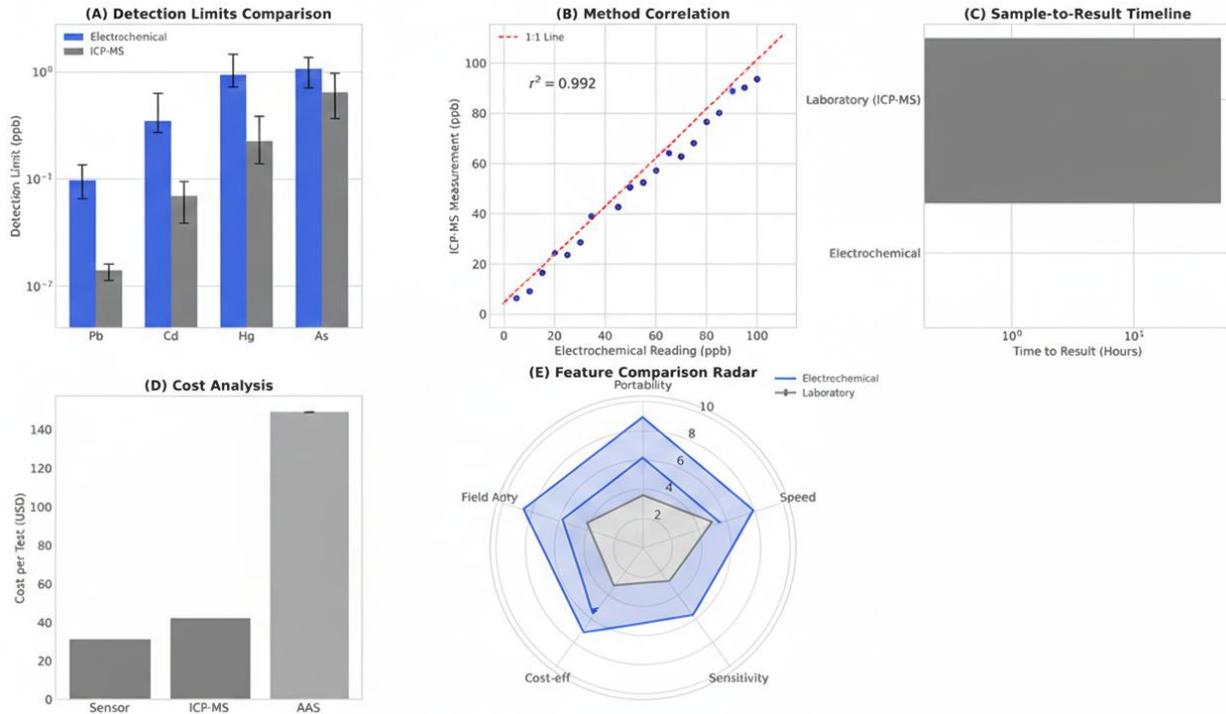


Figure 3. Comparison of the effectiveness of electrochemical sensors and traditional laboratory methods. A multi-panel comparison figure showing: a – bar graph comparing detection limits (ppb) for Pb, Cd, Hg, As between electrochemical sensors (blue bars) and ICP-MS (grey bars) with error bars; b – scatter plot showing correlation between electrochemical sensor readings and ICP-MS measurements ( $r^2$  value displayed) with 1:1 line; c – timeline comparison showing sample-to-result time: electrochemical (minutes) compared with laboratory methods (hours/days) using horizontal bars; d – cost comparison bar chart (USD per test) for different methods; e – radar chart comparing portability, speed, sensitivity, cost-effectiveness, and field applicability (0–10 scale) for both methods (Own development adapted from Bansod et al., 2017; Chajduk et al., 2023; Abdelmonem et al., 2025)

Table 4. Major deployment challenges and proposed solutions for IoT sensor networks in Nigeria

Challenge category	Specific issues	Proposed solutions	Implementation status
Technical	Biofouling, drift, matrix interference, and power supply	Self-cleaning protocols, automated calibration, solar/hybrid systems	Partially implemented; ongoing optimisation
Infrastructure	Network coverage, internet reliability, data storage	Edge computing, data buffering, satellite backup, local servers	Mixed; urban areas better served
Economic	High initial costs, limited funding, maintenance expenses	Phased deployment, partnerships, cost-sharing models, local fabrication	Pilot projects underway; scaling challenging
Human Capacity	Limited technical expertise, training gaps, staff turnover	Training programs, documentation, remote support, university partnerships	Growing but insufficient; ongoing efforts
Regulatory	Lack of standards, validation protocols, quality assurance	National guidelines development, inter-agency coordination, certification	In development; regulatory framework emerging
Environmental	Harsh conditions, vandalism, accessibility, security	Rugged enclosures, community engagement, strategic placement	Context-dependent; community buy-in crucial

Harmonisation with international standards, such as ISO 17025 for laboratory testing and ISO/IEC 17043 for proficiency testing, ensures credibility and facilitates data sharing across jurisdictions (Li et al., 2012). Certification programs for sensor systems and trained operators establish competency benchmarks and build stakeholder confidence (Chen et al., 2015).

Inter-agency coordination among environmental protection

agencies, water resource management bodies, health departments, and research institutions promotes consistent implementation and data interoperability (Nriagu et al., 2016). Regulatory frameworks must balance innovation encouragement with measurement reliability, establishing pathways for integrating new technologies while maintaining data credibility (Figure 4) (Ite et al., 2013).

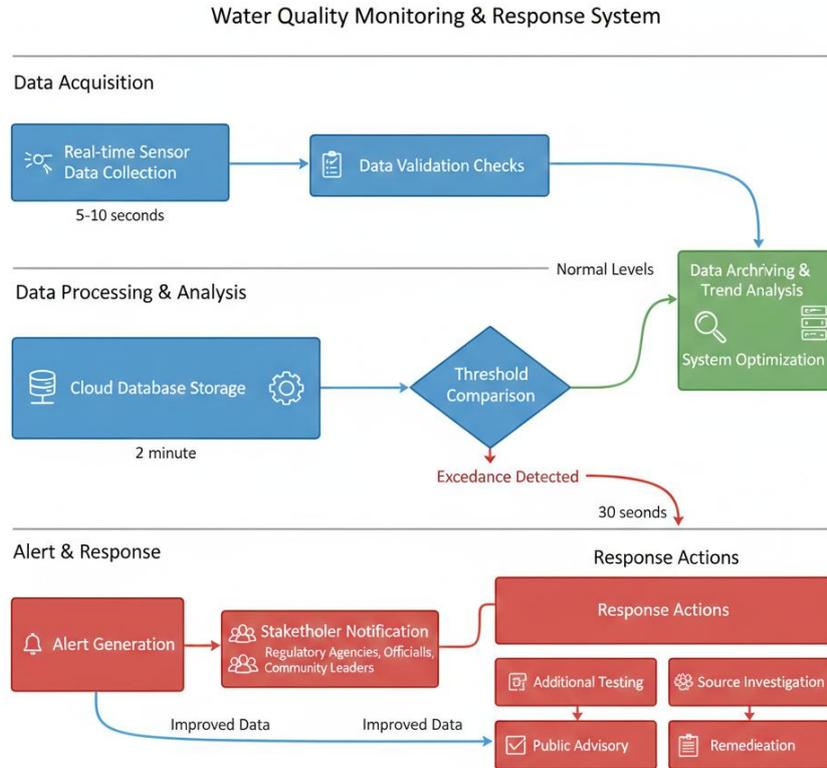


Figure 4. Workflow diagram for smart sensor data integration into water quality management decision-making. A detailed flowchart showing: a – top section: Real-time sensor data collection (sensor icon) → data validation checks (checklist icon); b – middle section: Cloud database storage (server icon) → automated analysis algorithms (gear icon) → threshold comparison (decision diamond) branching to: normal levels (green path) or exceedance detected (red path); c – bottom section for exceedance path: alert generation (bell icon) → stakeholder notification (multiple user icons: regulatory agencies, health officials, community leaders) → response actions (branching to: additional testing, source investigation, public advisory, remediation); d – feedback loops showing data archiving, trend analysis, and system optimization

(Own development adapted from Zhou et al., 2012; Mohammadi et al., 2018; Ikem et al., 2003; Adesiyani et al., 2018)

## UNRESOLVED GAPS IN SMART SENSOR WATER MONITORING

Despite substantial advances in smart electrochemical sensors and IoT integration, several critical gaps remain unresolved, limiting the full potential of these technologies for water quality management in Nigeria (De Camargo et al., 2023). Ultra-low-power sensors capable of multi-year autonomous operation have not yet been fully realised, restricting the ability to conduct long-term continuous monitoring (Liu et al., 2017). Similarly, the integration of advanced artificial intelligence and predictive modelling for real-time interpretation of complex environmental datasets remains limited, constraining data-driven decision-making (Liu et al., 2017; Bandonkar et al., 2016).

The simultaneous detection of multiple analytes, including heavy metals, pesticides, pharmaceutical residues, and microbial indicators, has not yet been implemented in a single platform suitable for the diverse chemical and hydrological conditions found across Nigerian water bodies (Arduini et al., 2016). Mechanisms for ensuring data security and traceability, such as blockchain integration, are still largely untested in field deployments (Kshetri, 2018). At the same time, community-

based monitoring programs, which could empower local populations with accessible sensor technologies and mobile applications, remain underdeveloped, limiting the potential for citizen science initiatives and environmental awareness (Buytaert et al., 2014).

Several technical and operational challenges persist. Long-term stability, anti-fouling performance, and sensor durability under variable climatic conditions and complex water chemistries require further investigation (Pasika & Gandla, 2020). High production and deployment costs, coupled with limited local manufacturing capabilities, hinder widespread adoption and scalability (Ejeian et al., 2018; Feng et al., 2023). In addition, comparative validation studies across different water chemistries, hydrological regimes, and climatic zones are largely lacking, creating gaps in data reliability and interoperability. The establishment of centralised data repositories and visualisation platforms for national-scale integration, analysis, and dissemination of water quality information is still incomplete (Pasika & Gandla, 2020).

Addressing these unresolved gaps is crucial to fully realise the potential of smart electrochemical sensors and IoT-enabled

monitoring systems for continuous, accurate, and large-scale water quality assessment in Nigeria.

## CONCLUSION

Smart electrochemical sensors integrated with IoT technologies constitute a significant advancement in monitoring and managing heavy metal contamination in Nigerian water bodies. Recent developments in nanomaterials, miniaturisation, and wireless communication have improved sensor sensitivity, selectivity, and field applicability, enabling real-time data acquisition across diverse aquatic environments.

Field deployments in the Niger Delta, mining-affected regions, and urban-industrial centres demonstrate the practical feasibility of these systems and highlight the specific environmental, technical, and infrastructural conditions that influence performance. The analyses of these deployments reveal that while sensors can provide continuous monitoring and strong correlation with laboratory-based measurements, technical challenges such as biofouling, sensor drift, and matrix interferences, along with connectivity and power limitations, remain significant factors affecting data reliability.

Economic and operational constraints, including high initial costs, limited local manufacturing, and the need for specialized technical expertise, further shape the scope and scale of deployment. At the same time, gaps in regulatory frameworks, data standardisation, and national-scale integration persist, constraining comprehensive water quality assessment and cross-site comparability.

Overall, the current body of research illustrates that smart electrochemical sensors and IoT systems are capable of transforming water quality monitoring in Nigeria, but substantial unresolved gaps remain in autonomous operation, multiplexed detection, long-term stability, data security, and national data integration. These findings identify clear areas where further investigation and systematic evaluation are needed to fully understand and leverage the potential of these technologies for large-scale environmental monitoring.

## Acknowledgement

The authors acknowledge the Research Hub Nexus Institute for supporting this work. We thank the numerous research groups and field teams whose deployment efforts inform this review.

## Author's statements

### Contributions

Conceptualization: M.A.O., M.A.A., E.I.O.; Data curation: C.A., A.S.A., J.E.; Formal Analysis: E.I.O., F.O.E.; Investigation: M.A.A., C.A., E.C.O.; Methodology: M.A.O., E.I.O., O.A.O.; Project administration: M.A.O.; Resources: F.E.A., J.E.; Supervision: M.A.O., E.I.O.; Validation: A.S.A., O.A.O.; Visualization: F.O.E., E.C.O.; Writing – original draft: M.A.O., M.A.A.; Writing – review & editing: all authors.

### Declaration of conflicting interest

The authors declare no conflict of interest.

### Financial interests

The authors declare they have no financial interests.

### Funding

Not applicable.

### Data availability statement

Not applicable.

### AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

### Ethical approval declarations

Not applicable.

### Additional information

### Publisher's note

Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## REFERENCES

- Abdelmonem, B. H., Kamal, L. T., Elbaz, R. M., Khalifa, M. R., & Abdelnaser, A. (2025). From contamination to detection: The growing threat of heavy metals. *Heliyon*, 11(1). <https://doi.org/10.1016/j.heliyon.2025.e41713>.
- Adamu, C. I., Nganje, T. N., & Edet, A. (2015). Heavy metal contamination and health risk assessment associated with abandoned barite mines in Cross River State, southeastern Nigeria. *Environmental Nanotechnology, Monitoring & Management*, 3, 10–21. <https://doi.org/10.1016/j.enmm.2014.11.001>.
- Adelantado, F., Vilajosana, X., Tuset-Peiro, P., Martinez, B., Melia-Segui, J., & Watteyne, T. (2017). Understanding the limits of LoRaWAN. *IEEE Communications Magazine*, 55(9), 34–40. <https://doi.org/10.1109/MCOM.2017.1600613>.
- Adeniyi, A., Ibidokun, M., & Oluwole, O. (2024). A comparative assessment of potentially harmful metals in the Lagos Lagoon and Ogun river catchment. *Physical Sciences Reviews*, 9(2), 921–930. <https://doi.org/10.1515/psr-2022-0246>.
- Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2024). Water infrastructure sustainability challenge in Nigeria: A detailed examination of infrastructure failures and potential solutions. *Water Supply*, 24(6), 2066–2076. <https://doi.org/10.2166/ws.2024.127>.
- Adesiyani, I. M., Bisi-Johnson, M., Aladesanmi, O. T., Okoh, A. I., & Ogunfowokan, A. O. (2018). Concentrations and human health risk of heavy metals in rivers in Southwest Nigeria. *Journal of Health & Pollution*, 8(19), 180907. <https://doi.org/10.5696/2156-9614-8.19.180907>.
- Adewumi, A. J., & Laniyan, T. A. (2023). Contamination, ecological, and human health risks of heavy metals in water from a Pb–Zn–F mining area, North Eastern Nigeria. *Journal of Water and Health*, 21(10), 1470–1488. <https://doi.org/10.2166/wh.2023.132>.
- Afkhami, A., Soltani-Felehgari, F., Madrakian, T., Ghaedi, H., & Rezaeivala, M. (2013). Fabrication and application of a new modified electrochemical sensor using nano-silica and a newly synthesized Schiff base for simultaneous determination of Cd<sup>2+</sup>, Cu<sup>2+</sup> and Hg<sup>2+</sup> ions in water and some foodstuff samples. *Analytica Chimica Acta*, 771, 21–30. <https://doi.org/10.1016/j.aca.2013.02.031>.
- Akinpelumi, V. K., Ezejiyor, A. N., Abdulai, P. M., Rovira, J., Frazzoli, C., & Orisakwe, O. E. (2025). Seasonal Variations of Physicochemical Parameters, Arsenic, Heavy Metals, and PAHs in Groundwater and Surface Water in Crude Oil Contaminated Community of Niger Delta, Nigeria: A Comparative Chemometric and Human Health Risk Assessment Analyses. *Water Environment Research*, 97(12), e70220. <https://doi.org/10.1002/wer.70220>.
- Aragay, G., Pons, J., & Merkoçi, A. (2011). Recent trends in macro-, micro-, and nanomaterial-based tools and strategies for heavy-metal detection. *Chemical Reviews*, 111(5), 3433–3458. <https://doi.org/10.1021/cr100383r>.
- Arduini, F., Calvo, J. Q., Palleschi, G., Moscone, D., & Amine, A. (2010). Bismuth-modified electrodes for lead detection. *TrAC Trends in Analytical Chemistry*, 29(11), 1295–1304. <https://doi.org/10.1016/j.trac.2010.08.003>.

- Arduini, F., Micheli, L., Moscone, D., Pallechi, G., Piermarini, S., Ricci, F., & Volpe, G. (2016). Electrochemical biosensors based on nanomodified screen-printed electrodes: Recent applications in clinical analysis. *TrAC Trends in Analytical Chemistry*, 79, 114–126. <https://doi.org/10.1016/j.trac.2016.01.032>.
- Bandodkar, A. J., Jeerapan, I., & Wang, J. (2016). Wearable chemical sensors: present challenges and future prospects. *Acs Sensors*, 1(5), 464–482. <https://doi.org/10.1021/acssensors.6b00250>.
- Bansod, B., Kumar, T., Thakur, R., Rana, S., & Singh, I. (2017). A review on various electrochemical techniques for heavy metal ions detection with different sensing platforms. *Biosensors and Bioelectronics*, 94, 443–455. <https://doi.org/10.1016/j.bios.2017.03.031>.
- Biyani, M., Biyani, R., Tsuchihashi, T., Takamura, Y., Ushijima, H., Tamiya, E., & Biyani, M. (2017). DEP-On-Go for simultaneous sensing of multiple heavy metals pollutants in environmental samples. *Sensors*, 17(1), 45. <https://doi.org/10.3390/s17010045>.
- Briffa, J., Sinagra, E., & Blundell, R. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon*, 6(9). <https://doi.org/10.1016/j.heliyon.2020.e04691>.
- Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., ... & Zhumanova, M. (2014). Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, 2, 26. <https://doi.org/10.3389/feart.2014.00026>.
- Campuzano, S., Pedrero, M., Yáñez-Sedeño, P., & Pingarrón, J. M. (2019). Antifouling (bio) materials for electrochemical (bio) sensing. *International Journal of Molecular Sciences*, 20(2), 423. <https://doi.org/10.3390/ijms20020423>.
- Cesarino, I., Moraes, F. C., Lanza, M. R., & Machado, S. A. (2012). Electrochemical detection of carbamate pesticides in fruit and vegetables with a biosensor based on acetylcholinesterase immobilised on a composite of polyaniline–carbon nanotubes. *Food Chemistry*, 135(3), 873–879. <https://doi.org/10.1016/j.foodchem.2012.04.147>.
- Chajduk, E., & Kalbarczyk, P. (2023). Comparison of the analytical performance of inductively coupled plasma Mass spectrometry and instrumental neutron activation analysis techniques in the elemental analysis of coal fly ash. *Minerals*, 13(12), 1484. <https://doi.org/10.3390/min13121484>.
- Chen, M., Xu, P., Zeng, G., Yang, C., Huang, D., & Zhang, J. (2015). Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: applications, microbes and future research needs. *Biotechnology Advances*, 33(6), 745–755. <https://doi.org/10.1016/j.biotechadv.2015.05.003>.
- Cui, L., Wu, J., & Ju, H. (2015). Electrochemical sensing of heavy metal ions with inorganic, organic and bio-materials. *Biosensors and Bioelectronics*, 63, 276–286. <https://doi.org/10.1016/j.bios.2014.07.052>.
- De Camargo, E. T., Spanhol, F. A., Slongo, J. S., Da Silva, M. V. R., Pazinato, J., de Lima Lobo, A. V., ... & Martins, L. D. (2023). Low-cost water quality sensors for IoT: A systematic review. *Sensors*, 23(9), 4424. <https://doi.org/10.3390/s23094424>.
- Domingo, M. C. (2012). An overview of the Internet of Things for people with disabilities. *Journal of Network and Computer Applications*, 35(2), 584–596. <https://doi.org/10.1016/j.jnca.2011.10.015>.
- Ejeian, F., Etedali, P., Mansouri-Tehrani, H. A., Soozanipour, A., Low, Z. X., Asadnia, M., ... & Razzmjou, A. (2018). Biosensors for wastewater monitoring: A review. *Biosensors and Bioelectronics*, 118, 66–79. <https://doi.org/10.1016/j.bios.2018.07.019>.
- Ericson, B., Landrigan, P., Taylor, M. P., Frostad, J., Caravanos, J., Keith, J., & Fuller, R. (2016). The global burden of lead toxicity attributable to informal used lead-acid battery sites. *Annals of Global Health*, 82(5), 686–699. <https://doi.org/10.1016/j.aogh.2016.10.015>.
- Fang, S., Da Xu, L., Zhu, Y., Ahafi, J., Pei, H., Yan, J., & Liu, Z. (2014). An integrated system for regional environmental monitoring and management based on internet of things. *IEEE Transactions on Industrial Informatics*, 10(2), 1596–1605. <https://doi.org/10.1109/TII.2014.2302638>.
- Feng, L., Song, S., Li, H., He, R., Chen, S., Wang, J., ... & Zhao, X. (2023). Nano-biosensors based on noble metal and semiconductor materials: emerging trends and future prospects. *Metals*, 13(4), 792. <https://doi.org/10.3390/met13040792>.
- Foster, C. W., Down, M. P., Zhang, Y., Ji, X., Rowley-Neale, S. J., Smith, G. C., ... & Banks, C. E. (2017). 3D printed graphene based energy storage devices. *Scientific Reports*, 7(1), 42233. <https://doi.org/10.1038/srep42233>.
- Geetha, S., & Gouthami, S. J. S. W. (2016). Internet of things enabled real time water quality monitoring system. *Smart Water*, 2(1), 1. <https://doi.org/10.1186/s40713-017-0005-y>.
- Goyal, A. K., & Nigam, A. (2025). Sensors for toxic metal ion detection in aquatic environment: current status and future perspectives. *Discover Applied Sciences*, 7(12), 1405. <https://doi.org/10.1007/s42452-025-07936-9>.
- GSMA. (2023). *IoT and essential utility services: Opportunities in low-and-middle income countries (Nigeria case)*. GSMA. <https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-for-development/wp-content/uploads/2023/04/IoT-and-Essential-Utility-Services-Opportunities-in-low-and-middle-income-countries.pdf>.
- Helmy, H. A., El-Rifaie, A. M., Youssef, A. A., Haggag, A., Hamad, H., & Eltokhy, M. (2025). Improving Solar Energy-Harvesting Wireless Sensor Network (SEH-WSN) with Hybrid Li-Fi/Wi-Fi, Integrating Markov Model, Sleep Scheduling, and Smart Switching Algorithms. *Technologies*, 13(10), 437. <https://doi.org/10.3390/technologies13100437>.
- Honeychurch, K. C., & Hart, J. P. (2003). Screen-printed electrochemical sensors for monitoring metal pollutants. *TrAC Trends in Analytical Chemistry*, 22(7), 456–469. [https://doi.org/10.1016/S0165-9936\(03\)00703-9](https://doi.org/10.1016/S0165-9936(03)00703-9).
- Ideriah, T. J. K., Abam, T. K. S., Uzamaden, G. I., & Okafor, C. (2024). Concentrations of Hydrocarbons and Heavy Metals in Groundwater from Andoni Local Government Area of Rivers State Nigeria. *International Journal of Research and Innovation in Applied Science*, 9(7), 97–108.
- Ighalo, J. O., & Adeniyi, A. G. (2020). A comprehensive review of water quality monitoring and assessment in Nigeria. *Chemosphere*, 260, 127569. <https://doi.org/10.1016/j.chemosphere.2020.127569>.
- Ikem, A., Egiebor, N. O., & Nyavor, K. (2003). Trace elements in water, fish and sediment from Tuskegee Lake, Southeastern USA. *Water, Air, and Soil Pollution*, 149(1), 51–75. <https://doi.org/10.1023/A:1025694315763>.
- Ite, A. E., Ibok, U. J., Ite, M. U., & Petters, S. W. (2013). Petroleum exploration and production: Past and present environmental issues in the Nigeria's Niger Delta. *American Journal of Environmental Protection*, 1(4), 78–90. <https://doi.org/10.12691/env-1-4-2>.
- Jan, F., Min-Allah, N., & Düşteğör, D. (2021). IoT based smart water quality monitoring: Recent techniques, trends and challenges for domestic applications. *Water*, 13(13), 1729. <https://doi.org/10.3390/w13131729>.
- Kadara, R. O., Jenkinson, N., & Banks, C. E. (2009). Characterisation of commercially available electrochemical sensing platforms. *Sensors and Actuators B: Chemical*, 138(2), 556–562. <https://doi.org/10.1016/j.snb.2009.01.044>.
- Kefala, G., Economou, A., Voulgaropoulos, A., & Sofoniou, M. (2003). A study of bismuth-film electrodes for the detection of trace metals by anodic stripping voltammetry and their application to the determination of Pb and Zn in tapwater and human hair. *Talanta*, 61(5), 603–610. [https://doi.org/10.1016/S0039-9140\(03\)00350-3](https://doi.org/10.1016/S0039-9140(03)00350-3).

- Kshetri, N. (2018). 1 Blockchain's roles in meeting key supply chain management objectives. *International Journal of Information Management*, 39, 80–89. <https://doi.org/10.1016/j.ijinfomgt.2017.12.005>.
- Lezi, N., Economou, A., Dimovasilis, P. A., Trikalitis, P. N., & Prodromidis, M. I. (2012). Disposable screen-printed sensors modified with bismuth precursor compounds for the rapid voltammetric screening of trace Pb (II) and Cd (II). *Analytica Chimica Acta*, 728, 1–8. <https://doi.org/10.1016/j.aca.2012.03.036>.
- Li, B., Xie, X., Meng, T., Guo, X., Li, Q., Yang, Y., ... & Pang, H. (2024). Recent advance of nanomaterials modified electrochemical sensors in the detection of heavy metal ions in food and water. *Food Chemistry*, 440, 138213. <https://doi.org/10.1016/j.foodchem.2023.138213>.
- Li, J., Guo, S., Zhai, Y., & Wang, E. (2009). High-sensitivity determination of lead and cadmium based on the Nafion-graphene composite film. *Analytica Chimica Acta*, 649(2), 196–201. <https://doi.org/10.1016/j.aca.2009.07.030>.
- Li, X., Liu, L., Wang, Y., Luo, G., Chen, X., Yang, X., ... & He, X. (2012). Integrated assessment of heavy metal contamination in sediments from a coastal industrial basin, NE China. *PLoS One*, 7(6), e39690. <https://doi.org/10.1371/journal.pone.0039690>.
- Liu, Y., Pharr, M., & Salvatore, G. A. (2017). Lab-on-skin: a review of flexible and stretchable electronics for wearable health monitoring. *ACS Nano*, 11(10), 9614–9635. <https://doi.org/10.1021/acsnano.7b04898>.
- López-Munoz, M. A., Torrealba-Melendez, R., Arriaga-Arriaga, C. A., Tamariz-Flores, E. I., López-López, M., Quirino-Morales, F., ... & López-Marcos, F. (2024). Wireless dynamic sensor network for water quality monitoring based on the IoT. *Technologies*, 12(11), 211. <https://doi.org/10.3390/technologies12110211>.
- Matthew, B. (2022). *Deployment challenges of IoT infrastructure in rural Nigeria*. [https://www.researchgate.net/profile/Bamidele-Matthew-2/publication/393579572\\_Deployment\\_challenges\\_of\\_IoT\\_infrastructure\\_in\\_rural\\_Nigeria/links/68702224dd6b84447df79c4a/Deployment-challenges-of-IoT-infrastructure-in-rural-Nigeria.pdf](https://www.researchgate.net/profile/Bamidele-Matthew-2/publication/393579572_Deployment_challenges_of_IoT_infrastructure_in_rural_Nigeria/links/68702224dd6b84447df79c4a/Deployment-challenges-of-IoT-infrastructure-in-rural-Nigeria.pdf).
- Milagres, R., & Burcharth, A. (2019). Knowledge transfer in interorganizational partnerships: what do we know?. *Business Process Management Journal*, 25(1), 27–68. <https://doi.org/10.1108/BPMJ-06-2017-0175>.
- Mohammadi, M., Al-Fuqaha, A., Sorour, S., & Guizani, M. (2018). Deep learning for IoT big data and streaming analytics: A survey. *IEEE Communications Surveys & Tutorials*, 20(4), 2923–2960. <https://doi.org/10.1109/COMST.2018.2844341>.
- Mohammadi, N., Khani, H., Gupta, V. K., Amereh, E., & Agarwal, S. (2011). Adsorption process of methyl orange dye onto mesoporous carbon material—kinetic and thermodynamic studies. *Journal of Colloid and Interface Science*, 362(2), 457–462. <https://doi.org/10.1016/j.jcis.2011.06.067>.
- Nriagu, J., Udofia, E. A., Ekong, I., & Ebuk, G. (2016). Health risks associated with oil pollution in the Niger Delta, Nigeria. *International Journal of Environmental Research and Public Health*, 13(3), 346. <https://doi.org/10.3390/ijerph13030346>.
- Odetunde, S. K., Yusuf, A. O., Sunmon, O., Oladetuyi, A. P., & Godspower, O. I. (2025). Ecological and Human Health Implications of Heavy Metal Pollution in Nigerian Artisanal Mining Communities: A Meta-Analytical Review (2010-2024). *Journal of Sustainability and Environmental Management*, 4(1), 71–80. <https://doi.org/10.3126/josem.v4i1.89879>.
- Ogbeide, O., & Henry, B. (2024). Addressing heavy metal pollution in Nigeria: Evaluating policies, assessing impacts, and enhancing remediation strategies. *Journal of Applied Sciences and Environmental Management*, 28(4), 1007–1051. <https://doi.org/10.4314/jasem.v28i4.5>.
- Ogunkunle, C. O., & Fatoba, P. O. (2013). Pollution Loads and the Ecological Risk Assessment of Soil Heavy Metals around a Mega Cement Factory in Southwest Nigeria. *Polish Journal of Environmental Studies*, 22(2), 487–493.
- Ololade, O. O., Mavimbela, S., Oke, S. A., & Makhadi, R. (2019). Impact of leachate from northern landfill site in Bloemfontein on water and soil quality: Implications for water and food security. *Sustainability*, 11(15), 4238. <https://doi.org/10.3390/su11154238>.
- Olowojuni, O., Olaifa, F. E., Oyebola, O. O., Ayotunde, D. T., Kelani, A. Z., & Olusola, S. E. (2025). Seasonal and spatial variations in water quality, heavy metal concentration in water, sediment and bioaccumulation in *Pseudotolithus* species from the Gulf of Guinea, Ondo state, Nigeria. *Environmental Sciences Europe*, 37(1), 1–25. <https://doi.org/10.1186/s12302-025-01221-7>.
- Oluwayemisi, A. M. B., Olatunde, O. J., Joshua, A. T., Adejumo, B. O., Alice, I. O., Kayode, B. M., & David, F. A. (2024). Environmental Cost and Firm Sustainability in Nigeria. *Acta Universitatis Danubius. Economica*, 20(3), 120–140. <https://www.ceool.com/search/article-detail?id=1372324>.
- Onunkwor, B. O., Oguntade, R., Babayemi, D. O., & Dele-Osinbanjo, J. S. (2022). *Toxicology impacts of heavy metal pollution of Ogun and Lagos fishing waters by sewages on the antioxidant status and nutritional value of prawn (Macrobrachium macrobrachion)*. <https://doi.org/10.51791/njap.v49i1.3419>.
- Onyena, A. P., Folorunso, O. M., Nwanganga, N., Udom, G. J., Ekhaton, O. C., Frazzoli, C., ... & Orisakwe, O. E. (2024). Engaging one health in heavy metal pollution in some selected Nigerian Niger delta cities. A Systematic review of pervasiveness, bioaccumulation and subduing environmental health challenges. *Biological Trace Element Research*, 202(4), 1356–1389. <https://doi.org/10.1007/s12011-023-03762-5>.
- Ouma, K. O., Shane, A., & Syampungani, S. (2022). Aquatic ecological risk of heavy-metal pollution associated with degraded mining landscapes of the Southern Africa River Basins: a review. *Minerals*, 12(2), 225. <https://doi.org/10.3390/min12020225>.
- Pasika, S., & Gandla, S. T. (2020). Smart water quality monitoring system with cost-effective using IoT. *Heliyon*, 6(7), e04096. <https://doi.org/10.1016/j.heliyon.2020.e04096>.
- Peng, Z., & Yang, H. (2009). Designer platinum nanoparticles: Control of shape, composition in alloy, nanostructure and electrocatalytic property. *Nano Today*, 4(2), 143–164. <https://doi.org/10.1016/j.nantod.2008.10.010>.
- Popli, S., Jha, R. K., & Jain, S. (2018). A survey on energy efficient narrowband internet of things (NB-IoT): architecture, application and challenges. *IEEE Access*, 7, 16739–16776. <https://doi.org/10.1109/ACCESS.2018.2881533>.
- Ray, P. P. (2022). A review on TinyML: State-of-the-art and prospects. *Journal of King Saud University-Computer and Information Sciences*, 34(4), 1595–1623. <https://doi.org/10.1016/j.jksuci.2021.11.019>.
- Raza, S., Wallgren, L., & Voigt, T. (2013). SVELTE: Real-time intrusion detection in the Internet of Things. *Ad Hoc Networks*, 11(8), 2661–2674. <https://doi.org/10.1016/j.adhoc.2013.04.014>.
- Sadiq, O., Hack-Polay, D., Fuller, T., & Rahman, M. (2022). Barriers to the effective integration of developed ICT for SMEs in rural Nigeria. *Businesses*, 2(4), 501–526. <https://doi.org/10.3390/businesses2040032>.
- Seneviratne, S., Hu, Y., Nguyen, T., Lan, G., Khalifa, S., Thilakarathna, K., ... & Seneviratne, A. (2017). A survey of wearable devices and challenges. *IEEE Communications Surveys & Tutorials*, 19(4), 2573–2620. <https://doi.org/10.1109/COMST.2017.2731979>.
- Serrano, N., Díaz-Cruz, J. M., Arino, C., & Esteban, M. (2016). Antimony-based electrodes for analytical determinations. *TRAC Trends in Analytical Chemistry*, 77, 203–213. <https://doi.org/10.1016/j.trac.2016.01.011>.
- Shahub, S., Upasham, S., Ganguly, A., & Prasad, S. (2022). Machine learning guided electrochemical sensor for passive sweat cortisol detection. *Sensing and Bio-Sensing Research*, 38, 100527. <https://doi.org/10.1016/j.sbsr.2022.100527>.

- Shaikh, F. K., & Zeadally, S. (2016). Energy harvesting in wireless sensor networks: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 55, 1041–1054. <https://doi.org/10.1016/j.rser.2015.11.010>.
- Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. *IEEE Internet of Things Journal*, 3(5), 637–646. <https://doi.org/10.1109/JIOT.2016.2579198>.
- Somerset, V., Leaner, J., Mason, R., Iwuoha, E., & Morrin, A. (2010). Development and application of a poly (2, 2'-dithiodianiline)(PDTDA)-coated screen-printed carbon electrode in inorganic mercury determination. *Electrochimica Acta*, 55(14), 4240–4246. <https://doi.org/10.1016/j.electacta.2009.01.029>.
- Švancara, I., Prior, C., Hočevar, S. B., & Wang, J. (2010). A decade with bismuth-based electrodes in electroanalysis. *Electroanalysis*, 22(13), 1405–1420. <https://doi.org/10.1002/elan.200970017>.
- Taivalsaari, A., & Mikkonen, T. (2017). A roadmap to the programmable world: software challenges in the IoT era. *IEEE Software*, 34(1), 72–80. <https://doi.org/10.1109/MS.2017.26>.
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In *Molecular, clinical and environmental toxicology: Volume 3: Environmental toxicology* (pp. 133–164). Springer. [https://doi.org/10.1007/978-3-7643-8340-4\\_6](https://doi.org/10.1007/978-3-7643-8340-4_6).
- Tiwari, R., Ranjan, N., Chaurasia, M., & Flora, S. J. S. (2025). Hyphenated Mass Spectroscopic Detection of Heavy Metals in Environmental and Biological Samples: A Review. *Journal of Trace Elements and Minerals*, 100273. <https://doi.org/10.1016/j.jtemin.2025.100273>.
- Umeogaju, F. U., Akaninwor, J. O., Essien, E. B., & Amadi, B. A. (2022). Heavy metal profile of surface and ground water samples from the Niger Delta region of Nigeria: a systematic review and meta-analysis. *Environmental Monitoring and Assessment*, 194(1), 46. <https://doi.org/10.1007/s10661-021-09688-6>.
- Umeogaju, F. U., Akaninwor, J. O., Essien, E. B., Amadi, B. A., Igboekwe, C. O., Ononamadu, C. J., & Ikimi, C. G. (2023). Heavy metals contamination of seafood from the crude oil-impacted Niger Delta Region of Nigeria: A systematic review and meta-analysis. *Toxicology Reports*, 11, 58–82. <https://doi.org/10.1016/j.toxrep.2023.06.011>.
- Wan, H., Sun, Q., Li, H., Sun, F., Hu, N., & Wang, P. (2015). Screen-printed gold electrode with gold nanoparticles modification for simultaneous electrochemical determination of lead and copper. *Sensors and Actuators B: Chemical*, 209, 336–342. <https://doi.org/10.1016/j.snb.2014.11.127>.
- Wang, J. (2005). Stripping analysis at bismuth electrodes: a review. *Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis*, 17(15–16), 1341–1346. <https://doi.org/10.1002/elan.200403270>.
- Wang, J., & Hui, N. (2019). Electrochemical functionalization of polypyrrole nanowires for the development of ultrasensitive biosensors for detecting microRNA. *Sensors and Actuators B: Chemical*, 281, 478–485. <https://doi.org/10.1016/j.snb.2018.10.131>.
- Wang, Z., Wang, H., Zhang, Z., & Liu, G. (2014). Electrochemical determination of lead and cadmium in rice by a disposable bismuth/electrochemically reduced graphene/ionic liquid composite modified screen-printed electrode. *Sensors and Actuators B: Chemical*, 199, 7–14. <https://doi.org/10.1016/j.snb.2014.03.092>.
- Xing, X., Liu, S., Yu, J., Lian, W., & Huang, J. (2012). Electrochemical sensor based on molecularly imprinted film at polypyrrole-sulfonated graphene/hyaluronic acid-multiwalled carbon nanotubes modified electrode for determination of tryptamine. *Biosensors and Bioelectronics*, 31(1), 277–283. <https://doi.org/10.1016/j.bios.2011.10.032>.
- Yılmaz, S., & Sadikoglu, M. (2011). Study of heavy metal pollution in seawater of Kepez harbor of Canakkale (Turkey). *Environmental Monitoring and Assessment*, 173(1), 899–904. <https://doi.org/10.1007/s10661-010-1432-5>.
- Zhang, H., Li, L., Wang, C., Liu, Q., Chen, W. T., Gao, S., & Hu, G. (2025). Recent advances in designable nanomaterial-based electrochemical sensors for environmental heavy-metal detection. *Nanoscale*, 17(5), 2386–2407. <https://doi.org/10.1039/D4NR04108A>.
- Zhang, Y., Qiu, M., Tsai, C. W., Hassan, M. M., & Alamri, A. (2015). Health-CPS: Healthcare cyber-physical system assisted by cloud and big data. *IEEE Systems Journal*, 11(1), 88–95. <https://doi.org/10.1109/JSYST.2015.2460747>.
- Zhou, P., Zheng, Y., & Li, M. (2012, June). How long to wait? Predicting bus arrival time with mobile phone based participatory sensing. In *Proceedings of the 10th international conference on Mobile systems, applications, and services* (pp. 379–392). <https://doi.org/10.1145/2307636.2307671>.