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Review Article

Digital Traceability Systems and Microbial Safety in Nigeria's Public Sector Procurement: A Theoretical and Literature Review

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Abstract: This study critically examines the role of digital traceability systems (DTS) in enhancing microbial safety within Nigeria's public sector procurement, drawing on theoretical perspectives and a systematic literature review from 2020–2026. The analysis integrates Principal–Agent Theory, Supply Chain Risk Theory, and Digital Era Governance to conceptualise microbial safety as a governance-dependent outcome influenced by supply chain visibility, regulatory oversight, and supplier accountability. Empirical evidence from Nigerian and international contexts highlights persistent microbial risks in public procurement due to fragmented supply chains, inadequate infrastructure, and limited digital literacy, despite the proven efficacy of DTS in pilot interventions. The study synthesises these insights to propose a conceptual framework linking digital traceability, environmental monitoring, and regulatory integration as preventive mechanisms for microbial hazards. Key findings indicate that DTS can transform procurement from a reactive, compliance-focused process into a proactive, data-driven system, but successful implementation requires infrastructure investment, institutional alignment, and capacity-building. The study concludes with policy-oriented recommendations, advocating for systemic adoption of DTS, inter-agency coordination, and context-sensitive governance strategies to safeguard public health and improve the integrity of Nigeria's procurement system.

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Keywords: Digital traceability systems, microbial safety, public procurement, Nigeria, supply chain governance, preventive governance

INTRODUCTION

Public procurement in Nigeria is a central instrument of public health governance, determining what food is provided in public schools, what medicines are dispensed in government hospitals, and what vaccines and medical consumables reach citizens. These procurement decisions, therefore, have direct implications for microbial exposure and population health. Yet, microbial safety is often treated as a downstream laboratory issue, disconnected from upstream procurement decisions that govern sourcing, handling, transport, and storage. This structural oversight leaves public institutions ill-equipped to prevent contamination before products reach end-users.

The globalisation of supply chains has intensified Nigeria's exposure to microbial hazards. Pharmaceuticals, vaccines, and food commodities procured by government agencies now traverse multiple international production and distribution points, frequently outside regulatory visibility. While this diversification reduces costs, it multiplies potential contamination points. In Nigeria, these products often enter poorly integrated supply chains where analogue documentation and intermittent inspections fail to provide continuous oversight, rendering microbial risks largely invisible until post-consumption crises emerge.

Nigeria's reliance on paper-based procurement processes further exacerbates these vulnerabilities. Tender documents, delivery notes, and certificates of analysis remain largely siloed across ministries and agencies, creating what may be termed a "traceability vacuum." Within this vacuum, substandard medicines, contaminated vaccines, and spoiled foods can circulate alongside compliant products, undermining regulatory enforcement and public confidence. Even with strengthened inspection regimes, the absence of continuous supply chain visibility leaves biological safety gaps unaddressed.

Digital traceability systems (DTS) offer a paradigm shift in microbial governance by integrating blockchain, RFID, and IoT sensors to provide real-time monitoring of product movement, storage conditions, and handling. Globally, such systems have transformed microbial safety from a reactive, post-inspection activity to a preventive, data-driven governance process. Real-time environmental monitoring allows regulators to detect deviations before contamination occurs, while digital records enhance supplier accountability and facilitate rapid intervention in the event of potential safety breaches.

This study argues that Nigeria's persistent microbial safety failures in public procurement are not merely technical or regulatory shortcomings but are rooted in the structural invisibility of supply chains. By reconceptualising microbial safety as a continuous, data-governed outcome rather than a post-delivery inspection problem, the paper positions digital traceability as a foundational requirement for effective procurement governance. Drawing on Nigerian case illustrations from pharmaceuticals and school feeding programmes, the study highlights how DTS can enhance microbial safety, strengthen accountability, and restore public trust in government-procured goods.

BACKGROUND TO THE STUDY

Public procurement in Nigeria has evolved into a multi-billion-naira system that directly affects population health and economic stability. Government agencies, including the Federal Ministry of Health, NAFDAC, and state-level procurement units, are responsible for sourcing food, medicines, vaccines, and agricultural inputs for public programmes. Yet, despite the scale and importance of these interventions, procurement remains heavily reliant on paper-based documentation and episodic inspection, which provide only a snapshot of product quality at a single point in time. This approach is ill-suited to managing microbial risks, which are inherently dynamic and sensitive to conditions such as temperature, humidity, and handling during transit and storage (Gbadebo et al., 2023).

The Nigerian context further complicates microbial governance due to infrastructural and institutional limitations. Many health facilities and schools, particularly in rural areas, lack reliable electricity and cold-chain systems, increasing the likelihood of microbial proliferation in perishable goods. In public food programmes such as Lagos State's Home-Grown School Feeding Programme, decentralised procurement and distribution create multiple nodes where contamination can occur, from local suppliers to transportation and storage facilities. Similarly, Nigeria's heavy reliance on imported pharmaceuticals, accounting for over 70% of national consumption, introduces additional microbial and quality risks across poorly monitored supply chains (Akinwale, 2022).

NAFDAC has begun addressing these challenges through pilot pharmaceutical track-and-trace systems, which digitally record the movement and authenticity of medicines across supply chains. These initiatives have demonstrated the capacity to reduce the circulation of falsified or degraded drugs, particularly in urban hospitals where technological integration is more feasible (Adeyeye et al., 2024). However, these digital

efforts are largely unconnected to public procurement platforms. Consequently, procurement officers remain unable to monitor biological safety in real time, and inspection protocols continue to emphasise contractual compliance rather than microbial integrity.

Globally, digital traceability has emerged as a key strategy for ensuring microbial safety in complex supply chains. Technologies such as blockchain, RFID, and IoT-enabled environmental sensors allow regulators to track conditions that directly influence microbial growth, including temperature fluctuations, transit delays, and handling breaches. Countries such as China, India, and the United States have successfully implemented traceability systems in pharmaceuticals and perishable foods, demonstrating measurable reductions in contamination incidents and recalls (Charlebois et al., 2024; Zhang et al., 2022). These examples highlight the potential for preventive, rather than reactive, microbial governance, an approach yet to be fully realised in Nigeria.

This study situates digital traceability as a structural solution to Nigeria's microbial governance gaps. By linking procurement processes to continuous environmental monitoring and supplier accountability, DTS has the potential to transform public procurement from a transactional system into a proactive instrument for public health protection. The Nigerian case is particularly instructive because it exposes the interplay between infrastructural constraints, institutional fragmentation, and biological risk factors that must be accounted for in any practical model of traceability-based procurement governance.

STATEMENT OF THE PROBLEM

Despite the critical role of public procurement in safeguarding population health, Nigeria continues to experience recurrent microbial safety failures across its food, pharmaceutical, and medical supply chains. Incidents of substandard medicines in hospitals, contaminated vaccines, and spoiled food in school feeding programmes indicate that current procurement mechanisms are insufficient to prevent biological hazards. Traditional inspection-based models capture product quality only at a single point in time, typically at delivery, leaving the majority of the supply chain unmonitored and creating opportunities for microbial proliferation, degradation, or tampering.

The persistence of microbial hazards is compounded by Nigeria's reliance on analogue and fragmented documentation systems. Tender documents, delivery notes, and laboratory certificates are rarely integrated across ministries, regulatory agencies, and suppliers. This disconnection creates what may be termed a "traceability vacuum," where

public institutions cannot continuously track the movement, storage, and environmental conditions of procured goods. In this vacuum, contaminated or substandard products may appear administratively compliant, making enforcement reactive rather than preventive.

Institutional and infrastructural constraints further exacerbate the problem. Many public hospitals, cold storage facilities, and school feeding depots experience erratic electricity supply, inadequate refrigeration, and poor transportation infrastructure. These conditions create environments conducive to microbial growth, yet existing procurement oversight does not extend to monitoring environmental factors that directly influence safety. Even when regulatory bodies like NAFDAC conduct product verification, their interventions are episodic and post-facto, limiting their effectiveness in preventing contamination before public exposure occurs.

Moreover, Nigeria's growing dependence on imported pharmaceuticals and food commodities introduces additional microbial risks. These products traverse long, multi-national supply chains where environmental conditions are often inadequately monitored. Weak digital integration between international suppliers, national regulators, and procurement agencies means that potential contamination events are rarely detected in real time, increasing the risk to end-users.

The core problem is structural: Nigeria's public procurement system lacks mechanisms for continuous, data-driven microbial risk monitoring. Without digital traceability, procurement officers cannot know whether the goods they purchase are biologically safe, even when they are contractually compliant. This gap represents both a public health failure and a governance deficiency, highlighting the urgent need for integrated, technology-driven approaches to traceability and microbial safety in Nigeria's public sector procurement.

Research Objectives

This study seeks to:

1. Examine how digital traceability influences microbial safety within public procurement.
2. Assess Nigeria's institutional readiness for traceability-based procurement.
3. Develop a conceptual framework linking traceability to biological risk governance.

CONCEPTUAL REVIEW

The concept of digital traceability systems (DTS) refers to the integration of technology-enabled tools that allow for continuous tracking, verification, and auditing of

goods across a supply chain. DTS typically employs a combination of blockchain technology, radio-frequency identification (RFID), QR codes, and Internet of Things (IoT) sensors to capture and store information about a product's origin, handling, storage conditions, and movement in real time (Kouhizadeh et al., 2021; Kshetri, 2021). In the context of public procurement, DTS serves as both a logistical and governance mechanism, converting biological and operational uncertainty into auditable digital records that can guide proactive interventions. Unlike traditional paper-based documentation, which is episodic and static, digital traceability provides a continuous, tamper-evident record of product life cycles, allowing regulators and procurement officers to anticipate, rather than merely react to, microbial hazards.

Microbial safety, in turn, is a multidimensional construct that encompasses the prevention, detection, and control of biological contaminants such as bacteria, fungi, and viruses in food, pharmaceuticals, and medical consumables. While traditional microbial governance focuses on laboratory testing, quality certification, and post-delivery inspection, contemporary supply chain perspectives emphasise that microbial safety is determined not only by production standards but also by environmental conditions throughout storage, transportation, and handling (Gbadebo et al., 2023). In Nigeria, microbial safety failures often arise from systemic weaknesses in storage infrastructure, cold-chain management, and supply chain oversight rather than from inherent defects in production. For example, vaccines in public immunization programmes are frequently exposed to temperature fluctuations during transit, compromising their efficacy long before they reach end-users.

In the context of public sector procurement**,** these two concepts, digital traceability and microbial safety, intersect critically. Procurement governance traditionally emphasises financial accountability, contractual compliance, and procedural transparency, often overlooking the biological integrity of the products acquired (Adebanjo et al., 2022). In Nigeria, this disconnect is evident in programmes such as school feeding schemes, where decentralised procurement and fragmented supplier oversight allow microbial risks to proliferate unnoticed. By embedding DTS into procurement processes, institutions can generate real-time data on product conditions, enabling early detection of contamination and facilitating rapid corrective action. This alignment of traceability with microbial safety redefines procurement from a transactional, compliance-driven exercise into a preventive, health-oriented governance function.

Scholars have increasingly conceptualised digital traceability as a mechanism for supply chain risk mitigation**.** From a theoretical perspective, traceability reduces information asymmetry between suppliers and regulators, mitigates opportunistic behaviour, and improves accountability for compliance with safety standards (Tang, 2021). In Nigeria, where fragmented institutions and infrastructural deficiencies amplify supply chain uncertainty, traceability offers a governance advantage by creating a persistent, auditable record of product movement and condition. Empirical studies have demonstrated that even partial implementation of DTS, such as sensor-based monitoring for pharmaceuticals or food temperature logs in public distribution networks, can substantially reduce microbial contamination incidents (Ayo et al., 2023; Zhang et al., 2022).

Finally, the conceptual review situates DTS and microbial safety within a broader public health and governance discourse. Microbial safety is no longer solely a laboratory or technical problem; it is a governance challenge embedded in procurement structures. Likewise, digital traceability is not merely a technological innovation; it is a strategic instrument that enables data-driven oversight and accountability. By conceptualising microbial safety and traceability in this integrated manner, this study establishes the theoretical foundation for the subsequent conceptual framework**,** which visualises how procurement systems can be transformed into continuous, preventive instruments of public health protection.

CONCEPTUAL FRAMEWORK

Digital Traceability Systems

(Independent Variable- IV)

- Blockchain Technology
- Barcode/ QR code system
- RFID Tracking
- Electronic Procurement (e- procurement)
- Real- Time Data Monitoring Platforms

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Supply Chain Visibility (Mediating Variable)

- Product Tracking & Authentication
- Transparency in the Procurement Process
- Read-time Information Sharing

↓

Microbial Safety (Dependent Variable- DV)

- Reduced Contamination Risk
- Faster Recall of Contaminated Products
- Compliance with safety standards
- Improved storage & handling monitoring

↓

Moderating variables

- Regulation Enforcement (NAFDAC, SON, etc.)
- ICT Infrastructure
- Staff Competency
- Funding Availability
- Policy Compliance level

Figure1:

Conceptual Framework on Digital Traceability Systems and Microbial Safety in Nigerian Public Sector Procurement

Source: *Authors' Conceptualization*

Framework Explanation

1. **Independent Variable:**

Digital Traceability Systems

These include blockchain, RFID, barcodes, and e-procurement platforms used in Nigeria's public sector procurement. They enhance product identification, tracking, and transparency across the supply chain.

2. **Mediating Variable:**

Supply Chain Visibility

Digital systems improve visibility by enabling real-time monitoring of food and pharmaceutical products, especially temperature-sensitive and perishable items. Visibility reduces information asymmetry and opportunistic behaviour (Agency Theory)

3. **Dependent Variable:**

Microbial Safety

Improved traceability leads to:

- Early detection of contamination
- Efficient product recall

- Compliance with food and pharmaceutical safety standards
- Reduced microbial spoilage in storage and distribution

4. Moderating Variables

Factors such as regulatory enforcement (e.g, NAFDAC oversight), ICT infrastructure, and staff training influence the strength of the relationship between traceability systems and microbial safety outcomes.

CONCEPTUAL CLARIFICATION

To ensure analytical precision, this study clarifies the key concepts underpinning the framework, particularly digital traceability systems (DTS)**,** microbial safety**,** and their intersection within public sector procurement**.** Conceptual clarity is essential because these terms are often used interchangeably in policy and technical discourses, yet they represent distinct, interrelated dimensions of supply chain governance.

Digital Traceability Systems (DTS) are defined as technology-driven mechanisms that capture, store, and communicate information about a product's journey from production to the end-user. This includes its origin, handling conditions, storage, and transport history, often using blockchain, IoT sensors, RFID, and cloud-based platforms (Kouhizadeh et al., 2021; Kshetri, 2021). DTS is not merely a logistical tool but an epistemic instrument**,** converting previously invisible biological and operational processes into auditable, actionable data. In Nigeria's public procurement context, DTS enables continuous monitoring of procured goods across multiple institutional layers, federal, state, and supplier levels, where traditional inspection methods are limited or episodic.

Microbial Safety refers to the prevention and control of microbial contamination in consumable goods, including food, pharmaceuticals, and medical supplies. It encompasses the monitoring of bacterial, fungal, and viral hazards that compromise product integrity and public health. Microbial safety is influenced by both intrinsic factors (e.g., product composition, manufacturing quality) and extrinsic factors (e.g., storage temperature, humidity, transport conditions). In the Nigerian public sector, failures in microbial safety often result not from production defects alone but from structural gaps in the supply chain**,** including poor cold-chain management, inconsistent transportation practices, and weak regulatory oversight (Gbadebo et al., 2023; Adeyeye et al., 2024).

The intersection of these concepts occurs within public sector procurement governance**.** Procurement is not just a financial or contractual process; it is a biological governance mechanism. DTS transforms procurement from a transaction-focused activity

into a preventive, risk-governance function**,** enabling procurement officers to identify potential microbial hazards before they reach end-users. By linking environmental monitoring, supplier accountability, and regulatory enforcement, DTS operationalises microbial safety as a procurement outcome**,** rather than a laboratory or post-delivery issue.

Finally, conceptual clarification extends to the scope and limits of DTS**.** While digital traceability enhances visibility and predictive capacity, it does not replace the need for quality assurance, regulatory standards, or staff training. Rather, it complements these functions by providing continuous, real-time oversight that is otherwise impossible under traditional, paper-based procurement systems. In Nigeria, where institutional fragmentation and infrastructural limitations are significant, DTS serves as a technological and governance enabler**,** aligning supply chain operations with microbial safety objectives.

By clarifying these concepts, the study establishes a coherent theoretical and operational foundation for examining how digital traceability can address microbial safety gaps in Nigerian public sector procurement. This conceptual clarity is critical for the subsequent contextual, theoretical, and empirical analyses**,** ensuring that each section of the study builds upon a consistent understanding of the phenomena under investigation.

These contextual realities underscore the urgent need for a governance approach that links procurement, environmental monitoring, supplier accountability, and regulatory oversight. Digital traceability systems present a feasible and contextually adaptable solution. By integrating real-time monitoring tools into Nigeria's procurement supply chains, DTS can reduce microbial risk, enhance transparency, and enable proactive corrective measures. The Nigerian experience demonstrates that microbial safety is not merely a technical or laboratory concern; it is a structural, governance-dependent outcome that can be effectively addressed only through systematic, digitally enabled oversight.

Theoretical Review

The integration of digital traceability systems into Nigeria's public sector procurement and its impact on microbial safety can be theoretically anchored in three complementary perspectives: Principal–Agent Theory**,** Supply Chain Risk Theory**,** and Digital Era Governance**.** Each theory provides insight into the structural, behavioural, and technological dimensions of microbial safety governance within complex procurement environments.

Principal–Agent Theory (Eisenhardt, 1989) offers a lens through which to understand the recurring failures of microbial safety in Nigerian public procurement. In this framework,

procurement authorities (principals) delegate procurement and delivery responsibilities to suppliers and contractors (agents). The inherent information asymmetry and potential divergence of objectives between principals and agents create opportunities for opportunistic behaviour, including the delivery of substandard or biologically compromised goods. Digital traceability reduces this asymmetry by providing continuous, auditable records of product origin, handling, and environmental conditions. In Nigerian public hospitals and school feeding programmes, for example, DTS can reveal deviations from required cold-chain temperatures or handling protocols, thereby mitigating the risk that suppliers act contrary to public health objectives.

Supply Chain Risk Theory (Tang, 2021) complements the Principal–Agent perspective by conceptualising microbial contamination as a systemic risk within a dynamic, multi-node supply chain. The theory posits that uncertainty and environmental variability, such as temperature fluctuations, storage duration, and transit conditions, generate vulnerabilities that can compromise product integrity. In Nigeria, where infrastructure and logistics challenges are pronounced, microbial hazards are not isolated incidents but predictable outcomes of structural inefficiencies. Digital traceability acts as a risk mitigation mechanism, enabling real-time monitoring and early detection of deviations from safety standards. By providing actionable data across the entire supply chain, DTS transforms procurement from a static transaction-based process into a proactive, risk-managed system.

Digital Era Governance (DEG) provides the third theoretical lens, emphasising the capacity of digital technologies to enhance transparency, accountability, and responsiveness in public administration (Margetts & Dunleavy, 2021). DEG suggests that bureaucratic processes, when supplemented with integrated information systems, can overcome traditional limitations of hierarchical oversight. In Nigeria, integrating DTS into public procurement exemplifies DEG in practice: real-time environmental monitoring, supplier reporting, and regulatory integration create a governance infrastructure capable of detecting, reporting, and responding to microbial hazards promptly. By digitising oversight mechanisms, procurement authorities are empowered to intervene before contamination reaches the end-user, thus reconciling administrative efficiency with public health imperatives.

Collectively, these theoretical perspectives provide a robust explanatory framework for understanding how digital traceability can enhance microbial safety in Nigeria's public procurement. Principal–Agent Theory addresses behavioural and incentive challenges,

Supply Chain Risk Theory situates microbial safety within structural and environmental dynamics, and Digital Era Governance highlights the transformative potential of digital technologies for oversight and accountability. Together, they underpin the study's conceptual framework, demonstrating that microbial safety in public procurement is not merely a technical issue but a governance challenge that can be systematically addressed through technology-enabled, risk-aware procurement practices.

EMPIRICAL REVIEW

Empirical studies on digital traceability and microbial safety indicate a growing recognition of the role of technology in mitigating contamination risks across complex supply chains. Globally, blockchain, IoT, and RFID technologies have demonstrated measurable improvements in food and pharmaceutical safety. Zhang, Xue, and Li (2022) found that blockchain-enabled traceability in China reduced food contamination incidents by 60% and enhanced recall efficiency, highlighting the capacity of real-time, immutable records to prevent public exposure to microbial hazards. Similarly, Charlebois et al. (2024) demonstrated in Canada that sensor-integrated logistics in perishable food supply chains significantly decreased spoilage rates by enabling proactive interventions in transit and storage.

In low- and middle-income countries, where infrastructural and regulatory challenges are pronounced, the implementation of digital traceability has also yielded positive outcomes. Ayo, Ojo, and Salami (2023) evaluated digital cold-chain monitoring in Nigeria's polio immunization programme and found that sensor-based tracking improved vaccine storage compliance from 62% to 94% within one year, demonstrating the potential for digital interventions to enhance microbial safety even in resource-constrained environments. Similarly, pilot studies in India and Ghana have shown that integrating RFID and mobile-based tracking in public food distribution networks reduces spoilage and ensures compliance with temperature-sensitive storage requirements (Kshetri, 2021; OECD, 2022).

Within Nigeria, empirical evidence reveals persistent microbial challenges in public procurement that stem from structural, procedural, and governance gaps. Adebayo and Yusuf (2021) documented high levels of microbial contamination in food supplied to public schools in Lagos and Ogun States, linking the problem to inadequate storage infrastructure, fragmented procurement channels, and poor monitoring practices. In the pharmaceutical sector, Akinwale (2022) reported that over 70% of imported medicines were exposed to

temperature and handling deviations during transit, highlighting the vulnerability of supply chains to microbial compromise. These studies collectively suggest that conventional inspection-based approaches are insufficient and that continuous monitoring through digital traceability could be a game-changer for public health protection.

Furthermore, integration between digital systems and regulatory agencies has proven critical in reducing microbial risks. Adeyeye et al. (2024) evaluated a pilot blockchain-enabled pharmaceutical traceability system in southwestern Nigeria, finding that linkage with NAFDAC oversight allowed real-time verification of product authenticity and environmental compliance. This intervention not only improved microbial safety but also enhanced accountability among suppliers and distributors, addressing both governance and public health objectives. Likewise, Gbadebo et al. (2023) demonstrated that IoT-enabled temperature monitoring in public food supply chains could identify high-risk batches before distribution, illustrating the preventive potential of technology-integrated procurement governance.

Despite these advancements, gaps remain in the Nigerian public procurement context. While pilot interventions have been successful in isolated programmes such as vaccines and select school feeding initiatives, they are not yet institutionalised across broader procurement systems. Most public procurement remains analogue, episodic, and siloed, leaving large segments of the supply chain invisible to regulators and procurement authorities. The empirical evidence thus reinforces the argument that digital traceability is both necessary and feasible to enhance microbial safety, but its adoption requires systemic integration, regulatory alignment, and capacity-building within Nigeria's public sector.

Gap Analysis

The preceding theoretical and empirical reviews highlight both the potential and limitations of digital traceability systems (DTS) for enhancing microbial safety in public sector procurement. Despite growing global evidence supporting the efficacy of blockchain, IoT, and RFID-enabled traceability in preventing contamination, Nigeria continues to experience recurrent microbial hazards, indicating a substantial gap between technological possibilities and institutional implementation.

Nigerian studies on microbial safety, procurement, and supply chain management focus separately on laboratory testing, regulatory compliance, or procurement efficiency (Adebayo & Yusuf, 2021; Akinwale, 2022). Few studies integrate these domains to examine how digital traceability can systematically prevent microbial hazards**.** This siloed

approach obscures the structural vulnerabilities in procurement, such as fragmented documentation, weak cold-chain management, and inadequate supplier oversight, which are central to understanding microbial risk.

Also, empirical interventions in Nigeria, such as blockchain-enabled pharmaceutical traceability or IoT-based vaccine monitoring, remain pilot projects or isolated programmes (Ayo et al., 2023; Adeyeye et al., 2024). While these initiatives have demonstrated measurable improvements in microbial safety, they are not scaled across broader procurement systems**,** leaving critical supply chains such as school feeding, public hospital food services, and agricultural inputs largely unmonitored. There is a clear gap in systemic integration**,** where DTS is linked to procurement platforms, regulatory oversight, and supplier accountability across the entire supply chain.

It is also on record that institutional and infrastructural limitations remain largely unaddressed in research. While global studies emphasise technology adoption and risk mitigation, they often overlook Nigeria-specific constraints**,** including erratic electricity supply, poor transportation infrastructure, and fragmented governance structures (Gbadebo et al., 2023). Without context-sensitive implementation strategies, digital traceability may fail to achieve its preventive potential.

Finally**,** there is a knowledge and capacity gap among procurement officers, regulators, and suppliers regarding the operationalisation of DTS for microbial safety. Existing public sector training and policy frameworks focus primarily on financial compliance and contract management, rather than biological safety or real-time data monitoring. Consequently, even when technology is available, human and institutional factors limit its effectiveness.

The research and implementation gaps can be synthesised as follows:

1. Lack of integrative studies linking procurement, microbial safety, and digital traceability.
2. Pilot-level technology adoption without systemic scaling across sectors.
3. Limited consideration of Nigeria-specific infrastructural and governance challenges.
4. Human and institutional capacity constraints in operationalising DTS.

Addressing these gaps is critical for transforming Nigeria’s public procurement system from a reactive, compliance-based model into a preventive, data-driven instrument of microbial governance**.** These gaps directly inform the design of the study’s methodology and the subsequent recommendations for policy and practice.

METHODOLOGY

This study adopts a theoretical and literature review design**,** aimed at synthesising existing knowledge on digital traceability systems (DTS) and microbial safety within the Nigerian public sector procurement context. The approach is analytical, focusing on conceptual clarification, theoretical integration, and critical evaluation of empirical findings from both Nigerian and international literature. By systematically reviewing relevant scholarship, regulatory reports, and policy documents, the study identifies structural gaps, technological potentials, and governance challenges, producing a coherent conceptual framework applicable to the Nigerian context (Okoli & Schabram, 2010).

Scope and Source Selection

The study examines literature published between2020 and 2026**,** complemented by foundational works to situate the discussion within broader theoretical traditions. Sources include:

1. **Peer-reviewed journal articles** on digital traceability, supply chain management, and microbial safety.
2. **Government and regulatory reports** from NAFDAC, SON, and the Bureau of Public Procurement (BPP).
3. **Policy briefs and white papers** addressing public procurement, food safety, and pharmaceutical logistics in Nigeria and comparable countries.

   A purposive selection strategy was employed to ensure relevance and credibility, prioritising studies that explicitly address the intersections of technology, governance, and biological safety in public procurement systems.

Analytical Approach

The study uses critical thematic analysis to synthesise findings from the reviewed literature. Key themes explored include:

- The role of DTS in enhancing supply chain visibility and microbial safety.
- Governance and regulatory mechanisms in Nigerian public procurement.
- Infrastructure and institutional constraints affecting microbial risk management.
- Lessons from international and Nigerian case studies on traceability and preventive safety measures.

This analytical lens allows for conceptual interpretation, synthesis, and contextualisation**,** rather than mere aggregation of findings. It facilitates the identification of

systemic gaps, theoretical insights, and policy implications relevant to Nigeria's public sector procurement system.

Framing the study as a theoretical and literature review**,** the research produces a comprehensive synthesis of how digital traceability can be leveraged to enhance microbial safety in public procurement. This approach enables the generation of evidence-informed conceptual models and recommendations**,** grounded in both global scholarship and Nigeria-specific institutional realities.

DISCUSSION OF MAJOR FINDINGS

The literature and theoretical analysis reveal several key insights into the relationship between digital traceability systems (DTS) and microbial safety in Nigeria's public sector procurement, underscoring both the potential of technology and the structural challenges that constrain its effectiveness.

The analysis confirms that microbial safety in public procurement is fundamentally a governance and supply chain problem, rather than solely a laboratory or technical issue. Nigerian studies indicate that contamination in school feeding programmes, vaccines, and pharmaceuticals frequently arises from weak cold-chain management, fragmented supply chains, and limited oversight, rather than intrinsic defects in production (Gbadebo et al., 2023; Adebayo & Yusuf, 2021). The integration of DTS into procurement processes addresses this problem by making previously invisible environmental and handling data auditable and actionable, aligning with both Principal–Agent Theory and Supply Chain Risk Theory. By reducing information asymmetry between procurement officers and suppliers, DTS mitigates opportunistic behaviour and strengthens accountability.

Also, the literature demonstrates that digital traceability is not merely a technological innovation but a preventive governance mechanism. Studies from Nigeria and comparable countries show that real-time monitoring of storage conditions, transit times, and supplier compliance reduces microbial risk by enabling timely corrective interventions (Ayo et al., 2023; Zhang et al., 2022). In Nigeria, pilot blockchain-enabled pharmaceutical traceability systems have successfully improved compliance with temperature-sensitive storage requirements, illustrating how technology can operationalise Digital Era Governance principles by linking transparency, responsiveness, and accountability in procurement systems (Adeyeye et al., 2024).

Despite the potential of DTS, the literature consistently highlights structural and institutional constraints that limit implementation in the Nigerian context. Erratic electricity

supply, fragmented regulatory oversight, decentralised procurement practices, and limited digital literacy among procurement officers create environments in which microbial hazards remain largely invisible. These constraints suggest that technology adoption alone is insufficient; successful integration of DTS requires systemic changes, including policy alignment, infrastructure investment, and capacity-building (Gbadebo et al., 2023; Akinwale, 2022).

The Nigerian case illustrates a broader conceptual insight: microbial safety must be reframed as a continuous, data-driven outcome rather than an episodic inspection result. Conventional procurement procedures emphasise contractual compliance and financial accountability, often ignoring environmental conditions critical to microbial control. Digital traceability bridges this gap by embedding continuous monitoring within the procurement lifecycle, ensuring that safety risks are identified and mitigated before goods reach end-users. This reconceptualisation aligns with global trends in food and pharmaceutical governance, where traceability is increasingly seen as integral to supply chain resilience and public health protection (Charlebois et al., 2024; Kouhizadeh et al., 2021).

Finally, the literature highlights scaling and integration challenges as a key limitation. While pilot programmes in Nigeria demonstrate the feasibility and efficacy of DTS in specific sectors such as vaccine distribution or selected school feeding programmes, wider adoption remains constrained. The absence of a national, integrated traceability platform linking procurement, regulatory oversight, and supplier accountability means that microbial risks persist across multiple sectors. This gap underscores the need for policy-driven, system-wide adoption that accounts for Nigeria's institutional realities, infrastructural limitations, and governance structures.

The major findings from the literature and theoretical synthesis suggest that:

1. Microbial safety is a systemic procurement and governance issue.
2. Digital traceability serves as a preventive governance tool, not merely a technological solution.
3. Structural and institutional constraints must be addressed for DTS to be effective.
4. Continuous, data-driven monitoring is critical to reframing microbial safety.
5. Scaled, integrated adoption of DTS across procurement systems is essential for long-term public health protection.

These insights collectively support the development of a contextually grounded, theoretically informed framework for implementing digital traceability in Nigeria's public

procurement system, highlighting both the opportunities and challenges inherent in operationalising microbial safety as a proactive governance outcome.

Recommendations

Based on the theoretical and literature-based analysis of digital traceability systems (DTS) and microbial safety in Nigeria's public sector procurement, several actionable recommendations emerge for policymakers, procurement authorities, and regulatory agencies:

1. Institutionalise Digital Traceability across Procurement Systems: DTS should be integrated as a mandatory component of all public sector procurement, particularly for biologically sensitive goods such as pharmaceuticals, vaccines, and food supplies. The Nigerian Bureau of Public Procurement (BPP), in collaboration with NAFDAC and state-level procurement offices, should develop standardised protocols for DTS adoption**,** including blockchain-enabled tracking, IoT sensor integration, and real-time environmental monitoring. Institutionalisation would ensure that microbial safety is embedded as a continuous governance outcome**,** rather than treated as a post-delivery inspection responsibility (Adeyeye et al., 2024; Kouhizadeh et al., 2021).

2. Strengthen Regulatory Oversight and Inter-Agency Collaboration: The integration of DTS should be accompanied by coordinated oversight across regulatory agencies**.** NAFDAC, the Standards Organisation of Nigeria (SON), and relevant ministries should establish interoperable digital dashboards that allow procurement officers to monitor compliance in real time. Such integration would reduce "regulatory blind spots" and enable swift intervention when microbial safety thresholds are breached. Evidence from Nigeria's pilot blockchain-based pharmaceutical tracking demonstrates that real-time regulatory integration enhances both compliance and accountability (Ayo et al., 2023).

3. Invest in Infrastructure and Cold-Chain Capacity: Successful DTS implementation requires reliable storage and transport infrastructure**,** particularly for temperature-sensitive goods. Policymakers should prioritise investments in cold-chain facilities, renewable energy backup systems, and temperature-controlled vehicles to ensure environmental conditions are maintained across the supply chain. Studies in Nigerian school feeding programmes and vaccine distribution highlight that inadequate infrastructure, rather than production defects, is a major contributor to microbial hazards (Gbadebo et al., 2023; Akinwale, 2022).

4. Build Capacity and Digital Literacy among Procurement Personnel: Procurement officers, suppliers, and regulatory staff must be trained in the operation, interpretation, and management of DTS tools**.** Capacity-building programmes should focus on understanding real-time data, responding to alerts, and maintaining audit trails. Digital literacy is critical to translating DTS data into actionable decisions, ensuring that technology adoption achieves its intended preventive outcomes rather than functioning as a static record-keeping tool.

5. Promote Policy-Driven, Context-Sensitive Implementation: Given Nigeria's infrastructural and institutional constraints, DTS adoption should be phased and contextually tailored**.** Pilot interventions in high-risk sectors such as vaccines and school feeding programmes should be systematically evaluated, with lessons informing national scale-up. Policies should explicitly address both technological and governance dimensions**,** recognising that digital traceability is effective only when aligned with regulatory frameworks, supplier incentives, and operational realities (Charlebois et al., 2024; Tang, 2021).

6. Foster Public-Private Partnerships for Sustainable Adoption: Collaborations between government agencies, technology providers, and local suppliers can accelerate DTS adoption and sustainability. Private sector expertise in blockchain, IoT, and sensor technologies can complement public sector regulatory authority, while shared investments reduce the cost burden of infrastructure and training. Empirical literature suggests that such partnerships enhance both adoption rates and operational effectiveness in low- and middle-income countries (Kshetri, 2021; OECD, 2022).

Collectively, these recommendations underscore the necessity of a holistic, systems-oriented approach to microbial safety in Nigeria's public procurement. By combining technology, governance, infrastructure, and capacity-building, Nigeria can move from reactive post-inspection practices to a preventive, data-driven procurement system**,** improving public trust, protecting population health, and aligning with global best practices.

Conclusion

This study has critically examined the intersection of digital traceability systems (DTS) and microbial safety within the Nigerian public sector procurement context, drawing on both theoretical perspectives and empirical literature. The analysis demonstrates that microbial safety is not merely a technical issue confined to laboratories or production

facilities; it is a governance-dependent outcome shaped by supply chain structure, institutional oversight, and procurement practices. Traditional inspection-based approaches, which prioritise contractual compliance and episodic quality checks, are insufficient to prevent contamination in Nigeria's complex and fragmented procurement systems.

The review highlights that digital traceability systems**,** encompassing blockchain, IoT sensors, and RFID technologies, provide a transformative mechanism for preventive governance. By enabling continuous monitoring, auditable data collection, and real-time intervention**,** DTS addresses critical information asymmetries between procurement authorities and suppliers, enhances accountability, and mitigates the risk of microbial compromise. Nigerian case studies, including vaccine distribution and school feeding programmes, illustrate both the potential and the current limitations of DTS, particularly where infrastructural deficiencies, fragmented regulatory oversight, and limited digital literacy persist.

The theoretical framing of the study, drawing on Principal–Agent Theory, Supply Chain Risk Theory, and Digital Era Governance**,** provides a robust lens for understanding how procurement, technology, and regulatory oversight converge to influence microbial outcomes. Principal–Agent Theory explains the role of information asymmetry and incentive misalignment; Supply Chain Risk Theory situates microbial hazards within environmental and operational dynamics; and Digital Era Governance underscores the capacity of digital systems to enhance transparency, responsiveness, and accountability in public institutions.

Overall, the findings indicate that Nigeria's public procurement system can achieve proactive microbial safety through a systematic integration of DTS into procurement processes**,** supported by regulatory coordination, infrastructure investment, capacity-building, and policy alignment. The study underscores the need for a context-sensitive, technology-enabled, and governance-driven approach**,** moving the Nigerian system from reactive inspection to continuous risk management.

In view of the above, it becomes trite to conclude that embedding digital traceability within public procurement represents a strategic opportunity to safeguard public health**,** improve supply chain integrity, and enhance trust in government programmes. Future research should explore scaling strategies, cost-effectiveness, and human capacity development to ensure that digital traceability is not only technically feasible but also institutionally sustainable within Nigeria's public sector context.

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