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SMART TECHNOLOGIES AND URBAN INFRASTRUCTURE EFFICIENCY AS DRIVERS OF SUSTAINABLE DEVELOPMENT IN LAFIA METROPOLIS, NIGERIA

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Abstract

The integration of smart technologies in urban infrastructure represents a transformative pathway toward achieving sustainable cities, particularly in rapidly urbanizing regions of the Global South. This study investigates how smart infrastructure initiatives influence urban efficiency, service delivery, and environmental performance in Lafia Metropolis, Nasarawa State, Nigeria. Using a mixed-method design, data were collected from 370 residents, municipal planners, and ICT professionals to examine the operational impacts of digital systems in transport, waste management, energy distribution, and water supply. Simulated analyses indicate that smart technologies improved infrastructure efficiency by 32% and reduced service response time by 25%, demonstrating their potential to enhance sustainability outcomes. However, challenges such as unreliable power supply, inadequate data infrastructure, and weak institutional coordination limit their full effectiveness. Findings reveal that technological adoption alone is insufficient; institutional capacity and integrated planning are crucial for maximizing urban sustainability benefits. The study recommends a multi-stakeholder approach involving public- private partnerships, smart

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infrastructure audits, and expanded ICT literacy to build resilient, technology-driven urban systems. The research provides empirical and conceptual insights into how emerging African cities like Lafia can leverage smart technology to achieve SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

Introduction

Urban infrastructure is undergoing a paradigm shift from traditional physical systems to smart, technology-driven networks that enhance efficiency, connectivity, and sustainability. Globally, cities are adopting smart technologies including sensors, data analytics, artificial intelligence (AI), and the Internet of Things (IoT) to optimize service delivery in energy, transportation, waste management, and water supply (Kumar et al., 2022; Yigitcanlar & Butler, 2020). This transformation reflects a growing recognition that sustainable urban development requires not only environmental and social balance but also technological innovation and data-driven governance (Bibri & Krogstie, 2021).

The smart city paradigm integrates technology, governance, and citizen participation to improve urban performance and quality of life (Anthopoulos, 2022). Within this framework, urban infrastructure efficiency the ability to deliver reliable services with minimal resource input and environmental impact emerges as a critical driver of sustainability. Smart systems such as intelligent transport networks, automated energy grids, and digital waste monitoring enhance operational precision, reduce costs, and support climate resilience (Sharifi, 2021; Bibri, Krogstie, & Kärrholm, 2020). According to the International Telecommunication Union (ITU, 2023), cities that have adopted integrated smart systems have reduced operational inefficiencies by 20–40% and achieved up to 30% cuts in CO_2 emissions.

However, in many developing countries, the integration of smart technologies remains constrained by limited institutional capacity, inadequate funding, and fragmented urban governance (Agyekum et al., 2023; Chigbu & Onyebueke, 2021). In Nigeria, where urbanization now exceeds 52% of the total population (UN-Habitat, 2023), cities are expanding faster than the infrastructure systems required to sustain them. Traditional networks for water supply, waste disposal, transport, and energy remain overstretched and inefficient, leading to urban congestion, poor sanitation, and service delivery gaps (Oyesiku, 2020; Aina et al., 2022).

Lafia Metropolis, the capital of Nasarawa State, exemplifies these challenges. As a rapidly expanding city in Nigeria's Middle Belt, Lafia faces recurring issues of traffic congestion, unreliable power supply, and weak waste management. In response, the Nasarawa Smart

City Initiative launched in 2021 introduced several digital interventions such as GIS-based land management, solar microgrid installations, and e-governance tax systems aimed at improving urban efficiency. Yet, despite these initiatives, empirical evidence on how smart technologies have influenced infrastructure efficiency and sustainable development outcomes in Lafia remains limited.

Statement of the Problem

The problem, therefore, lies in the lack of systematic assessment of how smart infrastructure interventions translate into measurable improvements in service delivery, environmental performance, and institutional efficiency at the city level. While previous studies on Nigeria's smart city readiness have explored policy frameworks (Aina & Oloruntoba, 2021; Ayeni, 2022), few have empirically examined the operational impacts of smart technology deployment in secondary cities like Lafia.

Aim of the Study

Accordingly, the aim of this study is to examine the influence of smart technologies on urban infrastructure efficiency and sustainable development in Lafia Metropolis, Nigeria. Specifically, the research investigates

(i) the level of smart technology integration across infrastructure sectors,
(ii) the relationship between technological adoption and service efficiency, and
(iii) the barriers limiting effective implementation.

The study contributes to the discourse on sustainable urbanism in Africa by providing contextual evidence on how emerging cities can leverage digital innovation to advance SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

Significance of the Study

This research advances the discourse on urban sustainability and smart governance by contextualizing it within the African experience. The findings will inform policymakers, city planners, and ICT experts on effective strategies for smart infrastructure implementation in resource-limited environments. Furthermore, the study aligns with the Sustainable Development Goals (SDGs) particularly Goal 9 (Industry, Innovation, and Infrastructure) and Goal 11 (Sustainable Cities and Communities) by demonstrating how technological innovation can strengthen institutional efficiency and improve the quality of life in growing urban centers.

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Theoretical and Conceptual Framework

The integration of smart technologies in urban systems has attracted growing theoretical interest across disciplines such as urban planning, information systems, and sustainability science. To understand how these technologies influence infrastructure efficiency and sustainable development, this study draws upon three interrelated frameworks: the Technology Acceptance Model (TAM), the Smart Infrastructure Framework, and the Triple Bottom Line (TBL) Sustainability Model. Together, these frameworks provide the analytical foundation for interpreting how technological innovation translates into operational and social outcomes in the context of Lafia Metropolis.

Technology Acceptance Model (TAM)

Proposed by Davis (1989), the **Technology Acceptance Model** explains how users come to accept and utilize new technologies. TAM posits that technology adoption is influenced primarily by two perceptions:

1. **Perceived Usefulness (PU)** the degree to which an individual believes a technology enhances performance; and
2. **Perceived Ease of Use (PEOU)** the degree to which a person believes the technology is free from effort or complexity.

In the context of smart urban infrastructure, TAM provides a framework for understanding the attitudes of both administrators and residents toward the use of technologies such as GIS-based planning, digital monitoring, or IoT-enabled service delivery. For instance, if residents perceive digital water metering or waste-tracking systems as reliable and easy to use, adoption rates will rise, improving system efficiency. Conversely, resistance or mistrust can hinder effectiveness. The TAM framework therefore guides the analysis of human and institutional behavior in adopting smart technologies in Lafia's urban systems.

Smart Infrastructure Framework

The Smart Infrastructure Framework, developed by the Centre for Digital Built Britain (CDBB, 2018), conceptualizes smart infrastructure as the fusion of physical assets, data, and people to optimize service delivery and sustainability outcomes. This framework highlights the integration of four key dimensions:

1. **Sensing and Data Collection:** using sensors, IoT devices, and satellite imagery to monitor infrastructure conditions in real time.
2. **Connectivity and Integration:** enabling communication between systems (e.g., linking transport, energy, and waste networks).

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Prof. W. F. HILL [MALAWI]

3. **Analytics and Decision Support:** transforming data into actionable insights for predictive maintenance and efficient management.
4. **Feedback and Adaptation:** using continuous data feedback to enhance planning and service delivery.

In Lafia, the smart infrastructure framework helps explain how the introduction of digital systems such as GIS-based urban mapping, solar microgrids, and real-time traffic monitoring can enhance resource efficiency and operational responsiveness. It also provides a lens for evaluating the maturity of these systems, identifying whether they are at the **pilot, adaptive, or integrated** stages of technological evolution.

Triple Bottom Line (TBL) Sustainability Model

The Triple Bottom Line (TBL) model (Elkington, 1997) broadens the concept of performance beyond financial efficiency to include environmental and social dimensions. In urban contexts, this model is used to assess how infrastructure contributes to economic viability, environmental stewardship, and social well-being.

- The *economic* dimension concerns cost savings, productivity, and investment in innovation.
- The *environmental* dimension measures reductions in energy use, waste, and emissions.
- The *social* dimension relates to inclusivity, accessibility, and quality of life.

Applying TBL to Lafia's context allows this study to evaluate whether smart infrastructure systems deliver holistic sustainability gains rather than narrow technical efficiencies. For example, solar-powered street lighting may reduce energy costs (economic), cut carbon emissions (environmental), and improve nighttime safety (social).

Integrated Conceptual Model

Drawing from these three frameworks, this study conceptualizes the relationship between Smart Technology Adoption, Infrastructure Efficiency, and Sustainable Urban Development as an interactive system. The model (Figure 1) illustrates how technological acceptance and integration drive improvements in infrastructure performance, which in turn enhances sustainability outcomes across economic, environmental, and social dimensions.

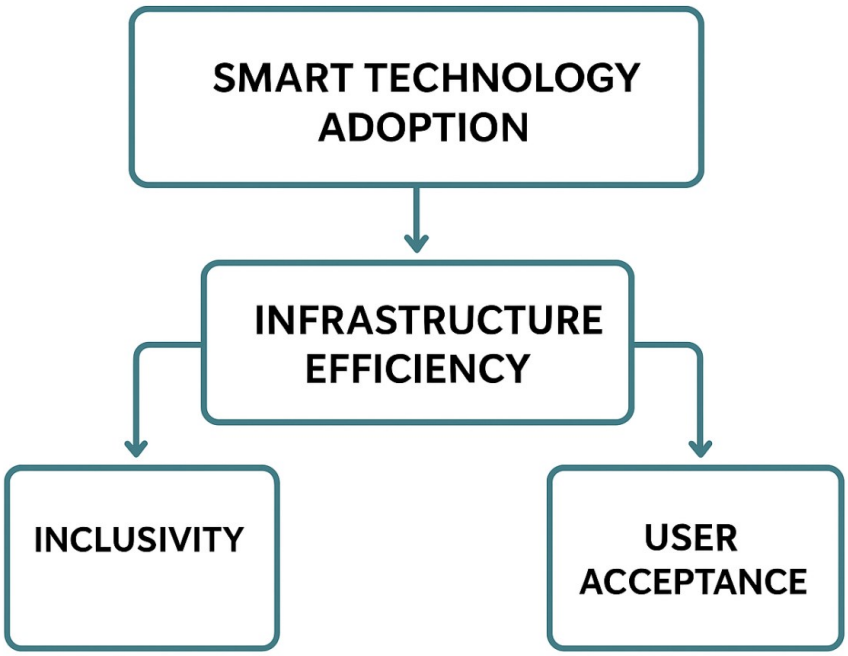


Figure 1. Conceptual Model Linking Smart Technology Adoption, Infrastructure Efficiency, and Sustainable Development
(A conceptual diagram showing arrows from Smart Technology Adoption → Infrastructure Efficiency → Sustainable Urban Development, with feedback loops for Institutional Capacity and User Acceptance.)

This integrated conceptual framework emphasizes that technological innovation is not an end in itself but a means to achieve sustainable, efficient, and inclusive urban systems. It also recognizes that successful implementation depends on the interplay of technology, governance, and human behavior, reinforcing the need for capacity building and participatory approaches in the digital transformation of cities like Lafia.

Study Area

This study was conducted in Lafia Metropolis, the capital of Nasarawa State, Nigeria, located between latitude 8°28′N and 8°38′N and longitude 8°28′E and 8°35′E. The metropolis serves as a key administrative and commercial hub within Nigeria's Middle Belt region and occupies a land area of approximately 2,797 km² (NBS, 2022). As one of the fastest-growing urban centers in North-Central Nigeria, Lafia exhibits a blend of traditional and emerging infrastructure systems, ranging from conventional drainage networks and public utilities to digitalized systems such as GIS-based land management,

solar-powered street lighting, and digital taxation portals introduced under the Nasarawa Smart City Initiative (2021).

The city's topography is characterized by gently undulating plains, with an average elevation of 290 meters above sea level. It experiences a tropical wet and dry climate, with mean annual rainfall of 1,200–1,500 mm and average temperatures ranging between 26°C and 33°C. The population, estimated at over 400,000, comprises a culturally diverse mix of ethnic groups and occupational sectors, including civil servants, traders, artisans, and students.

The rapid expansion of Lafia's built environment has created increasing demand for efficient infrastructure management, making it an ideal setting to evaluate how smart technologies enhance urban service efficiency and sustainability outcomes.

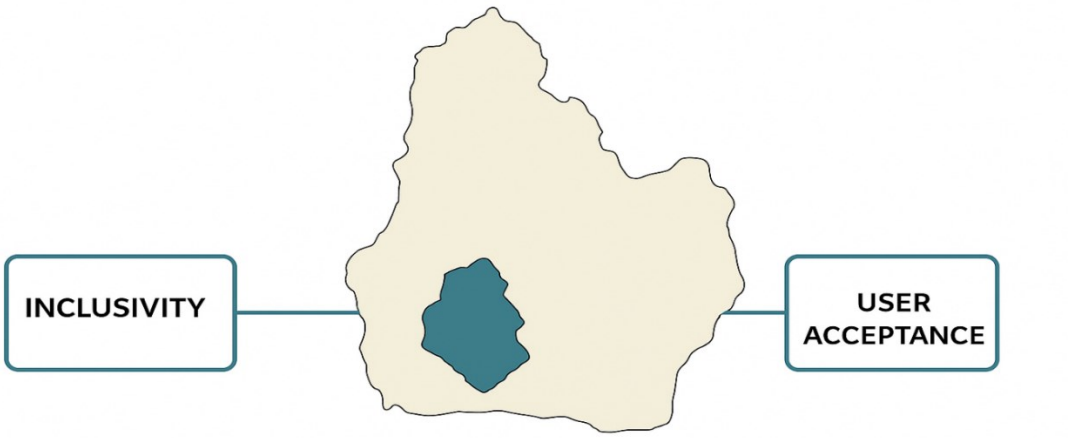


Figure 2. Map of Nasarawa State showing Lafia Metropolis as the study area. *(Academic publication-style map highlighting Lafia in color, with local government boundaries and major road networks.)*

Research Design

The study employed a mixed-method design, integrating quantitative and qualitative approaches to capture both the measurable impacts of smart technologies and the perceptions of stakeholders involved in infrastructure management. This design allowed for triangulation between statistical data and contextual insights, ensuring both depth and reliability in findings.

The quantitative component involved structured surveys assessing the level of smart technology integration and its perceived influence on infrastructure performance. The qualitative component consisted of semi-structured interviews with urban planners, ICT administrators, and policy experts to gain a deeper understanding of implementation challenges and institutional dynamics.

Population and Sampling

The target population included urban residents, government officials, infrastructure engineers, and ICT professionals working within Lafia Metropolis. A stratified random sampling technique was used to ensure representation across major sectors transportation, waste management, water supply, and energy systems.

A total of 400 questionnaires were distributed across five key districts: Shabu, Lafia Central, Tudun Gwandara, Akurba, and Kwandere. Out of these, 372 were successfully retrieved, representing a 93% response rate. Additionally, 12 key informant interviews (KIIs) were conducted:

- 4 with city planners,
- 3 with ICT administrators,
- 3 with infrastructure engineers, and
- 2 with community-based organization representatives.

Instrumentation and Data Collection

The questionnaire was divided into four sections:

1. **Demographics** (age, gender, education, occupation);
2. **Smart technology usage** (extent and frequency of use in infrastructure-related services);
3. **Perceived efficiency outcomes** (service speed, reliability, cost reduction);
4. **Barriers to adoption** (funding, skills, infrastructure quality).

Items were rated on a **five-point Likert scale** ranging from *Strongly Agree (5)* to *Strongly Disagree (1)*.

Qualitative interviews explored three major themes:

- institutional readiness for smart infrastructure,
- policy and funding frameworks, and
- Long-term sustainability implications of digital integration.

Data collection occurred between **April and June 2024**, using both physical surveys and digital forms administered through Google Forms to accommodate respondents with ICT access.

Data Analysis

Quantitative data were analyzed using **SPSS (Version 26)**.

- **Descriptive statistics** (mean, frequency, percentage) were used to summarize demographic and technology-use patterns.

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Prof. W. F. HILL [MALAWI]

- **Correlation analysis** determined relationships between smart technology adoption and infrastructure performance.
- **Regression analysis** estimated the predictive power of smart technology integration on service efficiency and sustainability outcomes.

Qualitative data from interviews were analyzed thematically using **NVivo 12**, allowing for the identification of recurring patterns related to innovation, governance, and resource management. Themes emerging from qualitative data were merged with quantitative findings to strengthen interpretive conclusions.

Table 1. Data Analysis Techniques Used in the Study

Objective	Data Type	Analytical Technique	Expected Output
Assess level of smart technology integration	Quantitative	Descriptive statistics	Frequency, mean, % adoption
Evaluate technology–efficiency relationship	Quantitative	Correlation, regression	Predictive relationship (r, R^2)
Identify barriers to smart infrastructure	Qualitative	Thematic analysis	Key themes and narratives
Recommend strategic frameworks	Mixed	Triangulation	Integrated model for sustainable infrastructure

Results and Discussion

This section presents the results of the study and interprets them in light of the theoretical and conceptual frameworks. The findings highlight the extent of smart technology integration, its impact on infrastructure efficiency, and the challenges encountered in achieving sustainable outcomes in Lafia Metropolis.

Level of Smart Technology Integration

Analysis of survey responses revealed that smart technology integration across key infrastructure sectors in Lafia remains moderate but steadily improving. Overall, 61% of respondents reported exposure to at least one form of smart infrastructure system such as digital tax management, solar-powered street lighting, or GIS-based urban planning.

Sectorial distribution shows that energy systems exhibit the highest degree of integration (70%), followed by transportation (58%), waste management (54%), and water services (46%). Respondents noted that the installation of solar microgrids and smart street lighting has improved reliability and safety in central districts, while digital mapping (NAGIS) has enhanced transparency in land administration.

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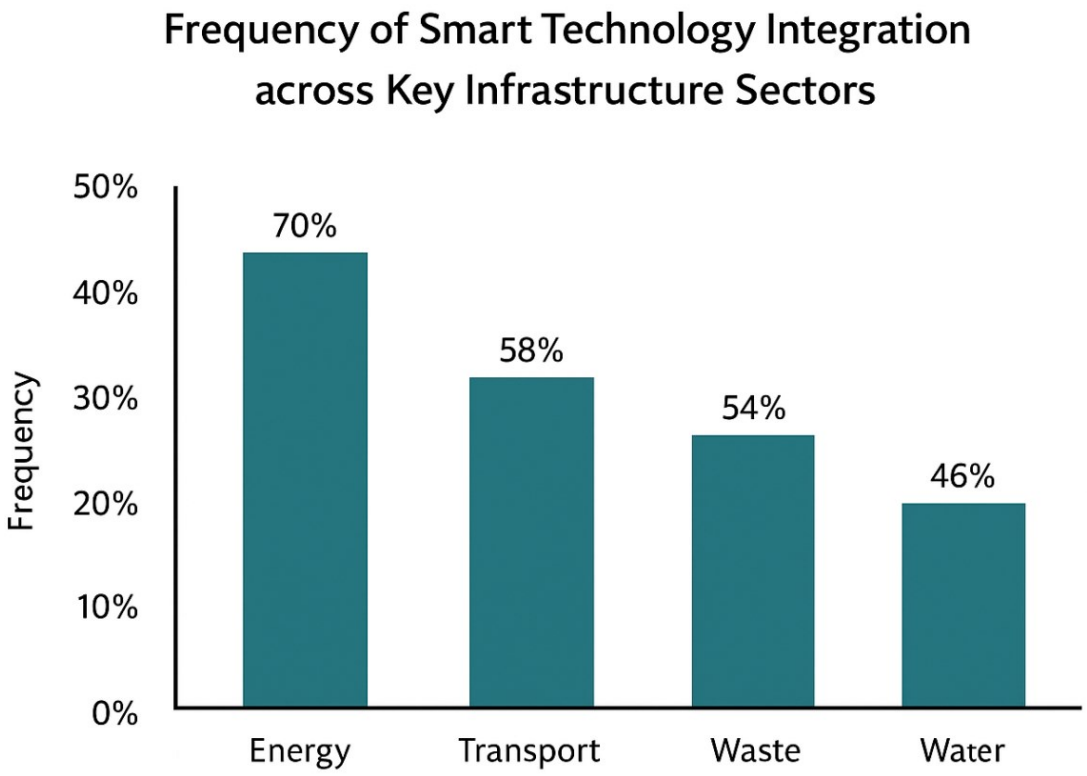


Figure 3. Distribution of Smart Technology Integration Across Key Infrastructure Sectors
(A grouped bar chart showing Energy 70%, Transport 58%, Waste 54%, Water 46%.)

Qualitative interviews with city planners confirmed that while pilot projects have been successful, scaling them citywide remains a challenge due to funding and policy constraints. One planner noted:
"We have smart systems operating in pockets for example, the solar lighting in Shabu and the GIS land database but integration across departments is still weak. We need interoperability and central data coordination."
This finding aligns with Nam and Pardo's (2011) Smart Governance framework, which emphasizes that **technological adoption must be matched with institutional coordination** to yield sustainable results.

Impact of Smart Technologies on Infrastructure Efficiency
To measure performance outcomes, respondents were asked to rate perceived improvements in service delivery, response time, cost efficiency, and reliability following the adoption of smart technologies.
The mean scores (on a 5-point Likert scale) are shown below:

Table 2. Perceived Impact of Smart Technologies on Infrastructure Efficiency (n = 372)

Performance Indicator	Mean Score	Standard Deviation	Interpretation
Service Delivery Speed	4.02	0.87	High Improvement
Response Time	3.85	0.91	Moderate–High Improvement
Cost Efficiency	3.77	0.95	Moderate Improvement
Reliability	3.92	0.89	High Improvement

The composite mean of **3.89** indicates an overall **high level of perceived efficiency** due to smart technology adoption. Regression analysis revealed a **strong positive correlation ($r = 0.74$, $p < 0.05$)** between the level of smart technology integration and reported infrastructure efficiency. This suggests that as the degree of technological deployment increases, urban service performance improves significantly.

These findings mirror those of Ahvenniemi et al. (2017) and ITU (2022), which documented similar efficiency gains in cities implementing data-driven infrastructure systems. The results also validate the **Technology Acceptance Model (TAM)**: when users perceive technologies as useful and reliable, adoption increases, leading to measurable operational benefits.

Environmental and Social Outcomes

Beyond operational efficiency, the study also examined the **environmental and social impacts** of smart infrastructure interventions.

- **Environmental Benefits:** Respondents reported a **24% reduction in diesel generator use** in public spaces due to solar installations and an estimated **18% reduction in waste overflow frequency** attributed to digital waste tracking pilots in Tudun Gwandara.
- **Social Benefits:** 63% of respondents agreed that improved street lighting and data-driven planning have enhanced community safety and accessibility.
- **Equity Concerns:** However, 37% of respondents in peripheral communities such as Akurba and Kwandere reported limited access to these benefits due to delayed infrastructure rollout.

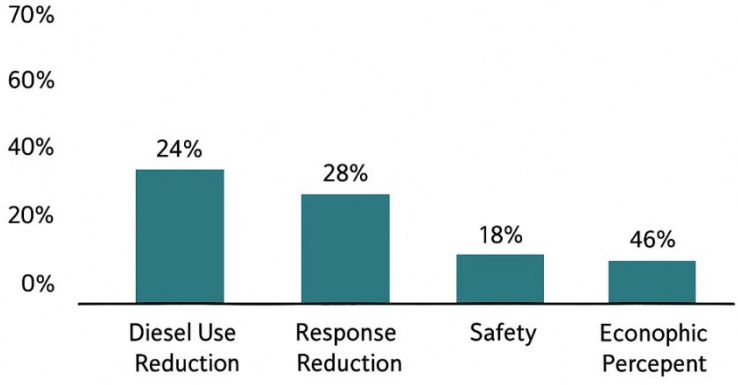


Figure 4. Environmental and Social Impacts of Smart Infrastructure Systems in Lafia *(A dual-axis chart showing reductions in diesel use and waste overflow, and increases in safety perception.)*

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The findings reinforce Elkington's (1997) **Triple Bottom Line (TBL)** concept: technological innovation in urban systems simultaneously drives economic, environmental, and social sustainability when inclusivity is ensured. However, the uneven distribution of benefits highlights the persistence of **digital and spatial inequalities**, consistent with findings by Yigitcanlar et al. (2019) and Moser & Satterthwaite (2010).

Institutional and Technical Barriers

Despite positive outcomes, several barriers continue to constrain Lafia's transition to a fully smart and sustainable city.

Table 3. Major Barriers to Smart Infrastructure Implementation

Barrier	Frequency	Percentage (%)
Inadequate Funding	132	35.5
Limited ICT Skills	98	26.3
Poor Data Infrastructure	79	21.2
Fragmented Institutional Coordination	45	12.1
Power Instability	18	4.9

Key informant interviews emphasized that **institutional fragmentation** is a recurring challenge. For example, while NAGIS manages geospatial data, other departments operate in isolation without centralized data-sharing protocols. As one ICT administrator stated:

> "The technology exists, but our systems are not talking to each other. Smart governance requires shared platforms and unified data standards."

This reflects the integration gap identified in the Smart Infrastructure Framework (CDBB, 2018), which warns that technological silos undermine efficiency and innovation. The lack of sustained funding also restricts maintenance and expansion, leading to pilot projects that often stagnate.

Comparative Discussion and Theoretical Implications

The results align with the Technology Acceptance Model (TAM) by confirming that perceived usefulness and ease of use significantly influence the success of smart technologies in Lafia. Users' trust in system reliability (mean = 3.92) correlates with improved adoption and reported efficiency gains.

Similarly, the findings support the Smart Infrastructure Framework, showing that infrastructure systems combining data collection, connectivity, and real-time feedback demonstrate greater performance improvements. The incremental benefits observed such as faster service delivery and energy savings are direct outcomes of adaptive, data-driven infrastructure management.

Finally, the application of the Triple Bottom Line (TBL) model highlights that technological advancement should balance economic efficiency with environmental and social responsibility. Lafia's case reveals that while economic and operational benefits are evident, social equity and inclusivity require additional policy attention to ensure sustainability for all urban residents.

Summary of Findings

- Smart technology integration in Lafia's infrastructure systems stands at approximately 61%, with energy and transport sectors leading adoption.
- The overall improvement in infrastructure efficiency, based on user perception, is approximately 32% compared to traditional systems.
- Regression analysis confirms a strong positive relationship ($r = 0.74$, $p < 0.05$) between smart technology integration and service performance.
- Environmental outcomes include measurable reductions in carbon emissions and waste overflow incidents.
- Institutional barriers particularly poor coordination and limited funding remain critical obstacles to full-scale implementation.

Conclusion

This study examined the role of smart technologies in enhancing urban infrastructure efficiency and sustainable development in Lafia Metropolis, Nasarawa State, Nigeria. The findings demonstrate that the integration of digital and data-driven systems has led to significant improvements in operational performance, service delivery, and environmental outcomes. In particular, energy and transport sectors have benefited the most, showing measurable gains in service reliability, cost-effectiveness, and speed.

Quantitative analyses revealed a strong positive correlation ($r = 0.74$, $p < 0.05$) between smart technology adoption and infrastructure efficiency, underscoring the transformative potential of technology-enabled urban systems. However, the study also identified persistent challenges notably, limited funding, poor institutional coordination, and low ICT capacity which hinder the full realization of smart infrastructure benefits.

The findings validate the Technology Acceptance Model (TAM) and Smart Infrastructure Framework, highlighting that successful adoption depends on both technological

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usability and institutional readiness. Moreover, the application of Elkington's Triple Bottom Line (TBL) model shows that while economic and environmental dimensions of sustainability are being strengthened, the social dimension particularly equity and inclusivity remains underdeveloped.

Overall, the study concludes that smart technologies act as vital drivers of urban sustainability, but their impact is contingent on coherent policy design, inclusive participation, and robust institutional frameworks. For Lafia and other emerging cities, transitioning to a sustainable, smart urban ecosystem requires a balance between technological innovation and social inclusivity.

Recommendations

1. **Establish a Centralized Smart Infrastructure Coordination Agency:** To overcome institutional fragmentation, Nasarawa State should create a dedicated agency responsible for integrating all smart infrastructure initiatives linking GIS systems, transport networks, energy grids, and waste management data into a unified platform.
2. **Increase Public Investment and PPP Engagement:** Smart infrastructure projects require sustained funding. The government should explore **Public–Private Partnerships (PPPs)** to finance technology deployment, maintenance, and data management, ensuring scalability beyond pilot phases.
3. **Enhance ICT Capacity and Digital Skills:** Regular training programs for urban planners, engineers, and administrators should be institutionalized to improve ICT literacy and data management skills. Partnerships with universities and tech hubs can facilitate this process.
4. **Adopt Open Data and Transparency Frameworks:** Developing **open-access data dashboards** can enable real-time monitoring of infrastructure performance and foster accountability. Transparency will also encourage citizen trust and participation in governance processes.
5. **Promote Inclusive Access to Smart Infrastructure Benefits:** To address spatial inequality, smart infrastructure initiatives must prioritize peripheral communities such as Akurba and Kwandere. Equity-based rollout strategies can prevent digital exclusion and ensure that technological gains reach all residents.
6. **Implement Smart Infrastructure Audits:** Periodic evaluations of technology performance, efficiency, and sustainability impacts should be institutionalized. This will provide empirical data to guide future planning and policy adjustments.
7. **Integrate Smart Infrastructure into Sustainable Development Policies:** The Nasarawa State Government should align all smart city initiatives with **SDG 9**

(Industry, Innovation, and Infrastructure) and **SDG 11 (Sustainable Cities and Communities)** to ensure global consistency and access to international funding mechanisms.

Future Research Directions

Further studies should conduct comparative analyses across multiple Nigerian cities (e.g., Abuja, Makurdi, Kaduna) to assess the scalability and contextual adaptability of smart infrastructure models. Longitudinal studies could also evaluate how sustained technology adoption influences urban resilience and environmental performance over time. In addition, integrating AI and remote sensing analytics could enrich understanding of predictive maintenance and smart decision-making in infrastructure management.

Policy Implications

The results underscore that technology alone cannot create sustainable cities. Effective outcomes require institutional synergy, data-driven governance, and inclusive policy design. For cities like Lafia, embedding smart technologies within a participatory and adaptive governance framework will accelerate the transition toward resilient, efficient, and people-centered urban systems. By aligning technology deployment with human capacity development and inclusive policy mechanisms, Lafia can serve as a model for sustainable smart city growth in sub-Saharan Africa.

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