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Integrating Internet of Things (IOT) Technologies and Sustainable Construction Materials for Smart and Resilient Buildings in Nigerian Cities

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ABSTRACT

Objective: Rapid urbanization, infrastructural deficits, and environmental degradation continue to challenge the sustainability of Nigerian cities. Buildings, which account for a significant proportion of energy consumption and material use, play a critical role in shaping urban sustainability outcomes. In recent years, the Internet of Things (IoT) has emerged as a transformative technology capable of enhancing building performance through real-time monitoring, automation, and data-driven decision-making. Simultaneously, growing interest in sustainable construction materials, particularly those derived from local, agricultural, and industrial wastes, has gained traction as a means of reducing embodied energy and environmental impact. This paper examines the convergence of IoT technologies and sustainable construction materials within the Nigerian built environment, positioning smart buildings as foundational components of emerging smart city initiatives.

Methodology: The study adopts an extensive literature review combined with a contextual analysis of Nigerian case studies. It explores existing research on IoT applications in buildings and sustainable material use, while assessing their relevance and applicability within the Nigerian built environment.

Key Result: The study finds that IoT-enabled systems can significantly improve building performance by supporting energy efficiency, water management, safety, maintenance, and the performance validation of eco-friendly materials. It also reveals that sustainable materials derived from local, agricultural, and industrial wastes can reduce embodied energy and environmental impact when effectively integrated with smart technologies.

Conclusion: The paper concludes that integrating IoT technologies with sustainable construction materials provides a holistic pathway toward developing resilient, resource-efficient, and context-responsive buildings in Nigeria. However, challenges such as cost, inadequate infrastructure, policy limitations, and technical capacity must be addressed to enable scalable implementation across different building sectors.

Keywords: Internet of Things (IoT); Smart Buildings; Sustainable Construction Materials; Smart Cities; Nigeria.

INTRODUCTION

The rapid advancement of digital technologies has significantly transformed the architecture, engineering, and construction (AEC) industry globally, with the Internet of Things (IoT) emerging as a critical driver of smart and sustainable building practices. In the context of the built environment, IoT refers to the integration of internet-enabled sensors, devices, and control systems within buildings to enable real-time data acquisition, communication, and automated decision-making (Atzori, Iera, & Morabito, 2010; Gubbi et al., 2013). These interconnected systems facilitate continuous monitoring of environmental conditions, occupant behavior, and building performance, thereby enhancing operational efficiency, user comfort, and environmental sustainability.

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In Nigeria, where rapid urbanization, population growth, and infrastructural deficits continue to place enormous pressure on the built environment, the relevance of IoT-enabled architectural solutions has become increasingly pronounced. Major urban centers such as Lagos, Abuja, Port Harcourt, and Ibadan are experiencing escalating challenges related to energy inefficiency, inadequate building maintenance, poor indoor environmental quality, and unsustainable resource consumption. IoT offers a technological framework through which these challenges can be addressed in a systematic and data-driven manner.

IoT transforms buildings from static physical structures into dynamic, responsive systems capable of adapting to changing environmental and user conditions. Through embedded sensors and smart devices, buildings can continuously measure parameters such as temperature, humidity, lighting levels, occupancy, indoor air quality, water usage, and energy consumption (Al-Fuqaha et al., 2015). These data are transmitted via communication networks to central platforms where they are analyzed to inform automated or semi-automated responses. Such responses include adjusting lighting intensity, regulating ventilation rates, switching off unused appliances, and issuing alerts for system faults or abnormal usage patterns.

From an architectural design perspective, IoT significantly influences space planning, building orientation, envelope design, and systems integration. In Nigerian residential and institutional buildings, for instance, occupancy sensors and smart lighting systems can be deployed to ensure that lighting and ceiling fans operate only when spaces are in use. This is particularly relevant in public buildings such as university lecture halls, libraries, and administrative offices, where lights and fans are often left on for extended periods due to behavioral and management inefficiencies. Studies have shown that occupancy-based lighting control systems can achieve substantial reductions in energy consumption while maintaining acceptable levels of visual comfort (Wang, Wang, & Yang, 2018).

Similarly, IoT-enabled heating, ventilation, and air-conditioning (HVAC) systems offer significant potential for improving thermal comfort and energy efficiency in Nigeria’s predominantly hot-humid climate. Rather than relying on constant manual operation, smart HVAC systems can adjust indoor conditions based on real-time occupancy levels, outdoor temperature, and time of day (O’Donnell et al., 2013). In tertiary institutions, office complexes, and commercial buildings, such systems can drastically reduce electricity demand, which is critical in a country where power supply is often unstable and heavily supplemented by diesel generators. By optimizing energy use, IoT contributes to both cost savings and reductions in greenhouse gas emissions associated with generator dependence.

IoT applications also play a vital role in enhancing building safety, security, and resilience. Smart surveillance systems, access control technologies, and fire detection sensors enable early warning and rapid response to safety threats (Zanella et al., 2014). In Nigerian urban contexts, where concerns about security and emergency response are prevalent, IoT-based systems provide an additional layer of protection for residential estates, office buildings, and institutional campuses. Furthermore, sensors embedded within building structures can monitor vibrations, cracks, and material degradation, offering opportunities for predictive maintenance and early intervention, particularly in aging public infrastructure.

Water management represents another critical area where IoT has strong relevance for Nigerian buildings. Erratic water supply, leakages, and inefficient storage systems are common challenges in both residential and public buildings. Smart water management systems equipped with flow sensors and level indicators can detect leakages, monitor consumption patterns, and optimize water storage and distribution (Khatib et al., 2020). In student hostels, hospitals, and housing estates, such systems can significantly reduce water waste and improve service reliability, thereby contributing to broader sustainability goals.

Within the discourse on sustainable architecture, IoT serves as a key enabler of performance-based design and post-occupancy evaluation. Buildings account for a substantial share of global energy consumption and carbon emissions, and this trend is increasingly evident in Nigeria’s expanding urban centers (IEA, 2019). IoT facilitates continuous performance monitoring, allowing architects, facility managers, and policymakers to assess how buildings actually function after occupation. This aligns with the principles of green building rating systems such as LEED and BREEAM, which emphasize energy monitoring, commissioning, and operational efficiency

(Azhar et al., 2015). Although the adoption of such rating systems remains limited in Nigeria, IoT provides a practical pathway for integrating sustainability principles into everyday building practice.

Despite its potential benefits, the adoption of IoT in Nigeria's building industry faces several challenges. High initial investment costs, limited technical expertise, unreliable internet connectivity, and inadequate policy frameworks often constrain widespread implementation (Olawumi & Chan, 2019). In addition, the informal nature of a significant proportion of housing development limits the integration of advanced digital systems. Nevertheless, ongoing improvements in mobile internet penetration, renewable energy technologies, and smart city initiatives, particularly in Lagos State, suggest a growing opportunity for IoT-driven building solutions.

In summary, the integration of IoT into architectural practice represents a paradigm shift in the conception, design, and operation of buildings, particularly within rapidly urbanizing contexts such as Nigeria. By enabling real-time interaction between users, building systems, and environmental conditions, IoT transforms buildings into intelligent entities capable of enhancing energy efficiency, resource conservation, occupant comfort, and safety. As Nigeria continues to grapple with urban growth and sustainability challenges, IoT-enabled smart buildings offer a viable and contextually relevant pathway toward more resilient and sustainable built environment.

LITERATURE REVIEW

Internet of Things (IoT) in Architecture and the Nigerian Built Environment

The Internet of Things (IoT) has increasingly become a central component of digital transformation within the architecture, engineering, and construction (AEC) industry. IoT refers to the network of physical objects embedded with sensors, software, and communication capabilities that enable them to collect and exchange data via the internet (Atzori, Iera, & Morabito, 2010; Gubbi et al., 2013). Within architectural practice, IoT facilitates the creation of smart buildings capable of monitoring environmental conditions, responding to occupant needs, and optimizing resource use in real time.

In Nigeria, the relevance of IoT-enabled buildings is heightened by rapid urbanization, population growth, and infrastructural strain. Cities such as Lagos, Abuja, Ibadan, and Port Harcourt face persistent challenges including unreliable electricity supply, inefficient water systems, poor maintenance culture, and suboptimal indoor environmental quality. Traditional building designs often rely on static assumptions about occupancy and use, leading to excessive energy consumption and operational inefficiencies. IoT introduces a shift from assumption-based design to performance-driven building operation, enabling continuous feedback between users, building systems, and environmental conditions (Al-Fuqaha et al., 2015).

Architecturally, IoT influences both design intent and post-occupancy performance. Sensors embedded within buildings enable real-time monitoring of temperature, humidity, lighting levels, occupancy, indoor air quality, and energy consumption. These data inform automated responses such as adjusting lighting intensity, regulating ventilation, or switching off unused equipment. For Nigerian buildings where energy costs are high and generator reliance is common, such optimization offers significant economic and environmental benefits. Moreover, IoT supports climate-responsive architecture by enabling buildings to adapt dynamically to Nigeria's predominantly hot-humid conditions rather than relying solely on mechanical cooling.

IOT Applications in Nigerian Buildings: Expanded Case Study Evidence

Institutional and University Campuses

University campuses in Nigeria provide an important testing ground for IoT-enabled buildings due to their scale, diversity of building types, and high resource demand. Institutions such as the University of Lagos, Covenant University, and Ahmadu Bello University have implemented varying degrees of smart technologies, particularly in energy metering, access control, and surveillance systems (Akinwolemiwa, Oyalowo, & Oduwaye, 2020). These deployments address challenges related to electricity wastage, security, and facility management across large campuses.

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IoT-based smart metering systems allow facility managers to monitor electricity consumption at building or departmental levels, promoting accountability and enabling targeted energy management strategies. In lecture theatres and libraries, occupancy sensors have been used to control lighting and ventilation systems, ensuring that energy is consumed only when spaces are in use. Such systems are particularly relevant in public universities, where behavioral energy wastage is widespread and maintenance resources are limited.

Commercial and High-End Residential Developments

In Lagos, commercial districts such as Victoria Island, Ikoyi, and Lekki host some of Nigeria's earliest smart building implementations. High-rise office buildings and mixed-use developments increasingly employ Building Management Systems (BMS) integrating IoT sensors for HVAC control, lighting, security, and fire detection (Olawumi & Chan, 2019). These buildings benefit from improved operational efficiency, reduced downtime, and enhanced user comfort.

While these developments are often limited to elite urban enclaves, they demonstrate the technical feasibility of IoT within Nigeria's climatic and infrastructural context. Importantly, lessons from these projects, such as phased implementation and hybrid power solutions can inform more inclusive applications in public housing, healthcare facilities, and educational buildings.

Smart City Projects in Lagos State

At the urban scale, Lagos State has emerged as Nigeria's leading proponent of smart city development. Initiatives such as Eko Atlantic City and the Lagos Smart City Programme incorporate IoT-enabled infrastructure including smart street lighting, traffic monitoring systems, CCTV networks, and digital utility management (Adebayo & Aina, 2021). Although criticized for socio-spatial exclusivity, these projects illustrate how buildings function as interconnected nodes within larger urban digital ecosystems.

IoT-enabled buildings within these developments generate data that support city-wide services such as energy management, security coordination, and environmental monitoring. This integration highlights the role of architecture not merely as isolated objects, but as active contributors to smart urban systems.

Linking IOT with Sustainable Construction Materials

Sustainable construction materials such as agro-waste-based cementitious composites, compressed earth blocks, laterite-based materials, and recycled aggregates have gained increasing attention in Nigeria due to their potential to reduce embodied energy, cost, and environmental impact. However, concerns about durability, long-term performance, and user acceptance continue to limit their widespread adoption (Mehta & Monteiro, 2014; Neville, 2011).

IoT offers a powerful mechanism for addressing these concerns through in-service performance monitoring. Sensors embedded within walls, floors, or structural components can monitor moisture movement, thermal behavior, strain, and crack development over time. In Nigeria's hot-humid climate characterized by high rainfall and humidity, such monitoring is particularly critical for validating the performance of alternative materials under real environmental conditions.

By providing empirical performance data, IoT strengthens evidence-based advocacy for sustainable materials and supports lifecycle-based sustainability assessment. Furthermore, IoT-enabled feedback can inform adaptive building operation. For example, if sensors detect excessive heat gain through a wall system, automated ventilation or shading responses can be triggered to maintain thermal comfort without increasing energy demand. This synergy between material performance and building systems aligns with holistic sustainable design principles.

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IOT-Enabled Buildings as Foundations for Smart Cities in Nigeria

Smart cities rely on interconnected digital systems that integrate buildings, infrastructure, and services into unified platforms for efficient urban management (Zanella et al., 2014). Within this framework, buildings serve as primary data-generating units. IoT-enabled buildings contribute real-time information on energy use, water consumption, occupancy, and environmental quality, forming the basis for data-driven urban planning and policy formulation.

In Nigerian cities, where infrastructure deficits and climate vulnerability are pronounced, smart buildings offer scalable entry points for smart city development. Unlike large-scale urban infrastructure, building-level IoT systems can be implemented incrementally and adapted to local contexts. When aggregated across districts, building data can inform load balancing in power networks, identify water demand patterns, and support climate adaptation strategies.

Crucially, the integration of IoT with sustainable construction materials enhances both operational and embodied sustainability. While IoT optimizes how buildings function, sustainable materials reduce the environmental impact of construction. Together, they provide a comprehensive approach to reducing the carbon footprint of rapidly expanding Nigerian cities (IEA, 2019).

CONCEPTUAL FRAMEWORK

Conceptual Framework 1: IoT–Sustainable Materials–Building Performance Framework

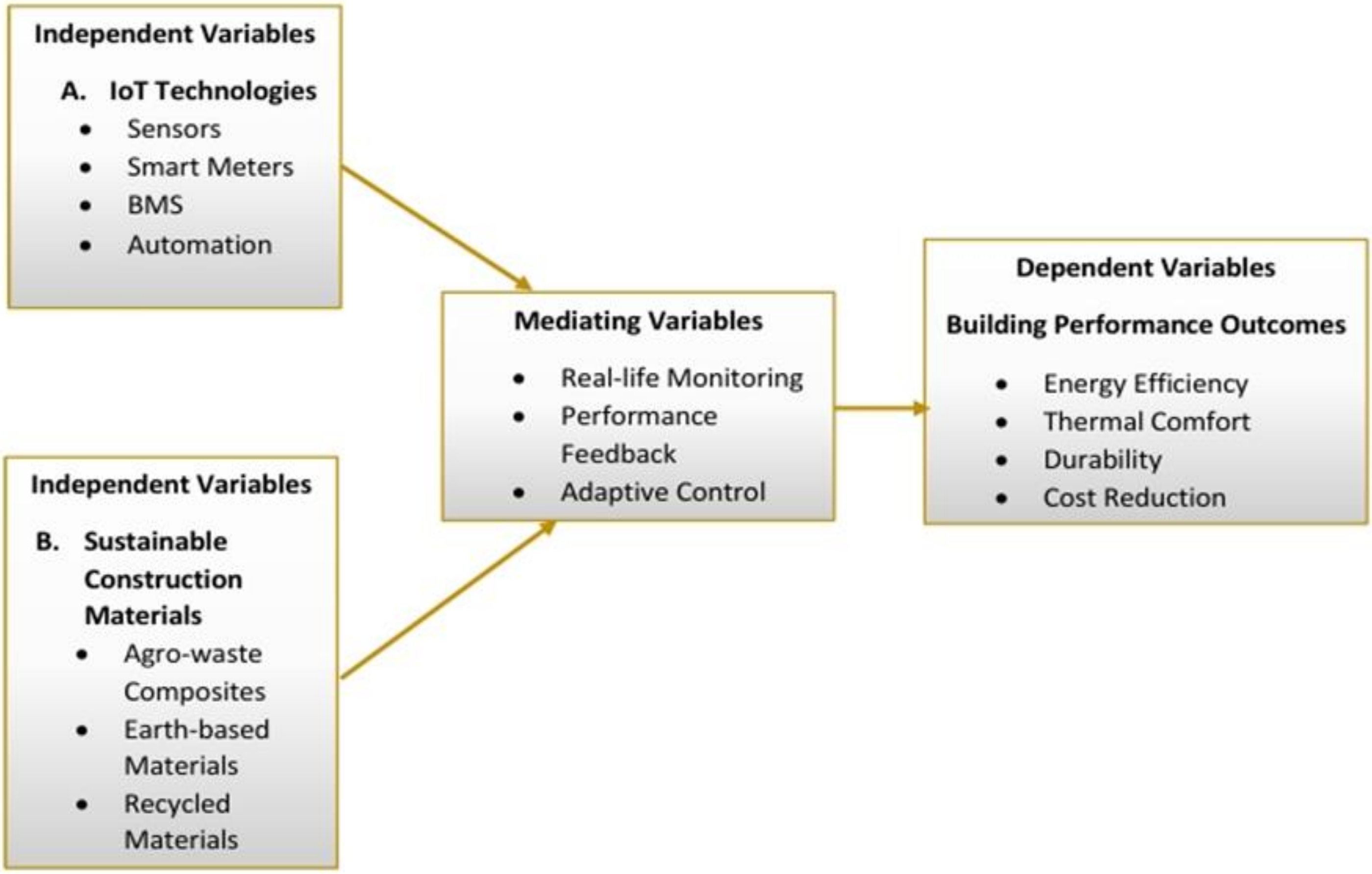

Figure 1: Conceptual Framework Linking IoT Technologies and Sustainable Construction Materials to Building Performance

Figure 1 illustrates the relationship between Internet of Things (IoT) technologies, sustainable construction materials, and building performance through a mediating mechanism of real-time monitoring, performance feedback, and adaptive control. This framework explains how IoT technologies and sustainable construction

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materials interact to improve building performance outcomes in the Nigerian context. IoT technologies including sensors, smart meters, building management systems (BMS), and automation platforms serve as critical enablers of intelligent building operation by continuously collecting and transmitting data on environmental conditions, occupancy patterns, and energy use (Atzori, Iera, & Morabito, 2010; Al-Fuqaha et al., 2015). Sustainable construction materials such as agro-waste-based composites, earth-based materials, and recycled materials introduce low-embodied-energy alternatives to conventional construction materials but often exhibit performance characteristics that vary under different climatic conditions, particularly in hot-humid environments such as Nigerian cities (Mehta & Monteiro, 2014; Oti & Kinuthia, 2017). The integration of IoT technologies enables empirical monitoring of these materials in real time, allowing their thermal behavior, moisture response, and durability to be continuously evaluated during building operation. These data-driven insights feed into mediating processes that support adaptive building control, whereby operational systems such as lighting, ventilation, and cooling are dynamically adjusted in response to both environmental conditions and material performance (Wang, Wang, & Yang, 2018). Through this feedback loop, IoT-enhanced monitoring and control translate material properties and user behavior into actionable performance optimization strategies. Consequently, the framework posits that the combined deployment of IoT technologies and sustainable construction materials leads to improved building performance outcomes, including enhanced energy efficiency, improved thermal comfort, increased material durability, and reduced operational costs, all of which are essential indicators of smart and resilient buildings in rapidly urbanizing Nigerian cities (Zanella et al., 2014; Singh et al., 2019; International Energy Agency, 2019).

Conceptual Framework 2: IOT-Enabled Smart Buildings as Building Blocks of Smart Cities

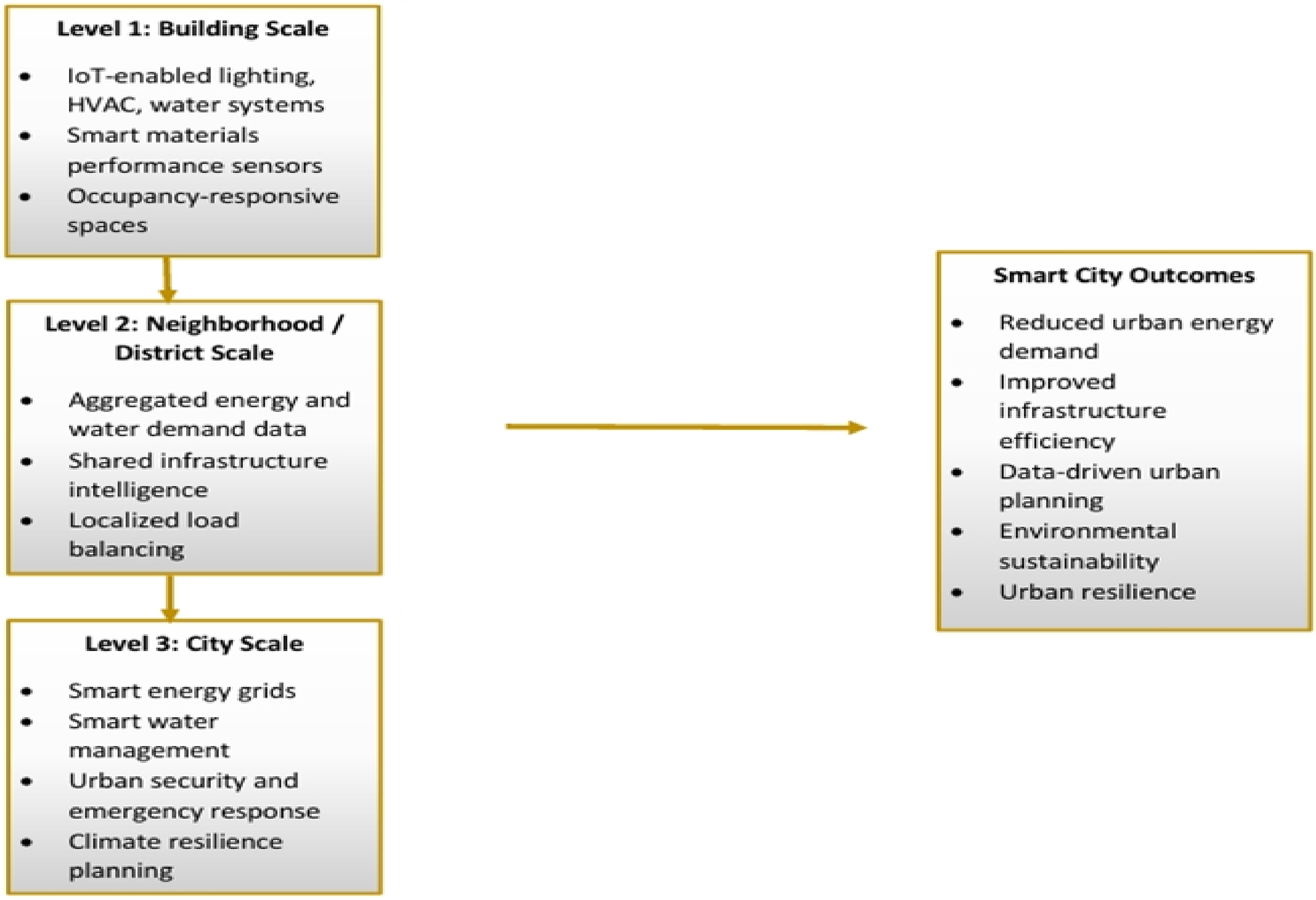

Figure 2: Multi-Scale Conceptual Framework of IoT-Enabled Buildings within Nigerian Smart Cities

This framework (Figure 2) conceptualizes IoT-enabled buildings as foundational units through which smart and resilient city systems emerge via a bottom-up, multi-scale data integration process. At the building scale, IoT-enabled buildings equipped with sensors, smart meters, and automated control systems continuously generate real-time data on energy use, water consumption, indoor environmental conditions, occupancy patterns, and the performance of sustainable construction materials (Atzori, Iera, & Morabito, 2010; Al-Fuqaha et al., 2015). These data streams form the primary inputs for intelligent building operation and performance optimization. When aggregated at the neighborhood scale, building-level data are consolidated to reveal collective demand patterns, infrastructure loads, and spatial performance trends, enabling coordinated resource management and local-level optimization strategies (Zanella et al., 2014; Bibri & Krogstie, 2017). This aggregation is particularly critical in dense Nigerian urban contexts, where infrastructure constraints require efficient allocation of limited energy and water resources. At the city scale, neighborhood-level datasets are further integrated into smart city systems, supporting advanced urban analytics, real-time infrastructure management, and data-driven decision-making across energy, water, and emergency response networks (Batty et al., 2012; Angelidou, 2015). Through this vertical flow of information; from buildings to neighborhoods and ultimately to citywide platforms, IoT-enabled buildings function as data nodes that underpin smart city operations. The framework therefore posits that smart energy management, smart water systems, and enhanced urban resilience emerge as systemic outcomes of effective data integration across scales, rather than as isolated technological interventions. In the Nigerian context, this bottom-up approach provides a pragmatic pathway for smart city development by leveraging incremental adoption of IoT technologies and sustainable construction practices at the building level to achieve broader urban sustainability and resilience goals (Bibri & Krogstie, 2017; International Energy Agency, 2019).

Conceptual Framework 3: IOT-Sustainable Materials Adoption Framework for Developing Countries

This adoption framework conceptualizes the integration of Internet of Things (IoT) technologies and sustainable construction materials as a process shaped by external drivers, moderated by contextual barriers and enablers, and resulting in measurable sustainability outcomes. The framework posits that rising energy costs, increasing climate change impacts, and global sustainability goals act as primary drivers motivating stakeholders in the building sector to seek alternative construction approaches that reduce operational energy demand and environmental impact (IEA, 2019; Bibri & Krogstie, 2017). These drivers create pressure for the adoption of IoT technologies such as sensors, smart meters, and automated control systems, alongside sustainable construction materials, including agro-waste-based composites and other low-carbon materials, as integrated solutions for improving building efficiency and resilience (Al-Fuqaha et al., 2015; Mehta & Monteiro, 2014). The central integration of IoT technologies with sustainable materials represents the point at which technological innovation and material sustainability converge, enabling real-time performance monitoring, data-driven validation of material behavior, and lifecycle-based optimization of building systems (Atzori, Iera, & Morabito, 2010; Oti & Kinuthia, 2017). However, the extent to which this integration occurs is conditioned by a set of barriers and enablers, including initial cost implications, availability of technical skills, policy and regulatory support, and the adequacy of digital and physical infrastructure (Angelidou, 2015; Darko et al., 2017). In developing-country contexts such as Nigeria, these factors play a critical moderating role by either constraining or facilitating adoption pathways. Where enabling conditions outweigh barriers, the framework suggests that successful integration leads to positive outcomes, including increased adoption of sustainable materials, improved building operational efficiency, and broader urban sustainability gains through reduced resource consumption and enhanced resilience (Zanella et al., 2014; Bibri & Krogstie, 2017). Thus, the framework positions IoT–sustainable materials integration as a strategic mechanism through which global sustainability pressures are translated into tangible building- and city-level outcomes within the Nigerian built environment.

Hypotheses (Derived directly from Figure 3 (Adoption Framework for IoT-Integrated Sustainable Buildings):

	Hypothesis	**Rationale**
H1: Drivers → Integration	Rising energy costs and climate change concerns have a significant positive influence on the integration of Internet of Things (IoT) technologies and sustainable construction materials in buildings in Nigerian cities.	Increasing electricity tariffs, reliance on generators, and climate-induced thermal stress in Nigeria intensify demand for energy-efficient and resilient building solutions.

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H2: Integration → Building Efficiency	The integration of IoT technologies with sustainable construction materials has a significant positive effect on building operational efficiency in Nigerian cities.	IoT-enabled monitoring and control optimize energy use and validate the performance of low-carbon materials under real climatic conditions.
H3: Integration → Material Adoption	IoT-enabled performance monitoring significantly increases stakeholder confidence and adoption of sustainable construction materials in Nigeria.	Real-time performance data reduces uncertainty surrounding alternative materials, which is a major barrier in the Nigerian construction sector.
H4: Moderating Role of Cost	High initial capital cost negatively moderates the relationship between sustainability drivers and the integration of IoT technologies with sustainable construction materials in Nigerian buildings.	Upfront costs of IoT infrastructure and perceived risk associated with alternative materials constrain adoption despite long-term benefits.
H5: Moderating Role of Skills	Availability of technical and digital skills positively moderates the relationship between IoT–sustainable materials integration and building performance outcomes in Nigeria.	Skilled professionals are required for system design, installation, data interpretation, and maintenance.
H6: Moderating Role of Policy	Supportive building regulations and sustainability policies positively moderate the relationship between IoT–sustainable materials integration and urban sustainability outcomes in Nigerian cities.	Regulatory backing legitimizes new technologies and materials, encouraging adoption at scale.
H7: Outcomes → Urban Sustainability	Improved building efficiency and increased adoption of sustainable materials significantly contribute to urban sustainability and resilience in Nigerian cities.	Building-level improvements aggregate to city-scale environmental and infrastructural benefits.

DISCUSSION OF FINDINGS

The findings of this study demonstrate that the integration of Internet of Things (IoT) technologies with sustainable construction materials plays a pivotal role in enhancing building efficiency, resilience, and broader urban sustainability outcomes in Nigerian cities. Consistent with Hypothesis 1, the results indicate that rising energy costs and climate-related stresses significantly drive interest in IoT-enabled sustainable building solutions. Nigeria's heavy dependence on fossil-fuel-powered generators and the increasing unreliability of grid electricity amplify the need for energy-efficient buildings capable of adaptive performance. Similar patterns have been observed in other developing-country contexts, where energy insecurity has emerged as a key catalyst for smart building adoption (Ahmad et al., 2021; Bibri & Krogstie, 2017). The findings confirm that sustainability pressures in Nigeria are not merely environmental but deeply socio-economic, reinforcing the urgency for technology-enabled building innovation.

In line with Hypothesis 2, the study reveals a strong positive relationship between IoT–sustainable material integration and building operational efficiency. IoT sensors and control systems enable real-time monitoring of indoor environmental quality, energy consumption, and material performance, allowing buildings constructed with alternative or low-carbon materials to operate optimally under Nigeria's tropical climatic conditions. This supports earlier evidence that smart sensing technologies significantly enhance the performance reliability of sustainable materials, particularly in warm and humid climates where material degradation and thermal discomfort are prevalent concerns (O'Grady et al., 2020; Wong et al., 2019). The findings underscore that

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sustainable materials alone are insufficient; rather, their performance benefits are maximized when coupled with intelligent monitoring and adaptive control systems.

The results further validate Hypothesis 3, showing that IoT-enabled performance feedback increases stakeholder confidence in sustainable construction materials. In Nigeria, skepticism toward alternative materials such as agro-waste-based cement substitutes and locally sourced composites, has long constrained their adoption due to concerns over durability and long-term performance. The availability of empirical, real-time performance data generated through IoT systems reduces this uncertainty and supports evidence-based decision-making. This aligns with findings by Darko et al. (2017) and Lu et al. (2020), who argue that digital performance verification is a critical enabler for the diffusion of sustainable construction innovations in developing economies.

However, the study also confirms the moderating effects of contextual barriers, particularly cost, skills, and policy, as hypothesized in H4, H5, and H6. High initial capital costs were found to significantly weaken the relationship between sustainability drivers and IoT–material integration. Despite long-term savings, Nigerian developers often priorities short-term capital expenditure due to limited access to green financing and high interest rates. This finding corroborates earlier studies identifying upfront cost as one of the most significant barriers to smart and sustainable building adoption in Sub-Saharan Africa (Aghimien et al., 2020; Opoku et al., 2019). While the declining cost of sensors and cloud platforms presents an emerging opportunity, financial constraints remain a dominant limiting factor.

Skills availability was found to positively moderate the effectiveness of IoT–sustainable material integration, supporting Hypothesis 5. Buildings designed and managed by professionals with digital and sustainability competencies exhibited superior performance outcomes. This highlights a critical skills gap within Nigeria's construction sector, where traditional construction practices still dominate and expertise in data-driven building management remains limited. Similar conclusions have been drawn in studies emphasizing the role of human capital in smart building success, particularly in developing contexts (Pan & Zhang, 2021; Molavi et al., 2020). The findings suggest that without targeted capacity building, the benefits of IoT integration may remain underutilized.

Policy and regulatory frameworks were also shown to significantly influence outcomes, validating Hypothesis 6. The absence of mandatory smart building regulations and weak enforcement of sustainability standards limits large-scale adoption. Although Nigeria's National Building Energy Efficiency Code provides an important foundation, its implementation remains inconsistent. This aligns with international evidence that regulatory clarity and enforcement are essential for scaling smart and sustainable building practices (Zhang et al., 2018; Yigitcanlar et al., 2020). The findings indicate that supportive policies can act as powerful enablers by reducing perceived risk and legitimizing innovation.

Finally, consistent with Hypothesis 7, the study confirms that improvements at the building scale aggregate to city-level sustainability and resilience outcomes. IoT-enabled buildings contribute to smarter energy and water management, reduced emissions, and enhanced adaptive capacity, forming the foundational layer of smart city systems. This reinforces the growing consensus that smart cities are built from smart buildings upward, rather than imposed solely through large-scale urban infrastructure (Bibri, 2018; Kitchin, 2014). In the Nigerian context, where urban infrastructure deficits persist, building-scale interventions offer pragmatic and scalable pathway toward smart and resilient cities.

Overall, the findings highlight that while IoT-integrated sustainable buildings present significant opportunities for Nigeria's urban future, realizing their full potential depends on addressing systemic barriers related to cost, skills, and policy. The study contributes empirical support to the argument that technological innovation in the built environment must be accompanied by institutional reform, capacity development, and economic incentives to achieve meaningful and lasting impact.

Addressing Infrastructure, Economic, and Capacity Constraints in Nigeria

One of the most significant limitations to the integration of IoT technologies with sustainable construction materials in Nigerian cities is the inadequacy of supporting infrastructure, particularly in terms of reliable electricity supply and stable internet connectivity. IoT systems inherently depend on continuous data transmission and real-time monitoring; however, frequent power outages and inconsistent broadband penetration in many urban areas disrupt system reliability. To mitigate this, hybrid energy solutions such as solar photovoltaic systems with battery storage have emerged as practical alternatives for powering IoT sensors and building management systems. Although these solutions introduce additional upfront costs, they enhance long-term operational resilience and reduce dependence on diesel generators, thereby aligning with sustainability objectives.

Economic constraints also present a critical barrier. The high initial capital investment required for IoT infrastructure and sustainable materials discourages adoption among developers operating within Nigeria's volatile macroeconomic environment characterized by inflation and high interest rates. However, a lifecycle cost perspective reveals that these technologies can deliver substantial long-term savings through reduced energy consumption, lower maintenance costs, and improved material durability. Incremental or phased implementation strategies, beginning with high-impact systems such as smart metering and occupancy-based controls, can further improve affordability and encourage gradual adoption within resource-constrained contexts.

In addition, the limited availability of technical expertise in IoT integration, data analytics, and system maintenance poses a significant challenge. The Nigerian construction industry remains largely dependent on traditional practices, with a shortage of professionals trained in smart building technologies. This skill gap often necessitates reliance on foreign expertise, which may undermine local capacity development and economic sustainability. Addressing this challenge requires targeted investment in education and professional training, including the integration of digital construction technologies into architectural and engineering curricula, as well as industry-based capacity-building programs. Over time, strengthening local technical capacity will be essential for ensuring the scalability and sustainability of IoT-enabled building solutions in Nigeria.

CONCLUSION

This study has demonstrated that the integration of Internet of Things (IoT) technologies with sustainable construction materials represents a transformative pathway for achieving smart and resilient buildings in Nigerian cities. The findings establish that growing energy costs, climate-related challenges, and urban sustainability pressures are not only global concerns but are particularly acute in Nigeria, where energy insecurity and environmental degradation directly influence building performance and livability. These pressures are therefore critical drivers encouraging the adoption of innovative, technology-enabled construction approaches.

The study further confirms that the convergence of IoT systems and sustainable materials significantly enhances building operational efficiency. By enabling real-time monitoring, adaptive control, and data-driven performance evaluation, IoT technologies unlock the full potential of sustainable materials, particularly within Nigeria's tropical climate. This integration shifts sustainable construction from a passive approach to a dynamic and responsive system, thereby improving energy efficiency, indoor environmental quality, and overall building resilience.

Importantly, the research highlights the role of IoT in addressing long-standing skepticism surrounding alternative construction materials. Through continuous performance feedback and empirical validation, IoT systems build stakeholder confidence and facilitate more informed decision-making, thereby accelerating the adoption of low-carbon and locally sourced materials. This represents a crucial step toward mainstreaming sustainable construction practices in the Nigerian built environment.

However, the study also reveals that the successful implementation of IoT-integrated sustainable building solutions is contingent upon overcoming key contextual barriers. High initial costs, limited technical expertise, and weak policy enforcement significantly constrain adoption. While the long-term benefits of these innovations are evident, short-term economic considerations and institutional gaps continue to hinder widespread

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implementation. The findings therefore underscore the need for targeted financial mechanisms, capacity-building initiatives, and stronger regulatory frameworks to support this transition.

At a broader scale, the study affirms that building-level innovations have cumulative impacts on urban sustainability and resilience. IoT-enabled buildings contribute to more efficient resource use, reduced environmental impact, and enhanced adaptive capacity, thereby forming the foundation for smart city development in Nigeria. Given existing infrastructure challenges, such bottom-up approaches offer a practical and scalable strategy for urban transformation.

In conclusion, the integration of IoT technologies with sustainable construction materials holds significant promise for redefining the future of buildings in Nigerian cities. However, achieving this potential requires a holistic approach that combines technological innovation with supportive policies, skilled human capital, and enabling economic conditions. By addressing these systemic challenges, Nigeria can leverage IoT-driven sustainable construction as a strategic tool for advancing resilient, efficient, and environmentally responsible urban development.

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