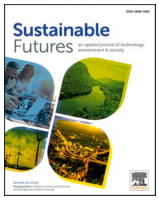
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Harnessing adaptive urban service frameworks and smart technologies for sustainable urban development in rapidly urbanising cities

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ABSTRACT

Rapid urbanisation and escalating climate change impacts pose significant challenges for sustainable urban governance in developing nations, particularly where infrastructural inadequacies and resource inefficiencies persist. This study examines how urban systems in rapidly growing cities in Nigeria can utilise smart technologies to enhance resilience, inclusivity, and environmental sustainability. The study's aim is to develop and evaluate an Adaptive Urban Service Framework (AUSF) that integrates digital innovations to foster low-carbon, climate-resilient, and inclusive cities. Objectives of the study include (i) identifying adaptive urban service models that improve resource efficiency, environmental sustainability, and quality of life, and (ii) assessing the extent to which these services strengthen urban resilience and social inclusivity under demographic and infrastructural pressures. A structured survey involving 286 respondents from selected Nigerian cities was conducted, and the data were analysed using SPSS Version 22. The correlation results reveal a positive relationship between adaptive urban service mechanisms and sustainability outcomes ($r = 0.987$, $p < 0.001$), indicating that improvements in smart technologies, resource efficiency, environmental sustainability, and quality of life strongly reinforce sustainable urban performance. Similarly, experts' evaluations demonstrate a positive correlation between Adaptive Urban Services (AUS) and the enhancement of resilience and inclusivity within smart urban environments ($r = 0.865$, $p < 0.001$). These findings collectively underscore that adaptive, smart-driven frameworks exert substantial synergistic effects on environmental sustainability, social inclusivity, and urban resilience, confirming that the effective integration of smart technologies serves as a strong determinant of sustainability outcomes in rapidly urbanising Nigerian cities. The paper offers a methodology that integrates digital innovation with climate-responsive planning, which theoretically advances urban systems theory. In practical terms, it provides policymakers and urban planners with a scalable road map for implementing adaptive service solutions that connect sustainability, equity, and technology. Overall, within similar emerging urban environments, the study highlights the transformative potential of adaptive urban services in furthering climate adaptation, fostering inclusion, and attaining sustainable urban development.

1. Introduction

Urbanisation is accelerating at an unprecedented rate, reshaping cities worldwide and placing increasing pressure on infrastructure systems, environmental resources, and governance structures. Globally, cities are confronted with the dual challenge of accommodating rapid population growth while mitigating the adverse impacts of climate change, environmental degradation, and socioeconomic inequality [1,2]. These challenges are particularly acute in developing countries, where urban expansion often outpaces institutional capacity, infrastructure provision, and service delivery. In this context, achieving sustainable urban development requires innovative, adaptive, and technology-enabled approaches capable of addressing complex and interrelated urban challenges.

Nigeria exemplifies these dynamics. As Africa's most populous country and one of the fastest urbanising nations globally, Nigeria faces mounting pressures on housing, transportation, energy supply, waste management, and public services [1,3]. Metropolitan areas such as Lagos, Abuja, and Port Harcourt are experiencing rapid demographic expansion, informal urban growth, and increased exposure to

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climate-related risks, including flooding, heat stress, and environmental pollution. These conditions underscore the urgent need for urban systems that are not only efficient but also resilient, inclusive, and responsive to dynamic socio-environmental conditions. In response to these global and local pressures, smart city paradigms have emerged as a strategic framework for enhancing urban performance through the integration of digital technologies, data-driven decision-making, and intelligent infrastructure [4,5]. Smart city initiatives aim to optimise resource use, improve service delivery, and enhance quality of life by leveraging tools such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and sensor networks. These technologies enable real-time monitoring, predictive modelling, and adaptive control of urban systems, supporting more efficient and sustainable management of cities [5,6].

Within this technological landscape, increasing attention has been directed toward Adaptive Urban Services (AUS) as a mechanism for translating smart technologies into practical urban outcomes. Adaptive urban services refer to urban systems designed to dynamically adjust to changing environmental, social, and economic conditions through flexible, data-driven strategies. In this study, AUS are operationalised as urban functions such as transportation, energy, waste management, housing, and healthcare that integrate digital tools to enhance responsiveness, continuity, and resilience under conditions of stress and uncertainty [6,7]. Unlike static infrastructure models, adaptive services prioritise flexibility, learning, and real-time feedback, allowing cities to respond more effectively to disruptions and long-term challenges.

The significance of Adaptive Urban Services (AUS) is increasingly underscored by global demographic projections. The world's population is expected to rise from 6.9 billion in 2010 to approximately 9.5 billion by 2050, with nearly 90 % of this growth concentrated in urban areas across Africa and Asia [4]. Sub-Saharan Africa is projected to experience some of the fastest urban growth rates globally, placing severe pressure on infrastructure systems that are already overstretched. In Nigeria, rapid urbanisation has intensified waste generation, greenhouse gas emissions, land-use conflicts, and biodiversity loss, revealing the limitations of conventional, rigid urban service models [1,4]. These dynamics highlight the need for adaptive, technology-enabled service frameworks capable of responding to evolving urban complexities.

Urban sustainability has consequently become central to global development agendas, most notably articulated through the United Nations Sustainable Development Goals (SDGs). SDG 11 emphasises inclusive, safe, resilient, and sustainable cities, integrating climate adaptation, low-carbon development, and social equity into urban governance. For Nigeria, highly exposed to climate hazards such as flooding, droughts, and heatwaves, urban resilience (RES) is a critical prerequisite for sustainable development [1]. In this study, urban resilience is defined as the capacity of urban systems to absorb shocks, adapt to change, and recover from environmental and socio-economic stresses while maintaining essential functions [5].

However, resilience alone is insufficient in contexts marked by deep socio-economic inequalities. Nigerian cities exhibit uneven access to housing, transport, energy, digital infrastructure, and public services, necessitating an explicit focus on inclusive development (INC). Inclusivity is conceptualised here as equitable access to and participation in adaptive urban services enabled by smart technologies, ensuring that no social group is marginalised due to income, age, gender, disability, or digital literacy barriers [6,8]. Without deliberate inclusion strategies, smart city interventions risk exacerbating existing inequalities. Although Nigeria has initiated smart city projects in cities such as Lagos, Abuja, and Port Harcourt, implementation remains fragmented due to infrastructural deficits, high costs, limited institutional capacity, and governance challenges [9,10]. While technologies such as IoT, AI, and data analytics offer significant potential to enhance energy efficiency, mobility, and resource management [8], their adoption has lagged behind urban growth, limiting their transformative impact.

A critical limitation of existing research is its geographic and contextual bias. Much of the smart city literature focuses on developed regions such as Europe and North America, where institutional capacity, infrastructure quality, and technological readiness differ significantly from those in sub-Saharan Africa. As a result, there is a paucity of empirical studies examining how adaptive urban services function in rapidly urbanising African cities, particularly in relation to resilience and inclusivity outcomes [9]. Few studies systematically address the unique challenges faced by African cities, including informal urbanisation, infrastructure deficits, governance constraints, and socioeconomic inequality. This gap underscores the need for context-specific research that examines how adaptive urban services, supported by smart technologies, can promote sustainable, resilient, and inclusive urban development in Nigeria. Rather than treating smart technologies as isolated technical solutions, there is a need to conceptualise them as components of integrated urban service frameworks that align technological innovation with governance structures, social needs, and environmental objectives.

Against this backdrop, the present study proposes Adaptive Urban Service Frameworks (AUSF) that integrate smart technologies to address Nigeria's urban sustainability challenges. The study adopts a holistic perspective, examining how AUS can enhance resource efficiency, environmental sustainability, and quality of life while simultaneously fostering resilience and inclusivity. Specifically, the objectives of the study are to:

(i) identify adaptive urban service models that integrate smart technologies to improve resource efficiency, environmental sustainability, and quality of life in rapidly urbanising Nigerian cities; and
(ii) evaluate the role of adaptive urban services in fostering resilience (RES) and inclusivity (INC) in the face of population growth, infrastructure demands (INFD), and climate change impacts.

To address these objectives, the study is guided by the following research questions:

(i) How can adaptive urban service models that integrate smart technologies contribute to improved resource efficiency, environmental sustainability, and quality of life in rapidly urbanising cities?
(ii) What role do adaptive urban services play in achieving resilience and inclusivity amid population growth, infrastructure demands, and climate change impacts in smart city contexts?

This study makes several key contributions to the literature. First, it provides empirical evidence from Nigeria, addressing a significant geographic gap in smart city research. Second, it advances a conceptual integration of smart technologies with adaptive urban services, resilience, and inclusivity, moving beyond technology-centric narratives. Third, through comprehensive survey analysis and the application of advanced statistical techniques, the study evaluates the relationships between adaptive services and key sustainability outcomes, offering evidence-based insights for policy and practice [1,5,7,11]. Ultimately, the study argues that Nigeria's urban challenges can be more effectively addressed through the deliberate integration of smart technologies within adaptive service frameworks that prioritise equity and resilience. Achieving this vision requires coordinated urban governance, inclusive policy design, and sustained investment in digital and physical infrastructure. For Nigeria and other developing countries facing similar urban pressures, adaptive and inclusive smart city strategies offer a viable pathway toward low-carbon, climate-resilient, and socially equitable urban futures.

The remainder of this paper is structured as follows. The next section reviews relevant literature on smart cities, adaptive urban services, resilience, and inclusivity. The methodology section outlines the research design, data collection, and analytical techniques employed. The results and discussion section presents empirical findings and

interprets their implications for urban sustainability in Nigeria. The final section concludes with policy recommendations and directions for future research.

2. Conceptual framework and literature

A testable conceptual model that explains how urbanisation challenges can be systematically addressed through adaptive, technology-enabled urban services to achieve sustainable urban planning and development is presented in Fig. 1. Rapid population growth, infrastructure deficits, and climate-related stressors constitute the primary pressures shaping contemporary cities, particularly in the Global South. Within the model, Adaptive Urban Services supported by digital technologies operate as the central mediating mechanism linking these challenges to sustainability outcomes. Two key causal pathways are specified: adaptive services enhance Urban Resilience (RES) by strengthening cities' capacity to absorb shocks and adapt to change, and they promote Digital Inclusivity (INC) by enabling equitable access to urban services. Together, RES and INC generate positive effects on sustainable urban development, including improved resource efficiency, enhanced environmental performance, better quality of life, and progress toward low-carbon growth aligned with the Sustainable Development Goals (SDGs). Feedback loops within the model indicate that sustainability gains can further reduce infrastructure stress and reinforce long-term adaptive capacity. This framework also highlights the critical roles of adaptive governance, digital innovation, and sustainability-oriented planning in advancing inclusive and resilient urban systems. By integrating theoretical insights with empirical evidence, it enables a structured comparison of approaches to adaptive smart services, with particular attention to Nigeria and other Global South contexts. The model demonstrates how technological innovation, institutional capacity, and socio-spatial inclusion can be coherently embedded within urban service systems to address context-specific constraints. Collectively, these elements provide a unified analytical foundation for the Adaptive Urban Service Framework (AUSF), bridging urban theory, policy discourse, and applied practice across multiple spatial and governance scales.

2.1. Urbanisation challenges and the need for an adaptive urban service framework (AUSF)

Urbanisation across Africa has accelerated markedly over the past two decades and is projected to continue rising, with the continent's urban population expected to reach approximately 722 million by 2026 [12,13]. This rapid growth is largely driven by rural-to-urban migration in search of economic opportunities, improved infrastructure, and access to social services. However, the pace of urban expansion has outstripped planning and service provision capacities in many African cities, intensifying challenges related to housing shortages, inefficient transportation systems, resource depletion, and environmental degradation. The sustained increase in urban populations since 2000, illustrated in Supplementary Information Figs. 1 and 2, underscores the urgency of adopting innovative and adaptive urban management approaches [12,13].

Regional disparities in urbanisation patterns further complicate urban governance across Africa. According to the United Nations World Urbanisation Prospects [14], North and Central Africa have surpassed the 50 % urbanisation threshold, while West Africa, particularly Nigeria, has recorded the highest absolute number of urban residents on the continent [14,15]. Lagos, one of Africa's fastest-growing megacities, exemplifies the pressures associated with rapid urban expansion. Nigeria's urban population is growing at an annual rate of approximately 4.3 %, and projections suggest that the country's urban population will double by 2037 [15]. Similar trends are evident in Central Africa, where cities such as those in the Democratic Republic of Congo are expected to accommodate more than 120 million urban residents by 2050 [16]. These variations reflect differences in economic structures, governance capacity, and infrastructure provision, reinforcing the need for context-specific urban strategies.

In Nigeria, accelerated urban growth has contributed to the proliferation of informal settlements characterised by limited access to electricity, clean water, sanitation, and reliable transportation. Overcrowding, traffic congestion, and environmental pollution have further reduced urban liveability and increased vulnerability to climate-related risks [2,17]. These challenges highlight the limitations of conventional, static urban service models and point to the necessity for adaptive and integrated frameworks capable of responding to dynamic urban conditions. Smart urban planning offers a pathway for addressing these challenges by promoting compact, mixed-use development, energy-efficient housing, and sustainable infrastructure systems. The adoption of renewable energy technologies, electric mobility, and green infrastructure such as urban parks and vertical greenery has been shown

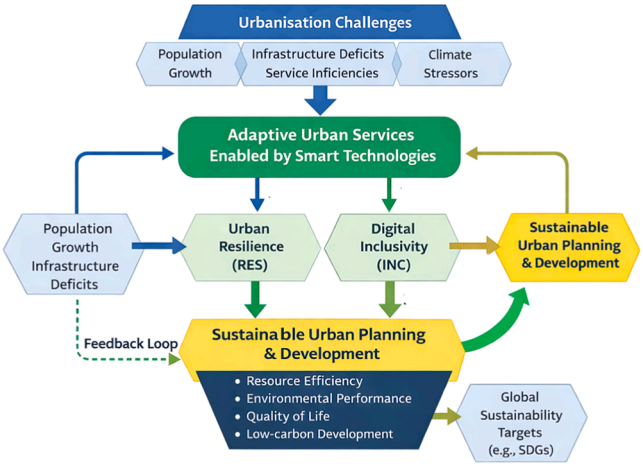


Fig. 1. Conceptual model linking urbanisation challenges, adaptive services, inclusivity, resilience, and sustainable development. Source: Authors' conceptualization.

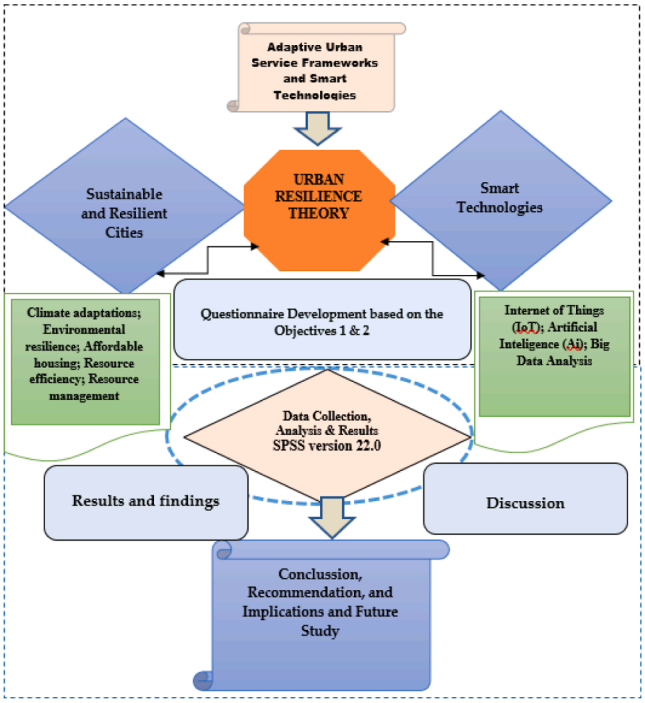


Fig. 2. The study's conceptual framework. Source: authors' conceptualisation.

to mitigate environmental impacts while enhancing public health and urban liveability [19]. Within this context, Adaptive Urban Services (AUS) play a critical role by enabling flexibility, real-time responsiveness, and user-centred service delivery. Citizen-oriented design is central to AUS, ensuring that services are inclusive, personalised, and accessible to diverse user groups. For instance, smart mobility platforms utilise real-time data to optimise public transport routes and schedules, improving efficiency while enhancing accessibility for persons with disabilities and other vulnerable populations [2,20].

The Adaptive Urban Service Framework (AUSF) integrates these principles across multiple strategic domains, as summarised in Supplementary Information Table 1. By aligning technological tools with operational strategies and targeted beneficiaries, the AUSF seeks to enhance urban resilience, sustainability, and inclusivity. Urban transportation planning emerges as a particularly critical domain within this framework, especially in rapidly urbanising contexts such as Nigeria, where congestion, emissions, and infrastructure deficits remain persistent challenges [21]. Embedding transportation systems within an adaptive framework underscores the importance of developing mobility solutions that are efficient, climate-responsive, and socially inclusive.

Low-carbon transport networks are central to achieving sustainable urban mobility, particularly in rapidly urbanising contexts where car-dependent systems exacerbate congestion, emissions, and spatial inequality [2,22]. In Nigerian cities such as Lagos and Abuja, ineffective transport planning has contributed to infrastructure deficits and service inefficiencies. Recent studies demonstrate that the integration of smart mobility technologies, including electric vehicles, intelligent traffic management systems, and real-time data analytics, can substantially reduce carbon emissions, optimise traffic flow, and enhance overall mobility performance [21,23–25]. Industry 4.0-enabled linear infrastructure supports smart city development by facilitating predictive maintenance, adaptive network management, and data-driven transport decision-making [24]. Beyond technological deployment, sustainable transport transitions require alignment with energy and governance frameworks. It was emphasised that green mobility strategies must be integrated with renewable energy expansion and national decarbonisation targets to maximise environmental benefits [25]. Similarly, [24] argues that effective smart transportation planning depends on coherent policy frameworks that address institutional capacity, system interoperability, and social equity. Transport systems must therefore be adaptive and inclusive, responding to diverse user needs rather than prioritising efficiency alone. These perspectives align with the African Urban Sustainability Framework (AUSF), which conceptualises transportation as both a functional service and a socio-environmental catalyst for inclusivity, resilience, and sustainable urban growth [2,26–27].

Energy efficiency further underpins adaptive urban systems, as cities remain major energy consumers. The deployment of smart grids and renewable energy technologies enables real-time monitoring and decentralised control, strengthening energy resilience and reducing environmental impacts [28]. In parallel, adaptive urban services increasingly support emergency management through context-aware monitoring, early warning systems, and rapid response mechanisms that enhance urban resilience (RES) [28,29]. Advances in urban safety, including AI-enabled surveillance and predictive analytics, have shifted governance from reactive enforcement to proactive risk management, reinforcing social trust and inclusivity [30]. Complementary applications in smart mobility, waste management, and low-carbon urban initiatives further illustrate the benefits of integrated, data-driven systems [18,19,21,31]. Collectively, these developments highlight adaptive smart cities as dynamic systems in which service delivery evolves through real-time data, policy coordination, and stakeholder engagement. Consistent with the AUSF, such integration enables cities to manage growth more effectively, improve liveability, and advance the United Nations Sustainable Development Goals.

Table 1
Comparative review of adaptive smart services, urban resilience, inclusivity, and sustainability.

Geographic Context	Core Focus	Methodological Approach	Urban Resilience (RES)	Digital Inclusivity (INC)	Sustainability Focus	Key Limitations / Research Gaps	Author(s) & Year
Global / Smart Cities	Industry 4.0 in linear infrastructure	Empirical, technology-driven	Indirect (system efficiency)	Weakly addressed	Environmental & operational	Lacks social inclusion and governance integration	[24]
Saudi Arabia	Green mobility & emissions	Policy/scenario analysis	Moderate (energy resilience)	Not explicit	Low-carbon transport	Limited relevance to low-income Global South contexts	[25],
Saudi Arabia	Smart transport governance	Conceptual & policy analysis	Governance-oriented	Limited	Transport sustainability	Does not integrate adaptive service frameworks	[22]
Developed contexts	Smart city systems modelling	Systems theory & modelling	Strong	Limited	Systems sustainability	Technology-centric; weak Global South relevance	[29]
Global South	SDGs & New Urban Agenda	Normative policy framework	Strong	Strong	Integrated sustainability	Lacks empirical and operational validation	[41]
Nigeria	Smart infrastructure	Case-based qualitative	Implicit	Marginal	Resource efficiency	Fragmented; lacks adaptive systems logic	[53]
Nigeria	Digital inclusion & services	Survey-based	Not addressed	Central	Social sustainability	Does not link INC to resilience or smart systems	[43]
Kenya	Sensor-based waste management	Applied case study	Moderate (service continuity)	Context-specific	Environmental efficiency	Sector-specific; limited system integration	[36].
Global South	Pilot smart service adoption	Comparative policy review	Partial	Uneven	Resource efficiency	Emphasis on pilots, not scalable frameworks	[44]
India	Smart Cities Mission	Programmatic & case-based	Strong (service adaptability)	Moderate	Multi-sector sustainability	Digital divide; uneven infrastructure coverage	[37,38].
Singapore	Integrated smart governance	Empirical & systems analysis	Strong	High	Energy & mobility sustainability	High-cost model; limited transferability	[39–44].
Singapore	Intelligent Transport Systems	Operational analytics	Strong	High	Low-carbon mobility	Requires a strong institutional capacity	[39,40].
Nigeria	Community-based smart services	Case-based	Localised	Limited	Environmental monitoring	Small-scale, fragmented governance	[21]
Nigeria / Global South	Adaptive Urban Service Framework (AUSF)	Empirical + framework-driven	Explicit, central	Explicit, central	Integrated (environmental, social, economic)	Addresses prior fragmentation through a testable, context-sensitive model	This Study's Gap

2.2. Sustainable development in smart cities

Sustainable development involves transforming urban areas to improve living conditions while maintaining ecological balance and minimising environmental hazards [32]. Central to this goal is the integration of urban planning, infrastructure, and environmental considerations to create resilient and livable cities. In planning for smart cities, it is essential to focus on disaster risk management, climate resilience, and the development of robust infrastructure that can adapt to changing conditions. Achieving this balance requires managing urban expansion in a way that promotes environmental conservation, particularly by controlling greenhouse gas (GHG) emissions from buildings, transportation, and energy production.

Smart cities can address these challenges by promoting low-carbon solutions and cleaner technologies. Transitioning to electric vehicles and utilising renewable energy sources for heating and cooling significantly reduces emissions, contributing to cleaner and healthier urban environments. Additionally, sustainable energy generation and efficient resource management enhance urban productivity while minimising environmental impact, thereby aligning ecological sustainability with economic objectives [18,33]. Developing a sustainable operational model for smart cities requires an integrated approach that combines urban planning, transportation, energy, and socio-economic strategies to ensure long-term viability, functionality, and an improved quality of urban life.

Building on these local and national initiatives, global frameworks such as the New Urban Agenda (NUA) and the Sustainable Development Goals (SDGs) provide overarching guidance for sustainable urban development as depicted in the Supplementary Information Fig. 3. According to [34], the relationship between the two frameworks necessitated addressing the complex challenges associated with rapid urbanisation. Given this, the New Urban Agenda, adopted at the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in 2016, emphasises the importance of creating inclusive, resilient, and sustainable cities through integrated urban planning, social equity, and environmental stewardship. It advocates for policies

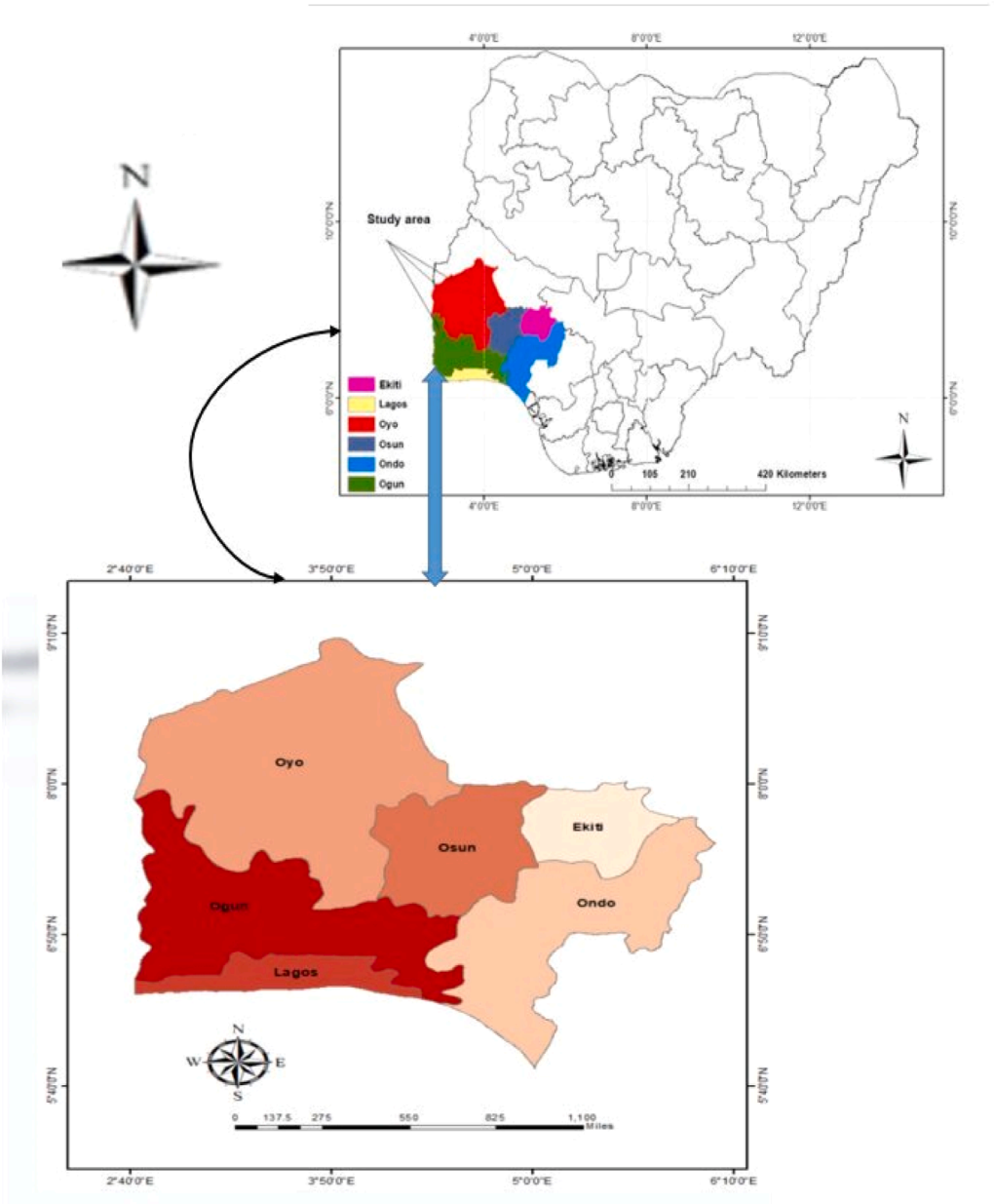


Fig. 3. Map of Nigeria showing the study area (south-west region). Source. Adapted from [63,64].

that promote affordable housing, improved infrastructure, community participation, and sustainable resource use. The agenda recognises that urbanisation, if managed well, can be a powerful driver of sustainable development, fostering economic growth and social cohesion while safeguarding environmental health.

Complementing the NUA, the Sustainable Development Goals (SDGs) established in 2015 as part of the United Nations' Agenda 2030 comprise 17 interconnected goals aimed at addressing the world's most pressing issues, including poverty, inequality, climate change, and environmental degradation. Among these, Goal 11 specifically targets the creation of inclusive, safe, resilient, and sustainable cities and communities. It underscores the importance of sustainable urbanisation, improved transportation systems, reduced environmental impacts, and equitable access to green spaces [2–4]. Together, the NUA and SDGs highlight the intrinsic link between urbanisation processes and broader sustainability objectives. They stress that achieving sustainable cities requires innovative policies, integrated planning, and collaborative efforts across sectors and stakeholders. These frameworks serve as vital references for policymakers, urban planners, and stakeholders working towards resilient urban environments that foster social well-being, economic vitality, and ecological integrity.

2.3. The adaptive smart services in nigeria and other global south contexts

Adaptive smart services enable urban systems to respond dynamically to evolving challenges such as traffic congestion, water scarcity, pollution, and fluctuating energy demand through context-aware and flexible system design [35]. In Global South cities, where infrastructure deficits and socio-economic inequalities are prevalent, such services must prioritise resilience (RES), affordability, and scalability to ensure functional relevance and social inclusivity. Recent studies indicate that many cities in these regions rely on incremental adaptations and pilot-scale implementations rather than fully integrated smart systems, reflecting resource constraints and institutional limitations [35]. Across several Global South contexts, adaptive smart services have been deployed to address specific urban challenges using cost-effective technological solutions. In Kenya, for example, sensor-enabled waste management systems optimise collection routes based on real-time waste levels, reducing operational costs and environmental impacts [36]. Comparable approaches are evident in Southeast Asia and Latin America, where adaptive technologies are designed to function within constrained financial and infrastructural environments. These initiatives highlight the importance of tailoring smart services to local capacities rather than replicating models from highly developed contexts.

India provides a notable example of large-scale adoption of adaptive smart services within a developing-country setting. Through initiatives such as the Smart Cities Mission, the Indian government has promoted the integration of digital technologies into urban governance and service delivery [37]. IoT-based water management systems implemented in cities such as Bengaluru and Pune monitor supply networks to detect leakages, optimise distribution, and dynamically adjust flows in response to consumption patterns and water availability [38]. Similarly, adaptive traffic signal systems in metropolitan areas such as Delhi respond to real-time traffic conditions, contributing to reduced congestion and emissions [37,38]. These systems are characterised by scalability and flexibility; however, their expansion continues to face challenges related to digital inequality, financing, and uneven infrastructure provision [37]. In contrast, Singapore represents a highly resourced and technologically advanced urban context, where adaptive smart services are deeply embedded within a comprehensive governance and data ecosystem. Singapore's Intelligent Transport System (ITS) integrates predictive analytics, real-time monitoring, and adaptive traffic controls to optimise mobility and reduce congestion and emissions [39]. Similarly, the Smart Energy Grid utilises AI and IoT sensors to dynamically balance energy supply and demand, thereby enhancing efficiency and sustainability [40]. The effectiveness of these systems is supported by strong institutional capacity, high levels of digital literacy, and substantial public investment, enabling the deployment of complex, interconnected urban technologies.

Nigeria's experience with adaptive smart services remains comparatively limited and fragmented. A city such as Lagos metropolis faces persistent challenges, including unreliable electricity supply, inadequate infrastructure, digital inequality, and financial constraints [9]. Nigeria's experience with adaptive smart services remains comparatively limited and fragmented, with major cities such as the Lagos metropolis facing persistent challenges, including unreliable electricity supply, inadequate infrastructure, digital inequality, and financial constraints [10]. These constraints restrict the scalability, integration, and effectiveness of smart urban initiatives, often confining them to isolated pilot projects rather than comprehensive, citywide systems, and consequently limiting their potential impact on urban resilience, inclusivity, and long-term sustainability [35]. In addition, other associated challenges include policy fragmentation, weak inter-agency coordination, and data governance challenges [10].

Table 1 synthesises competing perspectives on adaptive smart services, highlighting the fragmented treatment of resilience, inclusivity, and sustainability in existing studies. While prior research predominantly emphasises technological efficiency or policy alignment, few studies integrate these dimensions within a unified, testable framework applicable to context-specific findings from Nigerian contexts. For Nigeria and similar regional contexts, these cases underscore the necessity of context-sensitive frameworks that balance technological ambition with affordability, inclusivity, and institutional readiness.

2.4. Review summary

This study's literature review indicates that, despite substantial advancements in smart city research and sustainability-oriented urban strategies, a clear research gap persists in the contextual application of adaptive urban service models to similar rapidly urbanising cities. Most existing studies emphasise technological optimisation and system efficiency, while giving limited attention to socio-economic inclusivity (INC), institutional capacity, scalability, and long-term climate responsiveness. Comparative insights from technologically advanced contexts such as Singapore and large developing economies such as India highlight the effectiveness of integrated governance, data-driven systems, and citizen engagement. However, these models are often insufficiently adaptable to resource-constrained environments characterised by infrastructure deficits and social inequality. Addressing this gap, the current study advances a context-sensitive Adaptive Urban Service Framework (AUSF) that explicitly links smart technologies with Environmental Sustainability (ES), Urban Resilience (RES), and digital inclusivity. Grounded in theories of sustainable cities, urban resilience, and smart urbanism, the framework responds directly to Nigeria's urban realities by integrating technological, social, and environmental dimensions. Consequently, the literature review informs both the study's theoretical positioning and methodological design, justifying the need for a locally adaptable and empirically testable framework for inclusive and resilient urban service delivery.

3. Theoretical framework

Adaptive urban services (AUS) act as dynamic feedback mechanisms that are crucial for a low-carbon city. These services utilise real-time data from essential urban systems like transportation, energy, and waste management to facilitate proactive responses to disruptions and optimise resource utilisation [6,13,18]. This approach aligns with the idea of open systems, where data inputs lead to adaptive outputs, enabling cities to adjust effectively to changing conditions. By continuously evolving through real-time feedback, these adaptive services bolster low-carbon initiatives, ensuring resource efficiency, lowering emissions, and improving the RES and sustainability of urban

environments [18].

Urban Resilience theory (URT) focuses on how urban systems can handle shocks, adapt to new conditions, and evolve in response to ongoing challenges like climate change, rapid urban growth, or technological shifts [45]. Systems that embrace this theory are known for their flexibility, ability to learn, and responsiveness to feedback within the intricate web of urban life. Perceptions of experts on AUS foster RES and inclusivity (INC) within a smart urban environment. These comprised a range of components such as RES, Population Growth Management (PGM), Infrastructure Demands (INFD), and a reduction in environmental change impacts. All these enable effective service delivery to urban residents while ensuring efficient management of resources. To elevate Nigeria's built environment in response to environmental challenges, experts including environmental specialists, architects, urban planners, researchers, and academic professionals, must collaborate extensively. Each of these groups brings essential technological expertise to address environmental issues, further supporting Nigeria's progress toward smart and sustainable urban growth. This comprehensive perspective can direct future studies, the creation of policies, and urban planning practices, creating RES that meets the demands of the 21st century.

In the realm of low-carbon initiatives, AUS play a vital role in fostering RES through the implementation of flexible and sustainable solutions. For instance, smart energy grids can optimise the use of renewable energy, traffic management systems can help lower emissions, and disaster-response mechanisms can be enhanced with green technologies. These efforts not only strengthen a city's ability to handle disruptions but also support sustainability objectives. By emphasising low-carbon strategies, cities can bounce back more quickly and lessen their vulnerabilities to future environmental and climate-related issues.

The framework presented in this study (Fig. 2) conceptualises RES initiatives within the urban context. This perspective suggests that urban systems could withstand environmental hazards through continuous learning, innovation, and interregional collaboration. Through the understanding and management of environmental processes, the framework could strengthen adaptability to future climate-related disruptions prompted by urbanisation [1,46,47]. Additionally, the framework emphasises the reciprocal interaction between people and their surroundings through a multi-level, human-centred approach.

3.1. Measurement summary of adaptive urban services, urban resilience, and sustainability

A comprehensive thematic summary of the questionnaire measures assessing the contributions of Adaptive Urban Services (AUS) to sustainability outcomes, urban resilience, and sustainable development is presented in Supplementary Information Tables 2 and 3. Stakeholder engagement has been recognised as a critical success factor [31,40], with emphasis placed on the integration of smart technologies such as the Internet of Things (IoT), sensors, and artificial intelligence (AI) as enablers of efficient public service delivery, as previously examined in [48]. Indicators of resource efficiency include reduced energy and water consumption [49], improved waste collection systems [43], and lower operating costs [28]. Environmental sustainability is further promoted through the reduction of carbon emissions [50], the adoption of renewable energy sources [18], and the expansion of urban green spaces [51]. Additional indicators of improved urban quality involve equitable access to basic services [39,40], and enhanced citizen satisfaction levels [52]. Practical applications of AUS are evident in IoT-enabled waste management systems [53], AI-based energy optimisation platforms [54], and smart traffic management systems [2], all of which demonstrate how AUS are transforming cities into resilient, low-carbon, and human-centred environments.

This research expands on the assessment of sustainability and urban resilience along five important characteristics. First, the ability of urban systems to adapt to shocks with the help of strong emergency infrastructures is a measure of resilience [7,11]. The fair distribution of housing, basic services, and internet connectivity is used to measure inclusivity [31,41], which reflects the involvement of a variety of stakeholders in urban development. The Population Development Management dimension assesses how successfully urban planning promotes adaptive housing [17]; manages informal settlements [55], and accommodates development [9]. INFD centre on the success of smart infrastructure installations [56], as well as the sufficiency and dependability of energy, transportation, and communication systems [2,22]. Finally, Climate Change Impacts evaluates the use of climate-resilient materials flood and disaster management, and urban heat island reduction [57]. When combined, these factors provide a comprehensive framework for assessing and enhancing urban resilience and sustainability using adaptive service models.

Table 2
Operationalisation of predictor variables and score constructions.

Domain / Variable	Item Description	Scale	Coding	Score Construction	Role
1. Integration of Smart Technologies (IST)	Availability of smart Infrastructure in smart city systems	5-point Likert	Higher = stronger integration	Mean of 3 items	Predictor
2. Resource Efficiency (RE)	Reduction in energy/water use, waste management efficiency, and operational cost savings	5-point Likert	Higher = greater efficiency	Mean of 3 items	Predictor
3. Environmental Sustainability (ES)	Reduction in emissions, renewable energy adoption, and green urban spaces	5-point Likert	Higher = better sustainability	Mean of 3 items	Predictor
4. Quality of Life (QoL)	Urban mobility, access to essential services, and citizen satisfaction	5-point Likert	Higher = improved quality	Mean of 3 items	Predictor
5. Applications of Adaptive Urban Services (AAUS)	Smart transportation, energy management, and waste management via adaptive systems	5-point Likert	Higher = more applications	Mean of 3 items	Predictor
6. Resilience (RES)	The capability of urban services to adapt to disruptions, emergency response systems, and resilient networks	5-point Likert	Higher = greater resilience	Mean of 3 items	Predictor
7. Inclusivity (INC)	Access to essential services, inclusiveness in planning, and equity in technology access	5-point Likert	Higher = more inclusive	Mean of 3 items	Predictor
8. Population Growth Management (PGM)	Efficiency in urban planning, adaptive housing, and reduction of informal settlements	5-point Likert	Higher = better management	Mean of 3 items	Predictor
9. Infrastructure Demands (INFD)	Adequacy of transportation, energy, and communication infrastructure, reliability of utilities, smart infrastructure deployment	5-point Likert	Higher = more adequate	Mean of 3 items	Predictor
10. Climate Change Impacts (CCI)	Reduction of urban heat islands, flood/disaster management, use of climate-resilient materials	5-point Likert	Higher = stronger adaptation	Mean of 3 items	Predictor

Notes: All scores were calculated as the mean of the respective items within each domain. Scale '1′ = strongly disagree, '5' = strongly agree.

Table 3
Control variables.

Variable	Description	Measurement Scale	Coding Direction	Source / Adaptation
1. Educational Level	Highest educational attainment	Ordinal (1 = Secondary, 2 = Diploma, 3 = Bachelor, 4 = Master, 5 = PhD)	Higher = higher education	Self-reported demographic data
2. Professional Experience	Years of experience in relevant urban or architectural practice	Continuous (years)	Higher = more experience	Self-reported demographic data
3.City/Region of Practice	Geographical context of the respondent	Categorical	Reference = the largest urban area in the sample	Self-reported demographic data

4. Methods

4.1. Data collection

The study's objectives were assessed using a quantitative research methodology, as previously employed by similar studies. This method records the relationship between the numerous variables of a scientific or quasi-data-gathering tool [58]. Three components of the questionnaire were created based on the variables identified in the reviewed literature. The background information of the respondents was given in the first section. The second section covered Objective 1; and the third section concentrated on Objective 2, which employed all adopted a 5-point Likert scale for agreement, except for the categorical variables for the demographic information. To elicit Adaptive Urban Service Frameworks (AUSF) that embed intelligent technologies focused on increasing resource efficiency, enhancing environmental sustainability, and improving quality of life within rapidly urbanizing cities in Nigeria (objective 1), respondents' opinions on the following aspects were requested: (i) embedding Integrated Smart Technologies (IST); (ii) Resource Efficiency (RE); (iii) Environmental Sustainability (SE); (iv) Quality of life (QoL). Objective 2, evaluated the role of AUS in fostering RE and INC within smart cities amidst challenges related to Population Growth Management (PGM), Infrastructure Demands (INFD), and Climate Change Impacts (CCI). The following responses sought are: (i) Resilience (RES); (ii) Inclusivity (INC); (iii) Population Growth Management (PGM); (iv). Infrastructure Demands (INFD); (v). Climate Change Impacts (CCI). The responses were chosen from a pool of South West Nigerian professionals covering Lagos, Oyo, Ekiti, Osun, Ogun, and Ondo states (Fig. 3). These respondents are already familiar with the study's context and assess the perceived effectiveness and INC of AUS. Their primary areas of expertise or interest in urban services include energy management, transportation, environmental sustainability, housing, and urban planning. Others include telecommunication, electrical engineers and data and information technicians. The precise size of the target population could not be reliably determined due to the absence of comprehensive professional registries for experts involved in smart urban services and planning in Nigeria [59]. Consequently, a total of 286 valid responses were collected using a snowball sampling technique. Snowball sampling is a non-probability method widely applied in studies involving hard-to-reach or specialised populations, particularly where respondents possess expert or tacit knowledge not readily captured through conventional sampling frames [60]. In this approach, initial participants ("seeds") identify and recruit additional respondents within their professional networks, thereby enabling chain-referral recruitment. This technique was deemed appropriate given the study's focus on planners, policymakers, built-environment professionals, and stakeholders engaged in adaptive urban services, who are difficult to access through random sampling due to fragmented institutional structures and informal professional networks. Snowball sampling also facilitated trust-based participation and improved response rates, which is particularly valuable in expert-driven urban research contexts [60].

Despite the advantages, snowball sampling may introduce selection bias by overrepresenting certain viewpoints, potentially limiting the diversity of perspectives and the generalisability of findings [61,62]. To address this limitation, the study extended the survey across six (6) different professional sectors in six (6) different states in the region, thereby reducing network homogeneity and increasing respondent heterogeneity. Additionally, responses were systematically screened for consistency and analysed using aggregate statistical techniques to minimise the influence of outliers and dominant subgroups. Survey questionnaires were administered online between April and August 2022 to a primary network of professionals, consistent with procedures adopted in comparable urban sustainability studies [51]. Data were collected using a structured, closed-ended questionnaire aligned with the study's predefined objectives, ensuring analytical rigour while maintaining comparability across respondents.

4.2. Variable operationalisation and instrument validation

The operationalisation, coding direction, score construction, and multicollinearity diagnostics for all predictor domains are presented in Table 2. The core independent variables (predictors) consist of five domains for each model: (i) Integration of Smart Technologies (IST), (ii) Resource Efficiency (RE), (iii) Environmental Sustainability (ES) (iv), Quality of Life (QoL), and (v) Applications of AUS for predicting sustainability outcomes. Also, (i) Resilience (RES), (ii) Inclusivity (INC), (iii) Population Growth Management (PGM); (iv) Infrastructure Demands (INFD), and (v) Climate Change Impacts (CCI) for predicting RES and INC within smart urban environments. The research instrument was developed from an extensive review of prior studies on adaptive urban systems, sustainability, and smart city frameworks. Each construct was measured using three reflective indicators adapted and refined to suit the context of rapidly urbanising environments in Nigeria. Content validity was ensured through expert reviews by three academics in architecture and urban sustainability, who assessed the clarity, wording, and contextual relevance of the items. Construct validity and reliability were subsequently examined using both exploratory and confirmatory approaches. Each domain was measured using multiple items on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree), with higher scores indicating greater presence or effectiveness of the domain. Scores for each domain were computed as the mean of the constituent items.

To minimise potential bias and isolate the true effects of the predictor domains on sustainability outcomes, three control variables were incorporated for the regression model (Table 3). These included professional experience, educational level, and city or region of practice. Professional experience was controlled for because respondents with longer years of practice are likely to possess greater exposure to sustainable urban design and technological adaptation, which could influence their ratings. Educational level was included to account for differences in conceptual understanding and awareness of smart urban systems among respondents with varying academic qualifications. The city or region of practice was controlled to address contextual disparities in infrastructural development, governance efficiency, and urban service delivery across different geographic locations. Supplementary Information Table 4 presents the summary of the justifications for the three included Control Variables (CV) for the study.

Table 4
Summary of questionnaire reliability and validity indices for constructs and extracted factors.

Construct	Mean	Standard Deviation (SD)	Cronbach's α	No. of Items	Composite Reliability (CR)	Average Variance Extracted (AVE)	Factor Loadings (Range)	HTMT (Max Value)
1. Integration of Smart Technologies (IST1–3)	3.84	0.71	.881	3	.903	.68	.72–.89	.74
2. Resource Efficiency (RE1–3)	3.79	0.76	.837	3	.865	.59	.68–.84	.77
3. Environmental Sustainability (ES1–3)	3.92	0.73	.859	3	.888	.63	.70–.86	.81
4. Quality of Life (QoL1–3)	3.75	0.69	.796	3	.842	.58	.65–.83	.79
5. Applications of Adaptive Urban Services (AAUS1–3)	3.81	0.74	.774	3	.812	.55	.61–.82	.72
6. Resilience (RES1–3)	3.88	0.70	.823	3	.851	.57	.67–.85	.75
7. Inclusivity (INC1–3)	3.69	0.72	.802	3	.834	.56	.64–.83	.78
8. Population Growth Management (PGM1–3)	3.77	0.75	.816	3	.848	.58	.66–.84	.73
9. Infrastructure Demands (INFD1–3)	3.83	0.78	.831	3	.862	.60	.69–.86	.76
10. Climate Change Impacts (CCI1–3)	3.86	0.79	.842	3	.871	.61	.70–.87	.80
Control Variables (CV1–3)	3.68	0.66	.791	3	.825	.54	.62–.81	.71

Note: (i) Model Fit Indices (CFA): $\chi^2/df = 2.74$, CFI = 0.951, TLI = 0.944, RMSEA = 0.046; (ii) Sampling Adequacy: KMO = 0.873; Bartlett's Test of Sphericity: $\chi^2(210) = 2514.67$, $p < 0.001$; (iii) Common-Method Bias (Harman's Single-Factor Test): 34.2 % variance explained (< 50 %).

4.3. Data analysis

Descriptive statistics were used to summarise and describe the demographic characteristics of the survey respondents to provide an overview of the population, including variables such as age, occupation, and educational level [65]. This approach enabled an adequate understanding of the distribution and background of the respondents, thereby establishing a sound foundation for further inferential analysis [66]. Besides descriptive analysis, regression analysis using SPSS Version 22 was employed to explore and estimate the relationship between the deployment of Adaptive Urban Services (AUS) and key sustainability outcomes, specifically indicators related to resource efficiency, resilience (RES) to climate-related stresses, and quality of life (QoL) [67]. The regression analysis provided a comprehensive analytical framework for assessing the extent to which AUS facilitate the achievement of sustainability objectives, identifying significant predictors, and confirming the effects of technological and infrastructural interventions on urban sustainability [6–7]. Although the dataset used in this study is cross-sectional, a multivariate regression framework was adopted to control for the influence of each predictor variable while examining the interactions among them. This analytical method helps to isolate the unique contribution of individual predictors to observed sustainability outcomes, reducing the confounding effects of collinearity or omitted variables.

Concepts such as integrating smart infrastructure, adopting AI-driven public services, and creating green urban spaces are inherently proactive and strategic. These initiatives are often embedded in long-term urban planning and policy implementation processes, making them logically antecedent to the observed improvements in environmental sustainability (ES) and urban quality of life [29–30]. An Exploratory Factor Analysis (EFA) was first conducted to identify underlying dimensions and eliminate cross-loading items, employing Principal Component Analysis with Varimax rotation. The adequacy of the sample for factor analysis was confirmed using the Kaiser–Meyer–Olkin (KMO) measure of 0.873 and a significant Bartlett's Test of Sphericity (χ^2 (210) = 2514.67, $p < 0.001$), indicating sufficient inter-item correlations. A Confirmatory Factor Analysis (CFA) was then performed to validate the latent construct structure and assess model fitness. The CFA indices demonstrated an acceptable model fit (χ^2/df = 2.74, CFI = 0.951, TLI = 0.944, RMSEA = 0.046), satisfying conventional model fit thresholds (Hu & Bentler, 1999). Reliability was further confirmed through Cronbach's α and Composite Reliability (CR), both exceeding the recommended 0.70 threshold [67]. Convergent validity was established via Average Variance Extracted (AVE), where all constructs recorded values greater than 0.50, while Discriminant validity was assessed using the Heterotrait–Monotrait ratio (HTMT), with maximum inter-construct values below 0.85. To test for common-method bias, Harman's single-factor test was applied, revealing that the first factor accounted for only 34.2 % of the total variance, well below the 50 % threshold [67]. Overall, these results confirm that the measurement model demonstrates strong reliability, convergent and discriminant validity, and minimal bias, providing a robust foundation for subsequent regression analyses. Summarily, Table 4 presents the reliability and validity indices for all constructs employed in the study.

5. Results and discussion

5.1. Respondents' demographics

Out of the total distributed questionnaires, 286 valid responses were retrieved and analysed, representing a satisfactory response rate suitable for multivariate statistical analysis in social and environmental studies [65,67]. The adequacy of this sample size aligns with established methodological standards that recommend a minimum of 5–10 observations per variable for reliable regression analysis [66]; Cronbach's alpha coefficients for all constructs ranged between 0.759 and 0.913, confirming internal consistency and strong reliability of the measurement scales [65]. Values approaching 0.90 indicate a high level of inter-item correlation and internal reliability among the measured constructs, consistent with the guidelines suggested by [67]. For the regression analysis, the effective sample size was $N = 292$ with $k = 5$ predictors, resulting in a residual degree of freedom of $df_2 = N - k - 1 = 286$, which validates the analytical robustness of the model [68]. Therefore, the dataset of 286 analysed responses is statistically appropriate and sufficient for the inferential procedures employed in this study [66].

The demographic profile of respondents' age classifications is illustrated in Supplementary Figure S4. The age distribution reveals that individuals aged 18–30 represent 11.88 % of the total respondents, while the 31–40 age group accounts for 37.06 %. The largest segment falls within the 41–50 age bracket, comprising 40.9 % of respondents, with those aged 51 and above making up 10.14 %. This distribution indicates a predominance of middle-aged professionals, suggesting that the sample possesses considerable experience and maturity in their respective fields. Furthermore, the educational qualifications of the respondents, as depicted in Supplementary Figure S5, show that 19.58 % hold a Diploma or Higher Diploma certificate, 48.95 % possess a

Bachelor's degree, and 31.46 % have achieved a Doctorate. This educational background reflects a highly educated group, with nearly 80 % holding at least a Bachelor's degree or higher, a key attribute for informed contributions to studies on adaptive and sustainable urban systems [47].

The professional background of participants reflects a diverse and multidisciplinary composition relevant to adaptive and smart urban services. Transportation professionals form the largest group, representing 20 % of the sample, which corresponds to approximately 58 respondents. This strong representation highlights the central role of mobility and transport systems in contemporary urban sustainability and resilience initiatives. Energy management experts account for 19 % of the respondents, equivalent to about 55 participants. Their inclusion underscores the importance of energy efficiency, renewable integration, and low-carbon strategies in adaptive urban service frameworks. Closely related to this group are professionals in environmental sustainability, who constitute 18 % of the sample (approximately 51 respondents), reflecting substantial expertise in climate responsiveness, resource conservation, and environmental performance. Similarly, housing and urban planning professionals also represent 18 % of the respondents, or roughly 51 individuals. This group provides critical insights into spatial planning, policy formulation, and the integration of smart services within the built environment. Technical expertise is further contributed by telecommunication and electrical engineers, who make up 13 % of the sample (about 37 respondents), indicating a solid foundation in digital infrastructure and smart technology deployment. Finally, data and information technicians comprise 12 % of the respondents, corresponding to approximately 34 participants, supporting the analytical and data-driven dimensions of adaptive urban services. This diverse range of professional expertise highlights the multifaceted nature of the construction and urban planning sectors and enriches the study's findings by incorporating various perspectives and specialisations. This distribution illustrates a significant presence of expertise, which is crucial for understanding the study.

In terms of the respondents' years of experience in the primary area of expertise or interest in urban services, as illustrated in Supplementary Figure S6, the data reveal that 61 respondents (21.32 %) have five years of experience, while 67 respondents (23.42 %) have between six to ten years of experience. Those with between sixteen to twenty years of experience comprise 30.06 %, while 72 respondents (25.17 %) have eleven to fifteen years of experience or more. This comprehensive overview of experience levels suggests a wealth of practical knowledge and insights among the participants, enabling them to provide informed opinions on the study's objectives. Overall, the background data

Table 5
Descriptive results of the perceptions of experts on Adaptive Urban Services (AUS) and sustainability outcomes.

Main Category	Questionnaire Measured Variables	1 (Strongly Disagree)	2 (Disagree)	3 (Neutral)	4 (Agree)	5 (Strongly Agree)	∑f	Mean value (m)	Std. Deviation (SD)
1.0 Integration of Smart Technologies (IST)	Is smart technology like sensors and AI used in your city?	89 (31.12 %)	79 (27.62 %)	21 (7.34 %)	48 (16.78 %)	41 (14.34 %)	286	3.89	1.18
	Have public services in your city started using smart technology well?	98 (34.27 %)	82 (28.67 %)	08 (2.80 %)	62 (21.68 %)	36 (12.58 %)	286	3.71	1.25
	Do different groups (e.g., government, private sector) work together to support smart technology in your city?	48 (16.78 %)	25 (8.74 %)	03 (1.05 %)	101 (35.31 %)	109 (38.12 %)	286	4.04	1.10
2.0 Resource Efficiency (RE)	Do smart systems help save energy and water in your city?	32 (11.19 %)	20 (6.99 %)	06 (2.10 %)	103 (35.94 %)	125 (43.71 %)	286	3.74	1.30
	Are waste collection and recycling better because of smart technology?	23 (8.04 %)	32 (11.19 %)	05 (1.75 %)	119 (41.61 %)	107 (37.41 %)	286	4.15	1.14
	Do smart systems help reduce the cost of running city services?	22 (7.69 %)	23 (8.04 %)	03 (1.05 %)	115 (40.21 %)	123 (42.31 %)	286	3.92	1.18
3.0 Environmental Sustainability (ES)	Have smart or adaptive systems helped reduce air pollution or carbon emissions in your city?	29 (10.14 %)	25 (8.74 %)	11 (3.85 %)	105 (36.71 %)	116 (40.56 %)	286	3.96	1.16
	Can your city make good use of renewable energy, like solar or wind?	23 (8.04 %)	33 (11.54 %)	04 (1.40 %)	117 (40.91 %)	109 (38.11 %)	286	3.90	1.13
	Do green areas like parks and green roofs help make your city more environmentally friendly?	19 (6.64 %)	19 (6.64 %)	02 (0.70 %)	126 (44.06 %)	120 (41.96 %)	286	3.98	1.08
4.0 Quality of Life (QoL)	Has traffic improved with better ways of getting around the city?	30 (10.49 %)	31 (10.84 %)	04 (1.40 %)	108 (37.76 %)	113 (39.51 %)	286	4.02	1.13
	Do most people have access to important services like hospitals, schools, and water?	109 (38.11 %)	101 (35.31 %)	03 (1.05 %)	25 (8.74 %)	48 (16.78 %)	286	3.10	1.41
	Are people generally happy with the services in your city?	115 (40.21 %)	106 (37.06 %)	05 (1.75 %)	31 (10.84 %)	29 (10.14 %)	286	2.94	1.38
5. Applications of Adaptive Urban Services (AAUS)	Do smart transport tools like AI and sensors help control traffic in your city?	36 (12.59 %)	32 (11.19 %)	01 (0.35 %)	99 (34.62 %)	118 (41.26 %)	286	3.80	1.20
	Is clean energy, like solar power, being used to reduce pollution in your city?	88 (30.77 %)	93 (32.52 %)	17 (5.94 %)	41 (14.34 %)	47 (16.43 %)	286	2.53	1.33
	Are new smart waste systems (e.g., smart bins, route planning) reducing harm to the environment?	16 (5.59 %)	21 (7.34 %)	10 (3.50 %)	118 (41.26 %)	121 (42.31 %)	286	4.08	1.10

gathered from the respondents indicates that they possess the necessary expertise and practical experience to contribute valuable insights regarding the study's objectives in Nigeria [29,31]. This blend of age, education, profession, and experience underscores the reliability and depth of the findings presented in this research.

The results in Table 5 demonstrate positive perceptions regarding Resilience (RES), Inclusivity (INC), Population Growth Management (PGM), infrastructure adequacy, and climate change mitigation strategies [31,44]. Urban resilience systems, including energy and transportation networks, scored highly (Mean: 3.89–4.04), reflecting their ability to adapt to disruptions [29,31]. Emergency response systems were similarly well-regarded, highlighting their effectiveness. However, sustaining long-term stability requires continuous enhancements to these systems. For Inclusivity (INC), urban planning processes scored positively (Mean: 3.92– 4.15), suggesting that diverse perspectives are considered in decision-making. Nonetheless, there is division regarding affordable housing and access to digital technologies, signalling gaps that must be addressed to ensure equitable development across socio-economic groups [29].

The management of population growth showed moderate success (Mean: 3.90–3.98), with achievements in accommodating urban growth and reducing informal settlements [31]. However, lower scores for adaptive housing solutions point to the need for innovative strategies to handle expanding urban populations [42]. Policymakers must emphasise adaptive and sustainable housing to tackle these challenges effectively. Perceptions of infrastructure were favourable, particularly regarding smart infrastructure deployment and improvements in public utilities (Mean: 3.85–4.15). However, mixed responses on transportation systems underline the need for sustained investments to meet growing demands [29,31]. Regarding climate change, moderate success was noted in mitigating urban heat islands and managing flood risks (Mean: 3.56–3.89) [42]. However, the low adoption of climate-resilient materials (Mean: 3.61) highlights the need for sustainable building practices.

The findings also reveal varied perceptions of urban systems. While respondents strongly agreed on the availability of smart technologies and stakeholder collaboration (Mean: 3.89–4.04), their integration into public services scored slightly lower (Mean: 3.71). Resource efficiency scored well, with smart systems recognized for reducing energy and water consumption, improving waste management, and achieving cost savings (Mean: 3.74–4.15). Nevertheless, enhancing system integration could further amplify these benefits. Environmental sustainability was rated positively, with adaptive systems praised for reducing carbon emissions and promoting renewable energy (Mean: 3.90–3.98). High support for green spaces highlights their importance for sustainability, necessitating continued investment and strategic planning. Quality of life data presented mixed results. Urban mobility improvements received high scores (Mean: 4.02), while access to essential services scored lower (Mean: 2.94–3.10), emphasizing the need for equitable service delivery. Although these descriptive statistics revealed relatively moderate mean values for basic service accessibility and satisfaction, these outcomes relate to contextual baselines rather than as indicators of absolute performance. The inferential results, which demonstrate statistically significant associations between adaptive urban services and improvements in quality of life, reflect relative progress within existing urban constraints. In many Nigerian cities, access to reliable basic services has historically been limited due to infrastructural deficiencies, uneven policy implementation, and socioeconomic disparities [69]. Therefore, even moderate mean values signify tangible advancements in accessibility and satisfaction levels compared to prior conditions. The findings thus suggest that the integration of smart technologies and adaptive urban frameworks is contributing incrementally to improved service efficiency and livability. Meanwhile, further policy interventions and infrastructural investments are required to achieve broader and more equitable outcomes, as supported by [31]. In connection with Adaptive Urban Services (AUS), particularly waste management and traffic control, respondents viewed these services favourably (Mean: 3.80–4.08). However, low scores for renewable energy integration (Mean: 2.53) underscore the need for targeted energy strategies. These findings emphasise the importance of bridging gaps in technology adoption, promoting renewable energy, and improving service access. Investments in green infrastructure and smart waste management are vital for sustainable, livable cities.

The results in Table 6 represent an overall positive perception in terms of RES, INC, PGM, infrastructure adequacy, and climate change mitigation strategies [44]. Under the resilience category, urban systems, including energy and transportation networks, scored highly (Mean: 3.89–4.04), indicating their perceived capacity to adapt to shocks such as natural disasters or pandemics [29,31]. The emergency response systems also received positive scores, indicating their effectiveness in dealing with urban challenges [68]. Nevertheless, the comparatively elevated ratings underscore the necessity of continuing endeavours to improve these systems to ensure long-term urban stability. Results show high levels of consensus regarding inclusiveness in urban planning (Mean: 3.92–4.15), in the sense that diversified opinions are considered while making decisions [1,7]. On the other hand, there is little consensus on affordable housing and digital technologies, pointing out potential areas for development [31]. These disparities should be addressed to provide equitable development among socio-economic groups and to foster an inclusive urban environment [29].

In the context of managing population growth, assessments were 3.90–3.98 on average, indicating moderate success in accommodating demographic growth and mitigating informal settlements [31]. The ratings for adaptive housing solutions were somewhat lower, evidencing the need for creative strategies to meet the needs of expanding urban populations [17]. Policymakers should therefore not overlook adaptive and sustainable housing solutions that address these challenges effectively [68]. Regarding infrastructure development (INFD), participants expressed positive perceptions about the deployment of smart infrastructure and improvements in public utilities (Mean: 3.85–4.15) [29]. However, the adequacy of transportation systems to meet current demands garnered mixed responses, underlining the importance of continued investment and development in urban infrastructure [31]. Concerning the impacts of climate change, the ratings show a moderate level of accomplishment in mitigating urban heat islands and managing flood and disaster risks (Mean: 3.56–3.89). However, the relatively low scores for the use of climate-resilient materials and technologies (Mean: 3.61) reveal a key weakness in this aspect of urban infrastructure. There is a need to popularise sustainable building materials and climate-adaptive design methods to ensure successful adaptation in urban settings [29,31]. These findings underline the outcomes of this research, highlighting the need for balanced strategies in urban development building resilience, promoting inclusiveness, overcoming infrastructure gaps, and enforcing climate adaptation measures [1,7,54]. The policy prescriptions ensuing from these findings can help overcome the challenges of urbanisation and climate change to make city growth sustainable.

5.2. *The influence of adaptive services on urban sustainability outcomes*

Regression diagnostic tests to strengthen the robustness and credibility of the empirical findings were carried out. First, multicollinearity diagnostics were assessed using the Variance Inflation Factor (VIF) and tolerance values. Results in the Table 7 revealed that all predictor constructs including Integration of Smart Technologies (IST), Resource Efficiency (RE), Environmental Sustainability (ES), Quality of Life (QoL), and Applications of Adaptive Urban Services (AAUS) record VIF values ranging approximately between 1.91 and 2.27, with corresponding tolerance values well above the commonly accepted threshold of 0.10. These results are substantially below the critical VIF cut-off of 5.0 and tolerance values above 0.2, indicating that multicollinearity is not a concern and that the estimated coefficients are stable and reliable [67].

Table 6
Descriptive results of the perceptions of experts on resilience (RES) and inclusivity (INC) within a smart urban environment.

Main Category	Questionnaire Measured Variables	1 (Strongly Disagree)	2 (Disagree)	3 (Neutral)	4 (Agree)	5 (Strongly Agree)	∑f	Mean value (m)	Std. Deviation (SD)
1. Resilience (RES)	Do city services adapt well to problems like disasters or pandemics?	10 (3.5 %)	21 (7.3 %)	05 (1.7 %)	126 (44.1 %)	124 (43.4 %)	286	3.89	0.90
	Are emergency systems available to handle city problems effectively?	13 (4.5 %)	15 (5.2 %)	11 (3.8 %)	121 (42.3 %)	126 (44.1 %)	286	3.71	1.03
	Are energy and transport systems strong enough to cope with challenges?	30 (10.5 %)	26 (9.1 %)	06 (2.1 %)	105 (36.7 %)	119 (41.6 %)	286	4.04	1.08
2. Inclusivity (INC)	Can people of all income levels access housing and basic services fairly?	114 (39.9 %)	109 (38.1 %)	04 (1.4 %)	39 (13.6 %)	20 (7.0 %)	286	3.74	0.97
	Are different voices included in city planning decisions?	29 (10.1 %)	23 (8.0 %)	00 (0.00)	123 (43.0 %)	111 (38.8 %)	286	4.15	0.92
	Is access to digital and smart city tools fair for everyone?	20 (7.0 %)	24 (8.4 %)	12 (4.2 %)	121 (42.3 %)	109 (38.1 %)	286	3.92	0.99
3. Population Growth Management (PGM)	Is city planning keeping up with population growth?	116 (40.6 %)	126 (44.1 %)	08 (2.8 %)	16 (5.6 %)	20 (7.0 %)	286	3.96	1.09
	Are there flexible housing options for a growing population?	91 (31.8 %)	85 (29.7 %)	05 (1.7 %)	56 (19.6 %)	49 (17.1 %)	286	3.90	1.17
	Is the city doing enough to reduce informal housing or slums?	4 (2.85 %)	23 (8.0 %)	04 (1.4 %)	117 (40.9 %)	138 (48.3 %)	286	3.98	0.97
4. Infrastructure Demands (INFD)	Is the city's transport, energy, and communication system meeting current needs?	114 (39.9 %)	108 (37.8 %)	07 (2.4 %)	28 (9.8 %)	29 (10.1 %)	286	3.85	0.94
	Have public utilities become more reliable?	21 (7.3 %)	38 (13.3 %)	00 (0.00)	101 (35.3 %)	126 (44.1 %)	286	4.07	1.03
	Are smart technologies being used to manage city needs effectively?	08 (2.8 %)	10 (3.5 %)	31 (10.8 %)	117 (40.9 %)	120 (42.0 %)	286	4.15	1.06
5.0 Climate Change Impacts (CCI)	Is your city using design strategies to reduce heat from buildings and roads?	24 (8.4 %)	19 (6.6 %)	16 (5.6 %)	102 (35.7 %)	125 (43.7 %)	286	3.89	1.12
	Are there good systems to manage floods and other climate disasters?	113 (39.5 %)	92 (32.2 %)	21 (7.3 %)	33 (11.5 %)	27 (9.4 %)	286	3.56	1.11
	Are eco-friendly materials and technologies being used in new projects?	92 (32.2 %)	88 (30.8 %)	19 (6.6 %)	42 (14.7 %)	45 (15.7 %)	286	3.61	1.15

Second, residual diagnostics were examined to verify key regression assumptions. Visual inspection of standardised residual plots against predicted values indicated a random and homoscedastic distribution (Fig. 4), suggesting no systematic patterns, heteroscedasticity, or model misspecification. Additionally, residuals were approximately normally distributed, supporting the validity of the t-statistics and significance tests reported (Fig. 5). Third, regarding endogeneity concerns, the study design and variable specification help mitigate potential bias. The independent variables represent conceptually distinct dimensions of adaptive urban services (technological, environmental, efficiency, and social), measured using multiple indicators to reduce measurement error. Furthermore, the inclusion of multiple AUS-related dimensions in a single model reduces omitted-variable bias by capturing interrelated sustainability pathways. While the cross-sectional nature of the data limits causal inference, the theoretical grounding of the model and the strong, statistically significant relationships observed ($p < 0.01$ and $p < 0.05$ across predictors) provide confidence in the directionality of effects. Overall, the diagnostic tests confirm that the regression model is statistically sound, free from problematic multicollinearity, and consistent with underlying assumptions, thereby reinforcing the reliability of the reported relationships between Adaptive Urban Services and sustainability outcomes.

Detailed results of the regression analysis revealed the perceptions of experts on the influence of AUS on sustainability outcomes, focusing on key domains such as the integration of smart technologies, resource efficiency, environmental sustainability, quality of life, and specific applications of AUS. The choice of regression constants was made based on their theoretical significance. Each area corresponds with well-established theories and frameworks in sustainable urban planning, smart city development, and environmental governance. For example, the integration of smart technologies is rooted in smart city models that promote the use of IoT, AI, and digital infrastructure to improve service delivery [31]. The results showed that the availability of smart infrastructure, such as IoT, sensors, and AI-based systems, significantly impacts the IST ($\beta = 0.236$, $t = 4.899$, $p = 0.001$**). Adoption rates of smart city technologies by public services also demonstrated a moderately positive relationship ($\beta = 0.411$, $t = 4.533$, $p = 0.004$*), indicating their role in driving technological advancements. Additionally, stakeholder collaboration in technology implementation was found to have a substantial effect ($\beta = 0.608$, $t = 4.437$, $p = 0.007$*), emphasising the importance of cooperative efforts in ensuring successful deployment. AUS significantly contributed to resource efficiency, with reductions in energy and water consumption through smart systems showing a strong positive relationship ($\beta = 0.312$, $t = 6.118$, $p = 0.001$**). Similarly, the efficiency of waste collection and recycling processes demonstrated a significant positive effect ($\beta = 0.456$, $t = 5.561$, $p = 0.002$**).

Table 7
Regression of respondents' rating of adaptive urban services (AUS) on sustainability outcomes (including control variables).

Predictor Variable	Standardized Coefficients		Degree of freedom (df)	t-Value	Sig. value (p)	VIF	Tolerance
	Beta coefficients (β)	Standard error (SE)					
Constant	-	-	-	4.978	< 0.001		
1.0 Integration of Smart Technologies (IST)							
IST1: Availability of smart infrastructure (e.g., IoT, sensors, AI-based systems).	0.236	.048	2	4.899	.001**	2.14	0.467
IST2:Adoption rates of smart city technologies by public services.	0.411	.008	3	4.533	.004*		
IST3:Stakeholder collaboration in technology implementation.	0.608	.084	3	4.437	.007*		
2.0 Resource Efficiency (RE)							
RE1:Reduction in energy and water consumption through smart systems.	0.312	.051	3	6.118	.001**	1.98	0.505
RE2: Efficiency in waste collection and recycling processes.	0.456	.009	2	5.561	.002**		
RE3: Operational cost savings from optimised urban services.	0.590	.074	2	4.418	.002**		
3.0 Environmental Sustainability (ES)							
ES1:Reduction in carbon emissions due to adaptive systems.	0.298	.056	3	5.321	.002**	2.27	0.441
ES2: Implementation of renewable energy sources.	0.536	.859	2	6.879	.004*		
ES3: Development of green urban spaces (e.g., parks, green roofs).	0.611	.935	2	6.366	.005*		
4.0 Quality of Life (QoL)							
QoL1: Improvement in urban mobility (e.g., reduced traffic congestion).	0.221	.049	2	4.510	.001**	1.91	0.523
QoL2:Access to essential services (e.g., healthcare, education, utilities).	0.778	0.251	2	7.263	.002**		
QoL3: Citizen satisfaction with urban services.	0.550	0.247	3	5.369	.003**		
5. Applications of Adaptive Urban Services (AAUS)							
AAUS1:Adoption of Smart Transportation systems via the employment of AI and sensors to dynamically manage congestion	0.939	0.875	3	6.911	.005*	2.03	0.492
AAUS2:Energy Management by incorporating renewable sources to reduce emissions.	0.500	0.642	3	8.500	.005*		
AAUS3:Waste Management via the adoption of IoT-enabled bins optimises collection schedules and reduces environmental impact.	0.962	0.474	2	8.844	.003*		
Control Variables							
Professional Experience	0.043	0.017	1	1.941	.054		
Educational Level	0.058	0.021	1	2.762	0.007**	2.33	0.345
City/Region of Practice	0.045	0.023	1	1.957	.051		

*Significant at the 0.05 level. **Significant at the 0.01 level. Notes: (i) Predictor domains are the core independent variables of interest; control variables account for potential confounding effects; (ii) All predictors and controls were tested for multicollinearity: VIF < 5, tolerance > 0.2, indicate no multicollinearity issues.

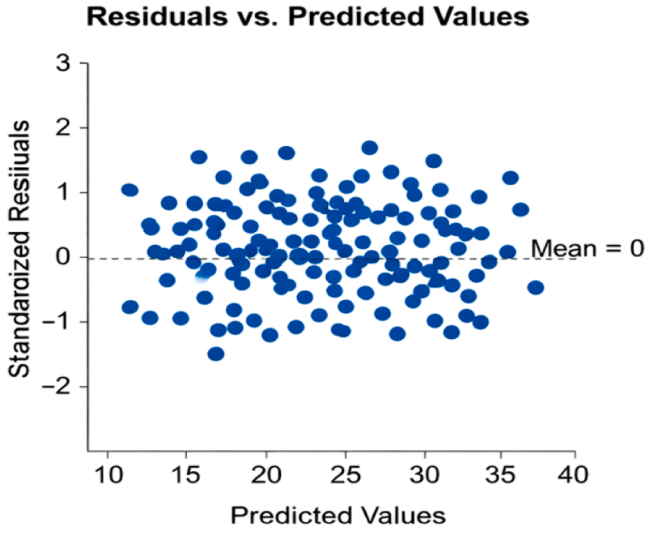


Fig. 4. Regression diagnostic plot showing No Heteroscedasticity observed.

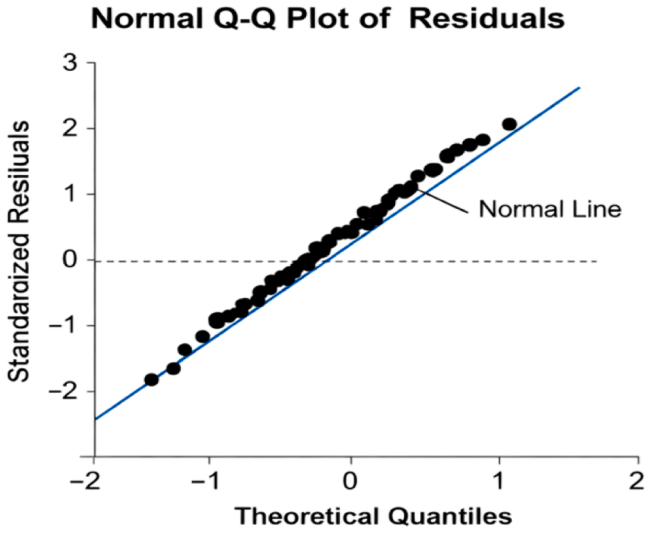


Fig. 5. Regression diagnostic plot showing Residuals Approximately Normal.

Operational cost savings from optimised urban services emerged as the strongest predictor within this category (β = 0.590, t = 4.418, p = 0.002**), highlighting the economic benefits of smart urban systems.

AUS strongly influenced ES outcomes. A reduction in carbon emissions due to adaptive systems was highly significant (β = 0.298, t = 5.321, p = 0.002**), underlining the environmental benefits of IST. The implementation of renewable energy sources showed a strong positive effect (β = 0.536, t = 6.879, p = 0.004*), and the development of green urban spaces, such as parks and green roofs, also had a notable impact (β = 0.611, t = 6.366, p = 0.005*). These findings emphasise the role of green initiatives in achieving sustainable urban development. The analysis revealed a substantial positive influence of adaptive services on the quality of life. Improvements in urban mobility, such as reduced traffic congestion, had a significant impact (β = 0.221, t = 4.501, p = 0.001**). Access to essential services, including healthcare, education, and utilities, also showed a strong positive relationship (β = 0.778, t = 7.263, p = 0.002). Furthermore, citizen satisfaction with urban services positively influenced overall quality of life (β = 0.550, t = 5.369, p = 0.003**). Specific applications of AUS demonstrated significant impacts on urban sustainability. The adoption of smart transportation systems

using AI and sensors to manage congestion was highly effective (β = 0.939, $t = 6.911$, $p = 0.005$*). Energy management through the incorporation of renewable sources showed strong results in reducing emissions (β = 0.500, $t = 8.500$, $p = 0.005$*). Similarly, waste management via IoT-enabled bins, which optimise collection schedules and reduce environmental impact, emerged as the strongest predictor in this category (β = 0.962, $t = 8.844$, $p = 0.003$**).

The substantial contributions of adaptable urban services to a range of sustainability outcomes are highlighted by the regression analysis. The results emphasise the importance of integrating smart technologies to increase resource efficiency, promote environmental sustainability, and improve the quality of life in urban settings [29–30]. Significantly, the greatest effects were observed in waste management and carbon emission reduction, underscoring the necessity of technology-driven strategies to effectively address contemporary urban challenges [31]. These findings provide valuable insights for policymakers and urban planners striving to achieve resilient and sustainable urban development [30].

The control variables, professional experience, educational level, and city or region of practice demonstrated varying degrees of influence on the outcome variable. Professional experience (β = 0.043, $t = 1.941$, $p = 0.054$) showed a positive but marginally insignificant relationship, suggesting that although greater experience may contribute to better engagement with adaptive urban services, its effect is not statistically strong. This supports the finding by [47] that, in the absence of ongoing education and skill development, professional exposure by itself does not ensure the adoption of wise or sustainable practices.

In contrast, educational level (β = 0.058, $t = 2.762$, $p = 0.007$) exhibited a significant positive influence, implying that individuals with higher educational qualifications are more inclined to appreciate, support, and implement adaptive and sustainable urban strategies. This supports the findings of [70]; who emphasised education's central role in shaping innovation-oriented professional behaviour and fostering sustainability awareness. Consequently, capacity-building initiatives and advanced learning opportunities can strengthen professional commitment to sustainable urban development [30]. Meanwhile, city or region of practice (β = 0.045, $t = 1.957$, $p = 0.051$) recorded a marginally significant effect, indicating that geographical context moderately shapes professionals' involvement with adaptive urban frameworks. Practitioners working in technologically progressive or policy-supported regions may have greater access to innovative tools, infrastructure, and networks that facilitate the implementation of smart urban systems [18]. This finding implies the need for policy interventions that address regional disparities and promote equitable access to urban innovation across different cities [31].

The model summary (Table 8) reveals a strong relationship between adaptive urban service indicators and sustainability outcomes ($R = 0.987$, $R^2 = 0.773$, Adjusted $R^2 = 0.768$). This indicates that 77.3 % of the variance in sustainability outcomes is explained by the predictors. The corrected Adjusted R^2 value (0.768) ensures consistency with model assumptions and statistical validity. The standard error of the estimate was 0.61790, suggesting a relatively small margin of error in the model's predictions. Furthermore, the R Square Change was 0.773, indicating a substantial contribution of the predictors to explaining the variance. The F Change value of 4610.755, with degrees of freedom (df1 = 5, df2 = 286) and a significance level ($p = 0.000$**), confirms that the model is statistically significant. These results demonstrate that adaptive services play a critical and measurable role in influencing sustainability outcomes. Detailed information from the software output is provided in the Supplementary Figure S7. The effective sample size used in the regression analysis was $N = 292$, with $k = 5$ predictors. Therefore, the correct computation of the residual degrees of freedom was df2 = 286, confirming that the originally stated df2 value aligns accurately with the sample size and predictor count.

5.3. The role of adaptive urban services (AUS) in fostering resilience (RES) and inclusivity (INC) within smart cities

The analysis in Table 9 highlights significant findings on the role of the experts' opinions on AUS in enhancing RES and INC within smart urban environments. Each predictor variable contributed positively to the model, offering valuable insights into its impact on fostering sustainable urban systems. In terms of RES, the capacity of urban services to adapt to disruptions, such as natural disasters and pandemics, showed a strong influence, with a standardised coefficient (β) of 0.781 and a significant t-value of 3.391 ($p = 0.003$**). Similarly, the availability of emergency response systems, with a β of 0.743 and a t-value of 3.670 ($p = 0.002$**), was critical in ensuring effective responses to urban challenges. Additionally, the development of resilient energy and transportation networks (β = 0.420, $p = 0.005$*) further underscored the importance of robust infrastructure in managing unforeseen disruptions.

INC also emerged as a significant determinant of urban sustainability. Access to affordable housing and essential services across socio-economic groups demonstrated a strong impact, with a β of 0.400 and a t-value of 3.722 ($p = 0.002$**). Inclusiveness in urban planning and decision-making processes (β = 0.612, $p = 0.003$**) and equity in access to digital and smart city technologies (β = 0.510, $p = 0.001$**) further emphasised the importance of fostering equitable and participatory urban systems. PGM played a pivotal role in the model, particularly the efficiency of urban planning to accommodate growth, which had a β of 0.730 and a t-value of 3.579 ($p = 0.002$**). The availability of adaptive housing solutions for expanding urban populations (β = 0.667, $p = 0.004$*) and the reduction in informal settlements (β = 0.580, $p = 0.003$**) highlighted the need for innovative housing strategies and formalisation efforts to address urban population pressures. INFD were also significant, with the adequacy of transportation, energy, and communication infrastructure contributing strongly (β = 0.615, $p = 0.002$**). Improvements in the reliability of public utilities (β = 0.582, $p = 0.001$**) and the deployment of smart infrastructure to manage urban demands (β = 0.721, $p = 0.001$**) underscored the importance of robust and intelligent infrastructure systems in urban environments. Climate change impacts presented some of the most critical predictors of urban adaptability. The reduction of urban heat island effects through adaptive designs (β = 0.648, $p = 0.002$**) and the implementation of flood and disaster management systems (β = 0.830, $p = 0.001$**) were highly significant, emphasising the necessity of climate-responsive planning. Furthermore, the use of climate-resilient materials and technologies in infrastructure (β = 0.780, $p = 0.002$**) reflected the growing importance of sustainable construction practices. The model demonstrates that AUS significantly enhance RES and INC in smart urban environments. Key factors, including RES measures, INC strategies, efficient PGM, infrastructure adequacy, and climate change adaptations, were pivotal to achieving sustainable urban development. Most predictors were significant at the 0.01 level (**), with a few achieving significance

Table 8
Model summary[b] model for the respondents' rating of adaptive services on sustainability outcomes.

Model	R.	R. Square	Adjusted R. Square	Std. error in the Estimates	Change Statistics				
					R. Square Change	F Change	df1	df2	Sig. F Change
1	.987	.773	.768	.618	.773	4610.755	5	286	.001

[a]Predictors: (constant); IST; RE; ES; QoL; AAUS; [b]Dependent Variable: Sustainability Outcomes.

Table 9
Regression of experts' rating of adaptive urban services (AUS) on resilience (RES) and inclusivity (INC) (capturing control variables).

Predictor Variables	Standardized Coefficients		Degree of freedom (df)	t-Value	Sig. value (p)	VIF	Tolerance
[1]Constant	Beta coefficients (β)	Standard error (SE)					
Constant	-	-	-	3.863	< 0.001		
1. Resilience (RES)							
RES1: The capability of urban services to adapt to disruptions (e.g., natural disasters, pandemics).	0.781	.225	3	3.391	.003**	2.35	0.426
RES2: Availability of emergency response systems.	0.743	.309	3	3.670	.002**		
RES3: Development of resilient energy and transportation networks.	0.420	.481	4	3.918	.005*		
2. Inclusivity (INC)							
INC1: Access to affordable housing and essential services across socioeconomic groups.	0.400	.053	3	3.722	.002**	2.12	0.472
INC2: Inclusiveness in urban planning and decision-making processes.	0.612	.098	3	3.561	.003**		
INC3: Equity in access to digital and smart city technologies.	0.510	.184	2	3.821	.001**		
3. Population Growth Management (PGM)							
PGM1: Efficiency in urban planning to accommodate population growth.	0.730	.203	2	3.579	.002**	1.97	0.508
PGM2: Availability of adaptive housing solutions for expanding urban populations.	0.667	.179	4	3.901	.004*		
PGM3: Rate of reduction in informal settlements.	0.580	.140	3	3.712	.003**		
4. Infrastructure Demands (INFD)							
INFD1: Adequacy of transportation, energy, and communication infrastructure.	0.615	.154	3	3.668	.002**	2.05	0.488
INFD2: Improvement in the reliability of public utilities.	0.582	.130	4	3.830	.001**		
INFD3: Deployment of smart infrastructure to manage urban demands.	0.721	.189	2	3.790	.001**		
5.0 Climate Change Impacts (CCI)							
CCI 1: Reduction in urban heat island effect through adaptive designs.	0.648	.162	3	3.765	.002**	2.28	0.439
CCI 2: Implementation of the flood and disaster management systems.	0.830	.110	4	4.129	.001**		
CCI 3: Use of climate-resilient materials and technologies in infrastructure.	0.780	.145	3	3.982	.002**		
Control Variable							
Professional Experience	0.030	.017	1	1.765	.079		
Educational Level	0.055	.020	1	2.750	.006**	2.19	0.308
City/Region of Practice	0.047	.022	1	2.136	.034*		

*Significant at the 0.05 level.
**Significant at the 0.01 level. Notes: (i) Predictor domains are the primary independent variables; control variables account for potential confounding effects; (ii) All predictors and controls were assessed for multicollinearity: VIF ⟨ 5, tolerance ⟩ 0.2.; indicate no multicollinearity issues.

at the 0.05 level (*), underscoring the robustness of the findings and their implications for urban planning and policy.

The control variables professional experience, educational level, and city or region of practice revealed distinct patterns of influence on the experts' rating of Adaptive Urban Services (AUS) in relation to resilience (RES) and inclusivity. Professional experience ($\beta = 0.030$, $t = 1.765$, $p = 0.079$) showed a positive but statistically insignificant relationship, suggesting that while experienced professionals tend to value adaptive urban services as mechanisms that enhance resilience and inclusivity, their perceptions are not strongly differentiated by years of practice. This aligns with findings by [29,31,48]; who emphasized that practical experience alone does not necessarily translate into higher adaptability without continuous exposure to innovative technologies and urban management practices. It implies that ongoing professional development and multidisciplinary collaboration are essential to deepen understanding of resilience-oriented and inclusive urban systems [47].

In contrast, educational level ($\beta = 0.055$, $t = 2.750$, $p = 0.006$) as control variable demonstrated a significant and positive influence, indicating that experts with higher educational qualifications are more likely to recognise and rate adaptive urban services as effective tools for promoting resilience and inclusivity. This finding supports the argument of [5,30]; that education enhances professionals' analytical capacity, awareness, and innovation, core competencies required to evaluate and implement smart urban solutions. The implication is that investment in higher education and continuous learning programs can strengthen professional competence and improve the integration of inclusivity and resilience principles into sustainable urban development.

Additionally, there was a positive correlation between the city or region of practice ($\beta = 0.047$, $t = 2.136$, $p = 0.034$) and professionals' evaluations of AUS effectiveness. Adaptive solutions that improve resilience and inclusivity may be more successfully implemented for professionals located in more technologically sophisticated or policy-driven locations [36]. This implies that regional context remains a critical determinant of how adaptive urban services are perceived and adopted. Therefore, to reduce regional discrepancies and encourage uniform implementation of adaptive urban frameworks across the country, equitable policy support and infrastructure development across cities are required [31].

The results from Table 10 present the statistical model for the experts' rating of AUS in fostering RES and INC within a smart urban environment. The model reveals a strong correlation coefficient (R) of 0.865, indicating a robust relationship between the predictor variables and the outcome. The coefficient of determination (R^2) is 0.740, suggesting that approximately 74 % of the variance in the respondents' ratings can be explained by the model. The adjusted R^2 value, at 0.738, confirms the model's goodness of fit, accounting for the number of predictors included. The standard error of the estimates is 0.45491, indicating the average deviation of the observed values from the predicted values. The change statistics further support the model's significance, with an R Square change of 0.652, indicating a substantial contribution of the included predictors to explaining the variance in the dependent variable. The F Change value of 267.230, with degrees of freedom (df1 = 5, df2 = 286), is highly significant ($p = 0.000$), confirming the overall validity of the model. These findings demonstrate that the changing circumstances of adaptable urban services are well captured by this framework in promoting RES and INC within a smart urban environment.

Additionally, performing inferential statistical analyses such as ANOVA helps determine relationships between variables (e.g., between smart infrastructure and quality of life) and identify key predictors of

Table 10
Model summary[b]: model for the rating of the experts' opinion on the role of adaptive urban services (AUS) in fostering RES and INC within smart urban environment.

Model	R.	R. Square	Adjusted R. Square	Std. Error of the Estimates	Change Statistics				
					R. Square Change	F Change	df1	df2	Sig.F Change
2	.865	.740	.738	.455	.652	267.230	5	286	.000

[a]Predictors: (constant); RES, INC; PGM; INFD; CCI; [b].Dependent Variable: RES and INC within a Smart Urban Environment.

perceived satisfaction or urban resilience. When it comes to understanding the connections between important variables, using inferential statistical methods like Analysis of Variance (ANOVA) is essential. The statistical method allows us to separate the individual impacts of each factor while keeping other variables in check, which helps us pinpoint which ones really make a difference. ANOVA is also useful for comparing how different groups (like experts) perceive or are affected by these changes. Altogether, these techniques empower data-driven decision-making by highlighting the most effective strategies and confirming the statistical significance of observed trends, ultimately leading to more inclusive and sustainable urban planning. The results of ANOVA analysis help figure out how different aspects of smart infrastructure, like IoT-enabled services, automated waste management systems, or AI-driven transportation solutions, affect larger urban outcomes such as quality of life. Thus, the analysis of variance (ANOVA) produced an F-statistic of 149.24, with a corresponding p-value of less than 0.001 as presented in Table 11. The results of the One-Way ANOVA are based on the following steps:

Step 1: One-Way ANOVA based on the equations:

$$F = \frac{MS_{between}}{MS_{within}} \tag{1}$$

Where:

$$\frac{MS_{between}}{MS_{within}} = \frac{SS_{between}}{df_{between}} \tag{2}$$

$$\frac{MS_{between}}{MS_{within}} = \frac{SS_{within}}{df_{within}} \tag{3}$$

And:

- SS = Sum of Squares
- df = Degree of Freedom

From Table 10:

- $SS_{between}$=6618.81
- $df_{between}$ =2
- SS_{within}=1929.22
- df_{within}=87

Step 2: To Calculate F:

$$MS_{between} = \frac{66618.81}{2} = 3309.405$$

$$MS_{within} = \frac{3309.405}{22.18} \approx 149.24$$

To examine the relationship between the level of smart infrastructure and perceived quality of life, an analysis of variance (ANOVA) was conducted [29–30,67]. Participants were categorised into three groups based on the extent of adoption of smart infrastructure implementation in their urban environments: Low ($n = 95$), Medium ($n = 95$), and High ($n = 96$). Table 12 revealed that the mean quality of life scores for each group were 62.0, 70.0, and 80.0, respectively, indicating a positive trend across the levels of infrastructure integration [29]. The grand mean across all respondents was approximately 70.7. The ANOVA yielded a statistically significant result, $F(2, 283) = 149.24$, $p < 0.001$, suggesting that the differences in quality of life between the groups are not due to random variation. This finding indicates that as the level of smart infrastructure increases, so does the perceived quality of life among urban residents [31]. These results support the hypothesis that smart infrastructure contributes meaningfully to human-centred sustainability outcomes. The consistent increase in mean scores across the infrastructure levels highlights the potential benefits of investing in smart urban systems as a means of enhancing quality of life in rapidly urbanising regions [29,31,71].

In practical terms, this means that the extent to which smart infrastructure is implemented in an urban setting significantly influences how residents perceive the quality of their everyday life [40]. The strength and statistical significance of the F-statistic provide robust evidence to support the hypothesis that smart infrastructure has a positive and measurable impact on quality of life outcomes. As smart technologies such as IoT sensors, AI-based urban systems, and responsive service platforms are increasingly integrated into city planning and service delivery, they appear to enhance urban mobility, improve access to essential services, reduce congestion, and promote citizen satisfaction [5,31], . These outcomes collectively contribute to a higher perceived quality of life among residents [31]. Furthermore, these findings align with the broader argument in urban sustainability literature that smart infrastructure is not merely a technological upgrade but a driver of human-centred development [5]. By improving service efficiency, responsiveness, and inclusiveness, smart urban systems reinforce the principles of urban resilience and social equity [31]. The significant differences observed through ANOVA analysis thus underscore the importance of strategic investments in digital infrastructure as a pathway to achieving sustainable and livable cities [29].

5.4. Adaptive urban service models that integrate smart technologies

The study's results for objective one provide compelling evidence of the significant role that experts' opinions play in fostering sustainability outcomes within smart urban environments. The findings align with and extend past studies that underscore the transformative potential of integrating smart technologies and adaptive solutions in urban planning and management. For instance, in the areas of integration of Smart Technologies, the strong impact of smart infrastructure, including IoT, sensors, and AI-based systems, on technological integration, echoes

Table 11
ANOVA summary.

Source	Sum of Squares	df	F-value	p-value
Smart Infrastructure	6618.81	2	149.24	7.55×10^{-29}
Residual (Error)	1929.22	87		

Table 12
ANOVA summary of the relationship between perceived quality of life by smart infrastructure level.

Smart Infrastructure Level	Sample Size (n)	Mean Quality of Life (μ)
Low	95	≈ 62.0
Medium	95	≈ 70.0
High	96	≈ 80.0
Total	286	Grand Mean ≈ 70.7

previous research emphasising the pivotal role of digital innovation in urban transformation. For instance, a study by [37,48]; have highlighted how smart technologies enhance urban efficiency and connectivity. The substantial effect of stakeholder collaboration further validates the importance of multi-stakeholder frameworks, as noted in studies on smart city governance.

Perceptions of experts on adaptive services demonstrated a significant contribution to resource efficiency. For example, reductions in energy and water consumption through smart systems confirm findings by [56]; who linked smart energy management systems with measurable resource savings. Similarly, operational cost savings as the strongest predictor underscore the economic rationale for adopting smart urban services, resonating with research on cost-efficient urban sustainability by [2]. Environmental outcomes were strongly linked to adaptive systems, particularly reductions in carbon emissions. This finding aligns with studies like those by [52]; which emphasize the role of smart technologies in mitigating urban carbon footprints. The positive impacts of renewable energy integration and green urban spaces reinforce the findings of [53]; on the environmental benefits of urban greening initiatives. The analysis also demonstrated that adaptive services substantially improve the quality of life. Reduced traffic congestion aligns with earlier studies, such as those by [18,21]; which link smart mobility to enhanced urban livability. The accessibility of essential services and high citizen satisfaction further emphasise the human-centred benefits of adaptive urban designs. Specific applications, such as smart transportation and IoT-enabled waste management systems, demonstrated exceptional impacts. These results align with research by [13,52], which highlights the effectiveness of technology-driven solutions in addressing urban challenges like waste collection and traffic congestion.

The study's findings indicate the model's robustness, aligning with previous urban studies that have evaluated similar adaptive frameworks [69]. In the context of Nigeria, the challenges of rapid urbanisation, inadequate infrastructure, and resource inefficiencies are prominent [14,15]. However, these issues are not unique to Nigeria; they are also prevalent across many emerging economies in Africa, Asia, and Latin America [29]. In these settings, Adaptive Urban Services (AUS), particularly those that integrate smart technologies, have proven essential for enhancing sustainability and resilience (RES). Moreover, selected developed cities, such as New York and London, while generally possessing greater resources, face analogous challenges related to climate resilience, ageing infrastructure, and the need for sustainable urban living [18,19]. These cities have increasingly turned to technology-driven strategies to mitigate environmental impacts and improve the quality of urban life.

The quantitative evidence from our study, which demonstrates significant impacts in areas including smart technology integration, resource efficiency, environmental sustainability, and quality of life, reinforces the critical role of AUS in advancing sustainability across diverse contexts [8,14,15]. By situating Nigeria's urban development challenges within the broader context of emerging economies and comparing them with those faced by developing cities, our study extends the existing literature and highlights the universal applicability of our theoretical framework and methodological approach. Policymakers and urban planners worldwide can leverage these insights to design and implement effective, technology-driven strategies that ensure resilient, inclusive, and sustainable urban environments [24]. Ultimately, our findings offer valuable lessons for cities seeking to optimise low-carbon and climate-adaptive urban development strategies [18,19,29].

5.5. *Adaptive urban services (AUS) in fostering resilience (RES) and inclusivity (INC)*

The results from study objective two consolidate robust experts' insights into the role of AUS in enhancing RES and INC within urban environments. These findings not only align with and contribute to the growing body of literature on sustainable urban development but also offer both confirmation and novel contributions that are applicable beyond the Nigerian context. In Nigeria, the results indicate that AUS significantly bolster RES against disruptions such as natural disasters and pandemics. This strong positive impact mirrors the findings of [17], who emphasise experts' adaptive opinion capacities in RES frameworks. However, when comparing these challenges within the broader context of emerging economies, similar patterns emerge. Cities in countries such as India and Brazil also face rapid urbanisation, infrastructure deficits, and resource constraints that necessitate resilient and adaptable urban services. This comparative perspective suggests that the adaptive strategies identified in Nigerian cities could serve as valuable models for other emerging urban centres grappling with analogous issues.

Furthermore, the significance of well-coordinated emergency response systems in Nigeria, as underscored by our findings, resonates with research by [11]. These systems are critical not only in Nigeria but also in other emerging economies where rapid urban growth exacerbates vulnerabilities. Selected developed cities, such as New York and London, though better resourced, similarly invest in responsive and coordinated urban systems to manage crises, demonstrating that the need for adaptive services transcends economic contexts. Regarding resilient infrastructure, our results highlight the necessity of robust energy and transportation networks, a finding that aligns with [13]. While Nigeria and other emerging economies often struggle with ageing or insufficient infrastructure, developed cities continuously work to upgrade their systems to meet increasing demands and mitigate shocks. This comparative analysis underscores that despite differences in economic status, cities worldwide benefit from flexible and resilient infrastructure solutions that can adapt to changing conditions.

Through better access to necessary services, this study validates the function of INC in urban systems. Arnstein's (1969) "Ladder of Citizen Participation," which highlights the significance of INC in urban administration, is echoed by the substantial influence of offering cheap housing and basic services in Nigerian urban areas. Interestingly, emerging economies are not the only ones facing this difficulty. As noted by [43], even mature cities have problems with fair access to public services and smart city technologies. These similarities imply that there are important lessons to be learned for promoting INC in developing urban areas from the adaptive urban service models tested in Nigeria.

There is a stronger need for participatory urban planning; the significant relationship between inclusiveness in urban decision-making corroborates past studies that advocate for participatory approaches, such as those discussed in [1,7],; which emphasise collaboration in planning processes as a pathway to equitable urban development. For PGM, the strong influence of urban planning efficiency and adaptive housing solutions reflects findings by [17]; who identified urban planning as a critical factor in managing the pressures of urbanization. The reduction of informal settlements aligns with [41]; emphasis on formalisation and the provision of affordable housing as pivotal strategies. The adequacy of transportation, energy, and communication infrastructure aligns with studies by [2,23],; which underscore the importance of infrastructure in meeting urban demands. Smart infrastructure deployment resonates with findings from [30]; highlighting the role of technology in addressing urban infrastructure challenges. In connection with the climate change impacts, the reduction in urban heat island effects through adaptive designs mirrors studies like, which emphasise the need for climate-responsive urban designs. Flood and disaster management systems further support findings by [45], on the integration of adaptive systems to mitigate climate risks. For climate-resilient materials, the use of sustainable materials and technologies aligns with studies such as those by [57]; which emphasise the role of green materials in reducing vulnerabilities in urban infrastructure. Overall, the study's model demonstrates a correlation and explanatory power, which are consistent with past models assessing urban RES and INC, such as the study by [7] and [17]. This confirms the validity of explaining the dynamics of AUS. The study's findings emphasise the criticality of integrating AUS to foster RES and INC in smart cities.

5.6. Study's contribution and framework's proposal

This study advances Urban Systems Theory by proposing an integrative framework that systematically links digital innovation with climate-responsive urban planning. By repositioning Adaptive Urban Services (AUS) as both technological enablers and socio-environmental catalysts, the study conceptualises AUS as a connective mechanism through which resource efficiency, environmental sustainability, and quality of life are jointly enhanced within a unified urban system (Fig. 6). Unlike prior studies that examine smart technologies in isolation, this research demonstrates how embedding smart infrastructure within adaptive service systems produces synergistic sustainability outcomes and improved citizen well-being. The proposed Adaptive Urban Service Framework (AUSF), therefore, represents a substantive conceptual contribution, aligning smart city theory with sustainability and resilience paradigms through a coherent and integrative model.

Empirically, the study provides robust evidence that adaptive, technology-enabled urban services exert a significant positive influence on sustainability performance, inclusivity (INC), and urban resilience (RES). The findings confirm that smart AUS function not merely as operational tools but as strategic instruments capable of strengthening environmental performance, improving resource efficiency, and enhancing cities' capacity to respond to infrastructural and climatic pressures. By empirically validating these relationships, the study moves beyond conceptual discourse and positions the AUSF as a data-driven framework with practical relevance for urban planning and service delivery in developing-country contexts. Importantly, the research highlights the interdependence of technological, environmental, and social dimensions in smart city development. Rather than treating digital innovation as an isolated driver, the findings demonstrate that sustainability outcomes and social inclusion are contingent upon the coordinated integration of smart infrastructure, adaptive governance, and inclusive service design. This integrated perspective provides a more nuanced understanding of adaptive urbanism, particularly in rapidly urbanising environments such as Nigeria, where infrastructural limitations and socio-economic inequalities remain pronounced. The study therefore underscores the need for urban policies that embed climate-smart and digitally inclusive planning mechanisms to ensure equitable distribution of the benefits of smart technologies.

Aligned with the United Nations Sustainable Development Goals (SDGs), the proposed framework emphasises the ecological and social value of adaptive service systems in reducing carbon emissions, improving environmental performance, and supporting sustainable urbanisation. The study offers policymakers and urban planners a scalable

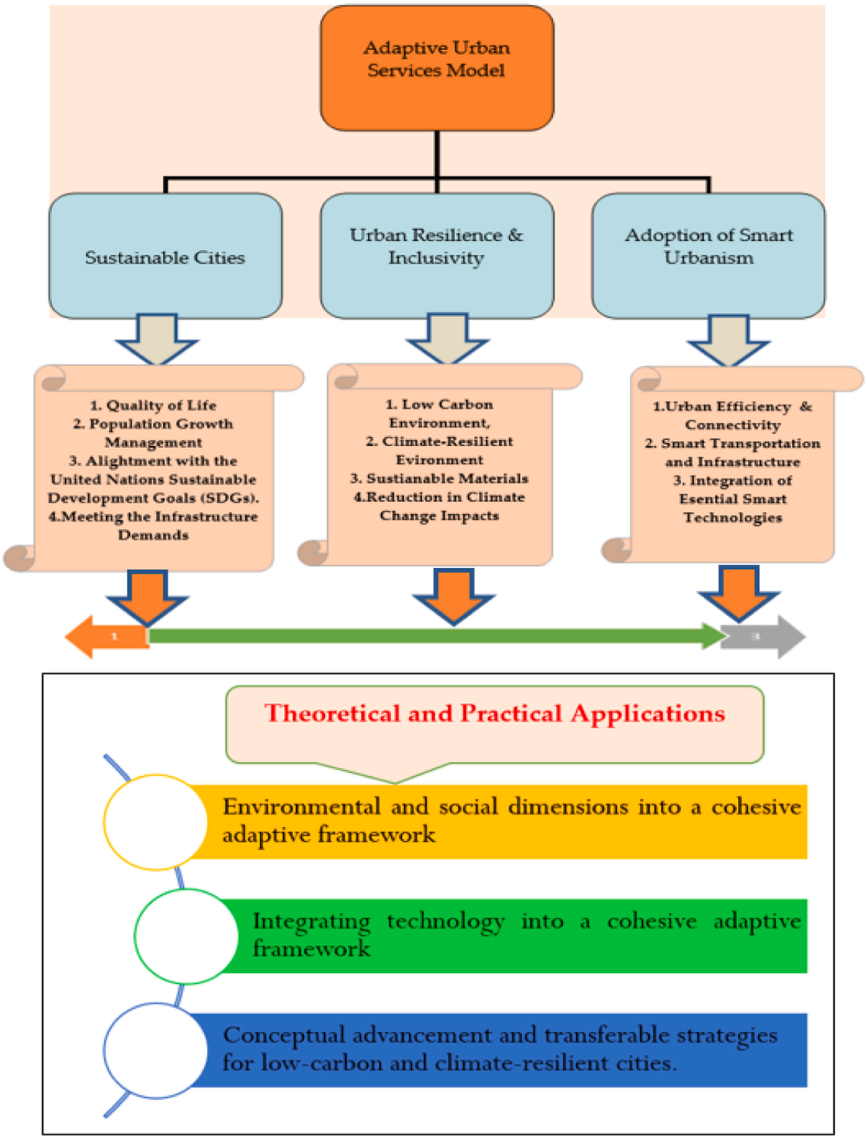


Fig. 6. The study's proposal for rapidly urbanising cities. Source: authors' conceptualisation.

and transferable blueprint for implementing adaptive, low-carbon, and inclusive urban solutions, particularly in developing nations. Overall, the theoretical and practical contributions converge in presenting a coherent framework that integrates technological innovation with environmental sustainability and social equity, thereby extending disciplinary boundaries while offering actionable strategies for building climate-resilient and inclusive urban futures.

6. Conclusion, recommendation and future study

This study demonstrates that the integration of smart technologies within an Adaptive Urban Service Framework (AUSF) provides a viable and systematic pathway for advancing sustainable, resilient, and inclusive urban development, particularly in rapidly urbanising contexts such as Nigeria. The empirical analysis confirms that technology-enabled adaptive service models can effectively address persistent infrastructural deficits and social challenges by enhancing resource efficiency, environmental performance, and overall quality of life. Significant positive relationships were observed between adaptive urban services and sustainability outcomes, indicating that such systems play a critical role in strengthening urban resilience (RES) and inclusivity (INC). These findings reinforce the value of a holistic approach to urban sustainability that integrates adaptive service delivery, smart technologies, environmental stewardship, and social equity within a unified framework.

Although the empirical evidence is grounded in Nigerian cities, the proposed AUSF is conceptually transferable to other rapidly urbanising regions that face comparable challenges related to infrastructure constraints, climate vulnerability, and uneven service provision. Comparative studies across diverse urban contexts are therefore recommended to enhance the external validity of the framework and to assess its applicability under varying institutional, socio-economic, and environmental conditions. The findings further underscore the central role of smart infrastructure investment, efficient resource management, and environmentally responsive urban systems in improving urban liveability. Strengthening data-driven decision-making processes and fostering multi-stakeholder collaboration are essential for improving service delivery and advancing inclusivity. Anchored in resilience theory, the study highlights that adaptive and flexible urban systems not only address present development pressures but also enhance cities' capacity to withstand future environmental and socio-economic shocks. The results provide valuable insights for urban planners, policymakers, and built-environment professionals by identifying expert-informed benchmarks that support evidence-based urban policy formulation and strategic planning. Actionable policy priorities emerging from the study include strengthening emergency response and climate-resilient infrastructure, promoting equitable access to smart technologies through participatory planning mechanisms, and encouraging adaptive design practices that reduce long-term environmental impacts.

Despite its contributions, this study recognises several implementation challenges that may constrain the effectiveness of smart urban solutions in practice. Persistent infrastructure deficits such as unreliable electricity supply, limited broadband coverage, and inadequate data systems can restrict the deployment and performance of technology-enabled urban services, particularly in resource-constrained cities. Policy incoherence and fragmented institutional responsibilities further complicate implementation, often resulting in weak inter-agency coordination, inconsistent regulatory frameworks, and limited integration across urban sectors. In addition, uneven levels of digital literacy among public officials and urban residents may hinder the effective use, maintenance, and uptake of smart technologies, thereby reducing their inclusivity and impact. Finally, the rapid pace of technological change raises concerns regarding the long-term relevance of specific solutions, as some systems may become obsolete before full benefits are realised. These challenges highlight the need for adaptive governance, sustained capacity-building, and continuous empirical validation to ensure that the Adaptive Urban Service Framework remains scalable, context-sensitive, and responsive to evolving urban conditions.

Future research should therefore adopt longitudinal and data-driven approaches to evaluate the long-term effectiveness of adaptive urban services across diverse urban settings. Further investigation into the socio-economic impacts of smart city initiatives is also needed, particularly with respect to accessibility, inclusivity, and quality-of-life outcomes for marginalised and vulnerable populations. In addition, examining public–private partnership models may provide insights into innovative financing and governance arrangements that support sustainable smart infrastructure in resource-constrained environments. By situating Nigeria's urban challenges within a broader, similar context, this study offers transferable lessons for cities seeking low-carbon, climate-adaptive, and socially inclusive development pathways.

Ethical statement

Informed consent was obtained from all individual participants included in the study.

Data availability

All data that support the findings of this study are included within the article (and supplementary files).

CRediT authorship contribution statement

Oluwagbemiga Paul Agboola: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Türkan Irgin Uzun:** Writing – review & editing, Visualization, Software, Methodology. **Hülya Soydaş Çakır:** Writing – review & editing, Validation, Software, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2026.101682.

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