frontiers in Sustainable Cities

TYPE Original Research
PUBLISHED 15 September 2026
DOI 10.3389/frsc.2026.1916019

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OPEN ACCESS

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RECEIVED 22 June 2026
REVISED 30 August 2026
ACCEPTED 31 August 2026
PUBLISHED 15 September 2026

CITATION
Agboola OP and Findikgil MM (2026) Toward climate-resilient cities: advancing sustainable and inclusive urban development through smart technologies in South-Western Nigeria. *Front. Sustain. Cities* 8:1916019. doi: 10.3389/frsc.2026.1916019

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Toward climate-resilient cities: advancing sustainable and inclusive urban development through smart technologies in South-Western Nigeria

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This study develops an integrative framework that combines a quantitative explorative study with a qualitative assessment of Urban Inclusivity (UI) to assess inequality in rapidly growing cities in Southwestern Nigeria. The objectives were to: (i) To assess the effectiveness and perceived performance of Adaptive Urban Service Delivery (AUSD); (ii) To assess the level of Adaptive Urban Services Delivery (AUSD) within smart environments; (iii) To identify and empirically validate the underlying dimensions and interrelationships of Adaptive Urban Service Delivery (AUSD); (iv) To determine the relative effects and contributions of Adaptive Urban Service Delivery (AUSD) to promote Smart Urban Environments (SUE); (v) To evaluate Urban Service Satisfaction (USS) and qualitative assessment of Urban Inclusivity (UI) across the eight case study cities in Southwestern Nigeria. Survey data from 402 respondents were analyzed using SPSS Version 22 through descriptive statistics, Chi-square analysis, multiple regression, one-way ANOVA, and Tukey HSD post hoc tests. The regression analysis revealed that resilience ($\beta = 0.357$, $p < 0.001$) was the strongest predictor of Adaptive Urban Services Delivery (AUSD), followed by inclusivity ($\beta = 0.291$, $p < 0.001$), Population Growth Management (PGM) ($\beta = 0.236$, $p < 0.001$), Infrastructure Demands (ID) ($\beta = 0.214$, $p < 0.001$), and Climate Change Impacts (CCI) ($\beta = 0.188$, $p < 0.001$). The overall regression model demonstrated substantial explanatory power ($R = 0.865$, $R^2 = 0.748$, Adjusted $R^2 = 0.744$, $F = 291.63$, $p < 0.001$). The ANOVA results revealed statistically significant differences in respondents' satisfaction with Adaptive Urban Services Delivery (AUSD) across the eight selected cities ($p < 0.001$). The Urban Inclusivity (UI) assessment also identified notable spatial variation, with Akure recording the highest inclusivity score (7), followed by Osogbo (6), while Lagos and Abeokuta recorded the lowest scores (3). Taken together, these findings indicate that AUSD is a multidimensional phenomenon involving technological capacity, infrastructure provision, inclusive governance, and climate responsiveness. These dimensions may contribute to improved Urban Resilience (UR), and AUDS when appropriately integrated. The proposed framework provides a context-sensitive approach for examining smart and inclusive urban development in rapidly urbanizing regions of developing countries. However, further empirical validation across other geographical and urban contexts is required to assess its broader applicability and transferability.

KEYWORDS

Adaptive Urban Services Delivery (AUSD), Climate Change Impacts (CCI), Environmental Sustainability (ES), Quality of life (QoL), Smart Urban Technologies (SUT), Sustainable Urban Development (SUD), Urban Inclusivity (UI), Urban Resilience (UR)

1 Introduction

Recent population projections indicate that the global population will continue to increase substantially, reaching approximately 9.5 billion by 2050 (United Nations Department of Economic and Social Affairs, Population Division 2024). This growth is occurring alongside rapid urbanization, particularly in Africa and Asia, where cities are expected to accommodate a substantial share of future population growth (O'Farrell et al., 2019). Sub-Saharan Africa is experiencing particularly rapid urban expansion, placing increasing pressure on infrastructure, public services, housing, natural resources, and environmental systems. Unplanned or poorly managed urban growth may contribute to increased waste generation, greenhouse-gas emissions, pollution, resource depletion, and biodiversity loss. These challenges highlight the need for innovative and adaptive approaches to urban development that can respond to changing demographic, environmental, and infrastructural conditions while ensuring that the needs of growing urban populations are met.

Smart city transformations integrate computerisation and the latest technologies, bringing forth the era of smart city development. The idea of a smart environment has evolved over the past few years as a significant research area that primarily aims at dealing with urban challenges, given the rapid urbanization of cities and has been broadly employed in recent urban planning (Bibri and Krogstie, 2020; Alotaibi et al., 2024). The backbone of this is Information and Communication Technologies (ICT), which are evolving into adaptive systems with the capacity to respond dynamically to changes in the temporal, spatial, and environmental domains (Folke et al., 2003; Rammel et al., 2007). They use real-time data in the urban service deliver to improve resource management, reduce costs, and increase operational efficiency. All this becomes important within the scope of truly responding to the challenges of urban life, which become problematic mostly when existing hardware and network constraints restrict such responsive areas. Thus, Adaptive Urban Services Delivery (AUSD) provide a unique opportunity to resolve issues of population growth, environmental disasters, and scarcity of resources in the context of a smart city, such services being so oriented by digital technologies, the Internet of Things, and data analytics (Kumar et al., 2020). The focus has recently switched to more complex technologies that are driving urban growth and are supported by broadband networks and collective intelligence.

To enhance liveability, achieve Environmental Sustainability (ES) and foster a more open and innovative urban environment, with the contribution of a multitude of stakeholders, Information and Communication Technologies (ICTs) are now considered as critical enablers in municipal government and management (Geropanta, 2020; Agboola et al., 2015). Placed at the service of smart technologies, such as Internet of Things sensors and devices, the city can rely on the data gathered and processed in real-time and at all levels in order to respond to challenges and emerging opportunities. This allows the municipality to take swift and well-informed decisions while ensuring reactive and effective measures to changing circumstances. In addition, adaptive systems allow for creating a resilient and sustainable environment for urban regions by facilitating proactive measures and optimal resource governance (Folke et al., 2003; Rammel et al., 2007). These technologies are helpful as urban areas continue growing in size and changing due to the complexities of urbanization, while also ensuring (ES), and a better Quality of Life (QoL) for residents.

Being the most populous city and a key economic hub in Nigeria, Lagos was estimated to have about 21 million residents; hence, classified as a megacity (Alotaibi et al., 2024; Doussard et al., 2024; Alabi et al., 2025). The rapid nature of its urbanization and that of other major cities in Southwest Nigeria has placed immense pressure on its infrastructure, resource management, and ES. Hence, a need for innovative responses to such urban challenges. The same urban challenges are being experienced in other major cities in terms of their road networks, drainage systems, and power grids, which are often stretched beyond their limits by their growing population. Also, traffic congestion reduces productivity and contributes to air pollution, further deteriorating the QoL in these cities. These, therefore, necessitate integrating Smart Urban Technologies (SUT), such as predictive infrastructure maintenance, to greatly enhance related urban mobility, energy distribution, and water resource allocation among others (Alshaflut, 2024; Batty, 2008; Zygiaris, 2013; Van Hoang, 2024). Based on these multidimensional challenges, this study aims to propose models for AUSD frameworks with integrated smart technologies that inspire and promote healthy city growth, which will increase resilience, optimize resource utilization, and social inclusion in Nigeria. Objectives of the study include:

- RO1. To assess the effectiveness and perceived performance of Adaptive Urban Service Delivery (AUSD);
- RO2. To assess the level of Adaptive Urban Service Delivery (AUSD) within Smart Urban Environments (SUE);
- RO3. To identify and empirically validate the underlying dimensions and interrelationships of Adaptive Urban Service Delivery (AUSD);
- RO4. To determine the relative effects and contributions of Adaptive Urban Service Delivery (AUSD) to promote Smart Urban Environments (SUE);
- RO5. To assess the Urban Service Satisfaction (USS) and qualitative assessment of Urban Inclusivity (UI) across the eight case study cities in Southwestern Nigeria

The study examines the contribution of AUSD to sustainable and efficient urban development. The integration of smart technologies into AUSD can help cities reduce environmental pressures, improve resource management, and enhance quality of life (QoL). These functions are particularly relevant to Nigeria and other developing countries, where cities face interconnected challenges related to infrastructure, environmental change, population growth, and social inclusion. Against this background, the study evaluates Adaptive Urban Service Delivery (AUSD) in eight selected cities in Southwestern Nigeria, with emphasis on its contribution to resilient, sustainable, and inclusive smart urban environments. Specifically, the study assesses the effectiveness and perceived performance of AUSD; examines the level of AUSD within smart urban environments; identify and empirically validate the underlying dimensions and interrelationships of AUSD; determine the relative effects and

contributions of AUSD to the development of Smart Urban Environments (SUE); and evaluate Urban Service Satisfaction (USS) and the qualitative assessment of UI across the selected case-study cities.

Accordingly, the study develops an evidence-based understanding of how AUSD, supported by smart technologies, can improve urban infrastructure, optimize resource utilization, enhance service responsiveness, and promote social inclusion. By addressing these objectives, the paper contributes empirical evidence on the potential of AUSD frameworks to support Sustainable Urban Development (SUD) and Urban Resilience (UR) in rapidly urbanizing contexts. The findings are expected to provide useful insights for urban planners, policymakers, infrastructure managers, and other stakeholders seeking to design and implement more responsive, efficient, inclusive, and sustainable urban service systems in Nigeria and other developing-country contexts.

In relation to the manuscript's organization, the first section of the manuscript dealt with the introduction and review of literature related to the research subject. The second part related to the study's method to execute the research objectives, followed by the third segment focusing on the analysis of results and discussions. The study's last section concludes with actionable recommendations to strengthen Environmental Sustainability (ES) and Urban Resilience (RE), through AUSD in Nigeria.

2 Review of literature

2.1 Study's gap matrix

Several studies have examined the roles of technology, infrastructure, and integrated systems in advancing smart-city development (Batty, 2008; Zygiaris, 2013; Van Hoang, 2024). Other research has assessed how smart technologies can improve the efficiency, accessibility, and convenience of urban service delivery (Bibri and Krogstie, 2020; Alotaibi et al., 2024; Geropanta, 2020). However, much of this literature has focused primarily on technological and infrastructural capabilities, with comparatively limited attention to the adaptive capacity of urban services to respond to the changing needs of urban populations. This limitation is particularly relevant in developing countries, where inadequate infrastructure, institutional constraints, digital inequalities, and limited financial resources may restrict the effective implementation of smart-city technologies. Similarly, previous studies have investigated the contribution of urban systems to sustainability and resilience (Meerow et al., 2016; Sharifi, 2016; Nghiem et al., 2026), but much of this research has been undertaken in contexts characterized by relatively strong institutions, established infrastructure, and greater capacity to implement long-term climate and urban development strategies (Nghiem et al., 2026; Adelekan, 2016). These conditions differ considerably from those found in many developing countries, where rapid urbanization, informal settlements, infrastructure deficits, governance challenges, and resource constraints create additional barriers to sustainable urban transformation. Nigerian cities therefore provide an important context for examining how AUSD can contribute to smart, sustainable, and resilient urban development. Despite growing interest in smart cities and UR, the application of adaptive urban service approaches within the Nigerian context remains comparatively underexplored. This study addresses this gap by examining the role of AUSD in supporting sustainable and resilient smart urban development in Southwestern Nigeria, drawing on Urban Systems Theory (UST) as the underlying conceptual perspective.

Furthermore, this study advances science by focusing on the role of AUSD in promoting inclusive and resilient smart cities. UST has been used extensively to understand the relationships between transportation and climate change (Bretagnolle et al., 2006). However, the role of this theoretical framework in promoting AUSD is not well established. Most previous studies have focused on transportation and environmental systems while paying limited attention to the urban service provision processes. Thus, there is a need to understand how various urban systems can be adapted to promote UR. In view of this, this study explores the adaptation processes in urban service provision. Understanding the role of AUSD will promote the development of more effective policies and strategies for promoting sustainable cities. From another point of view, previous studies have focused on examining the factors that contribute to inclusive smart cities. For instance, inclusivity has been achieved through the provision of digital infrastructure and services (Das, 2024; Caird and Hallett, 2019). However, the ability of an AUSD to meet the diverse needs of the urban poor is rarely examined. While inclusive cities emphasize the need for meeting the needs of all citizens, it is important to assess if the service system can deliver the intended results. It is on this premise that this paper addresses this gap by examining the relationship between inclusive AUSD and SUE.

2.2 Urbanizing responsibly toward sustainable and inclusive strategies

Rapid urbanization has become one of the main challenges of sustainable development, especially in developing countries where urban population growth often outpaces essential infrastructure and public services. While smart city initiatives have often focused on technological innovation and digital transformation, new evidence indicates that technology alone is unable to address the fundamental imbalances embedded into rapidly expanding urban environments. Several smart city initiatives run the risk of exacerbating existing inequalities as they prioritize technologies without considering the needs of vulnerable communities, which has led to an increasing recognition that responsible urbanization should consider technological innovation as well as inclusive planning, equitable service delivery and citizen participation.

Nigeria is a good example of the kinds of urbanization challenges that are being faced. With an annual urban population growth rate of ~4.3% and five of Africa's thirty largest cities, Nigeria is one of the fastest urbanizing countries on the continent (United Nations Department of Economic and Social Affairs, Population Division 2024). Projections indicate that Nigeria's urban population will double by 2037 and put immense pressure on housing, transportation networks, water supply, energy systems, waste

management, and other critical urban services (United Nations, Department of Economic and Social Affairs, Population Division 2018). While urbanization has generated economic opportunities and accelerated infrastructure development, it has also exacerbated the expansion of informal settlements, environmental degradation, traffic congestion, inadequate public services, and reduced urban liveability (Khorrami et al., 2021; Valcárcel-Aguiar et al., 2019). However, while existing literature has extensively documented these challenges, much of the research is problem-oriented and there has been comparatively limited attention to developing integrated adaptive strategies that can simultaneously improve UR, UI, and service responsiveness. This imbalance necessitates devising urban development schemes that go beyond the provision of traditional infrastructure and transition to AUSD that are responsive to emerging demands (O'Farrell et al., 2019).

Recent studies have emphasized climate-sensitive strategies such as compact and mixed developments, provision of affordable housing, adoption of renewable energy, and enhanced green building design for sustainable cities (Grace et al., 2023). Although these strategies have huge potential, most previous studies examine them as independent variables in isolation without understanding their interaction and integration within a broader framework of urban processes and systems. Similarly, there has been limited focus on leveraging their combined potential through AUSD that are responsive to evolving built and natural environments and accommodate diverse human needs. Failure to adopt this integrative approach undermines the ability to achieve smart urbanization that addresses the multifaceted challenges of urbanization.

The notion of sustainable development requires not only adapting the existing built environments to enhance the wellbeing of society but also ensuring that the processes are environmentally sustainable and conserve or restore the degraded systems (Taheri et al., 2026). Thus, the role of urban planning in promoting smart city development should be geared toward building adaptive capacity to environmental changes by reducing vulnerability to the impacts of disasters and climate change while also promoting sustainable development. The key to achieving sustainable cities lies in balancing development needs and conservation efforts while also reducing greenhouse gas (GHG) emissions that are primarily generated in the built environment, transport, and energy supply sectors (Albino et al., 2015). By shifting to sustainable production and consumption of energy, smart cities can increase production rates while also lowering GHG emissions compatible with sustainable development (Agboola, 2026).

This review shows that sustainable urbanization requires more than just smart technologies; it also requires the interrelated social, economic, and environmental dimensions of urban development. In other words, climate-smart and adaptive urban development will involve the combined potential of smart technologies, adaptive urban systems, resilience and responsive governance, to promote sustainable development. This is compatible with the broader objective of achieving multiple sustainable development goals (SDGs) through optimized use of urban resources, improved service delivery, improved governance structures, citizen-oriented development and environmental conservation. As such, while attempting to fill the gap, this study explores how AUSD, bolstered by SUT to promote resilient, inclusive, and sustainable urban growth in fast urbanizing Nigerian cities and is conceptually grounded in this integrated perspective.

AUSD, therefore, emerged as a vital paradigm for developing sustainable urban cities. AUSD differ from traditional approaches to urban service delivery in that they use modern technology and connection to provide more responsive, efficient, and reliable services (Meerow et al., 2016). In addition, through AUSD, the emphasis is placed on delivering services based on the needs and wants of the citizens rather than on the centrality of technology to urban development. However, there is insufficient empirical evidence on the role of AUSD and sustainable urban outcomes in achieving inclusive governance, user satisfaction, and sustainable urbanism.

The role of renewable energy technologies, smart water systems, smart grids, and green technologies in promoting ES and UR has been established (Adeshina et al., 2024; Agboola and Nia, 2025). However, most previous studies have focused on reviewing the role of individual technologies in isolation while ignoring their role in combination with governance, citizens, and responsive services to promote UR. As a result, there is a need to develop a framework that combines climate adaptation strategies and AUSD within the context of smart governance to achieve sustainable urbanism. However, studies on the ability of AUS to achieve sustainable urbanism by considering governance, infrastructure, utilities, transportation, environment, and communities are minimal. This study, therefore, seeks to fill this research gap by developing and empirically testing a theoretical framework for achieving sustainable urbanism in Nigeria.

3 Conceptual framework, variable measurement and analytical procedures

3.1 Conceptual framework

Urban System Theory (UST) conceptualizes cities as complex adaptive systems consisting of interconnected social, physical, technological, economic, and ecological subsystems (Bettencourt, 2021; Storper and Scott, 2016). From this perspective, urban systems are subject to pressures from within (e.g., population growth, demographic change, infrastructural limitations, and rising demands for public services) and external to the system (e.g., pandemics, environmental degradation, and climate change). A city's capacity to maintain its essential functions amid such pressures is determined by its ability to anticipate risks, adapt to the new reality, respond to shocks, and recover while maintaining or improving its essential functions. As such, this study considers CCI as a key aspect of UR (Sharifi, 2016; Nghiem et al., 2026).

Within the theoretical framework, smart technologies offer technological and informational capabilities that can contribute to building resilient urban systems. Technology-enabled AUSD can facilitate continuous monitoring, timely information exchange, predictive decision-making, efficient resource allocation and responsive service delivery (Bibri and Krogstie, 2020; Albino et al., 2015). IoT networks, digital data platforms, remote sensing systems

and real-time analytics can function as feedback mechanisms within urban systems by collecting, analyzing and transmitting information on changing environmental and urban conditions (Agboola, 2026). Such capabilities can enhance climate adaptation by promoting risk identification and preparedness, improving the responsiveness of infrastructure and services and guiding climate-informed urban planning. As such, the conceptual framework described in this study establishes connections between smart and adaptive urban technologies, CCI and UR and sustainability outcomes. Notably, while the conceptualization assumes that technological advancement can build UR, its effectiveness is dictated by the extent to which it enhances adaptive capacity and is used to respond to climate-related pressures.

This study conceptualized CCI as a mechanism through which technology-enabled urban services can be translated to improved resilience outcomes, while inclusivity and digital equity are treated as cross-cutting conditions for ensuring that the benefits of smart and adaptive urban development are equitably distributed. Collectively, these perspectives indicate that smart technologies function primarily as enabling mechanisms for strengthening urban adaptive capacity. The framework therefore incorporates inclusivity, citizen satisfaction, and sustainability as complementary dimensions of urban performance and provides a basis for quantitatively examining the relationships among these constructs in rapidly urbanizing environments.

As illustrated in Figure 1, the conceptual framework positions CCI as a central mechanism linking smart and AUSD with climate-resilient and sustainable urban outcomes. The framework therefore moves beyond the assumption that technological adoption directly produces UR. Instead, it proposes that smart technologies provide information, monitoring, communication, and decision-support capacities that can strengthen climate adaptation, while effective adaptation can translate these technological capabilities into improved resilience and sustainability outcomes. On the other hand, smart technologies in cities can have direct impacts on urban outcomes through more efficient provision of services, effective resource management, increased institutional responsiveness, and improved decision-making. The proposed relationships thus recognize both the direct and indirect role of smart technologies via CCI.

This study's framework is multi-layered, taking into account economic, social, environmental, and technological aspects of urban adaptation, as well as the adaptation capacity itself. The economic layer includes such indicators as cost-effectiveness, resource efficiency, scalability of solutions, and long-term viability and sustainability of adaptation options. The social layer emphasizes the value of digital inclusion and accessibility of smart technologies, community engagement, participation, and general access to services. The environmental layer highlights the importance of environmental sustainability, conservation of resources, and reliance on renewable energy sources. The technological layer considers the use of ICT, smart tools, and sensors, as well as the availability of information and data. Finally, the adaptation capacity is concerned with the ability to anticipate, respond to, and recover from climate impacts. Thus, smart technologies can be seen as enablers of climate adaptation and UR (Sharifi, 2016; Nghiem et al., 2026). Their role is determined by their capacity to contribute to adaptation, which in turn depends on the extent to which they promote awareness and preparedness, support responsive governance, foster adaptive planning, manage resources efficiently, and ultimately ensure effective AUSD. This framework allows a more comprehensive assessment of the contribution of smart technologies to building CCI in cities (Bibri and Krogstie, 2020; Ahvenniemi et al., 2017).

3.2 Variable measurement and analytical procedures

The measurement of variables, and the constructs examined in this study were operationalised through composite indices following factor validation. Measurement items were adapted from established conceptualisations and indicator frameworks in the smart city, urban sustaiability, CCI and UR literature (Bibri and Krogstie, 2020; Meijer and Bolívar, 2016). Smart sustainable city frameworks, for example, identify ICT infrastructure, digital monitoring, technology-enabled services, resource management, environmental performance and social inclusion as important dimensions of urban development (Kim, 2025). Similarly, UR research highlights adaptive capacity, preparedness, response, and the ability of urban systems to maintain essential functions under climate-related disturbances (Sharifi, 2016; Nghiem et al., 2026). The use of established measurement dimensions provides a theoretically grounded basis for assessing the constructs and strengthens the content validity of the measurement framework. The study's conceptualization highlights the relationships among AUSD, CCI, UR, ES, and UI. AUS were measured using indicators reflecting real-time responsiveness, smart infrastructure deployment, ICT-enabled service delivery, information monitoring and the capacity of urban services to respond to changing conditions. These indicators are consistent with established smart sustainable city performance frameworks, which identify ICT infrastructure, digital monitoring, dynamic public services, and technology-enabled resource management as important components of SUD (Kim, 2025; Esteban-Narro et al., 2025). They also correspond with research emphasizing the role of information, monitoring, and responsive service systems in strengthening urban adaptive capacity (Sharifi, 2016; Nghiem et al., 2026). AUSD therefore represent the technological and operational foundation through which urban systems can improve their responsiveness to climate-related and other urban pressures.

CCI constitutes a central analytical dimension of the framework. It captures the extent to which urban systems are capable of anticipating, preparing for, responding to, and adjusting to climate-related risks and changing environmental conditions. This operationalisation is consistent with established adaptation frameworks that emphasize preparatory measures, vulnerability reduction, and strengthening adaptive capacity (Esteban-Narro et al., 2025; Turner et al., 2026; Baraka Munyaka et al., 2026). In the context of AUSD, adaptation is understood as the process through which technological and institutional capacities are translated into practical actions, including climate-risk monitoring, responsive planning, adaptive infrastructure management, efficient resource

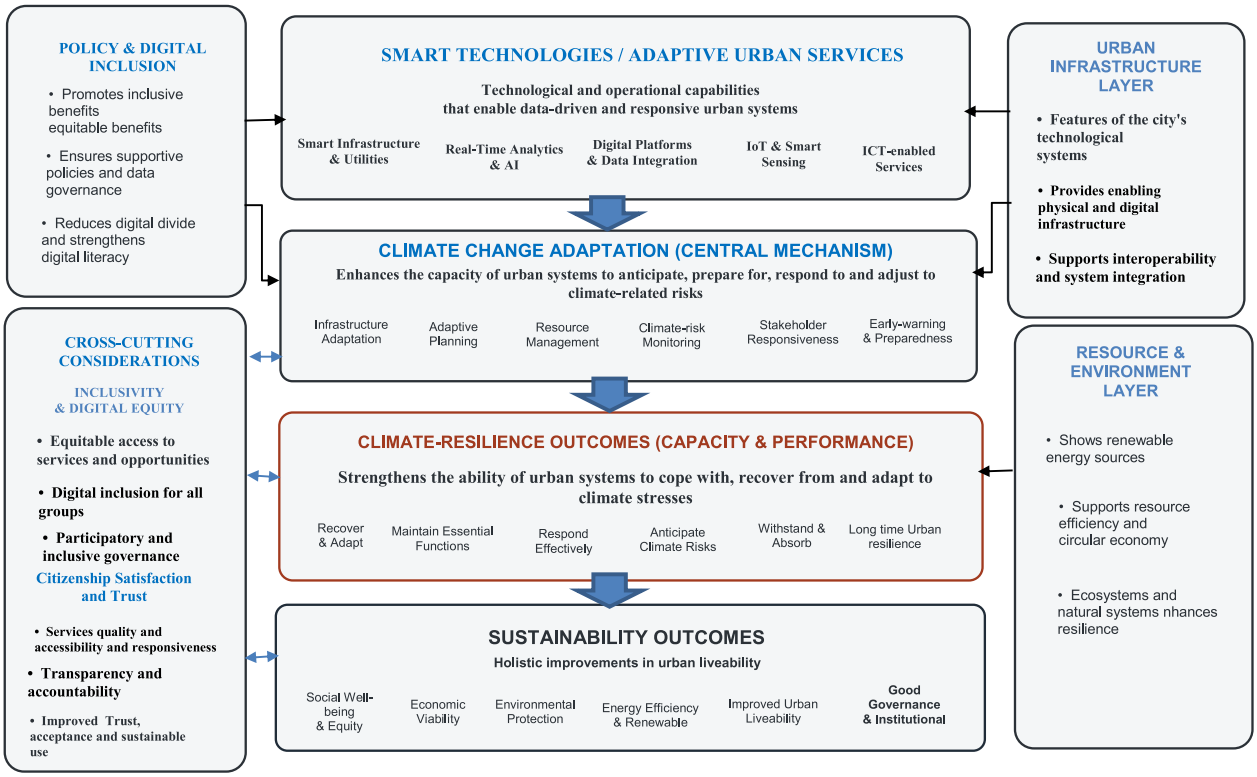


FIGURE 1
Study's conceptual model. Source: Developed by the authors.

utilization, preparedness, and improved responsiveness of urban services. Thus, CCI represents an important pathway through which smart and adaptive technologies can contribute to UR (Sharifi, 2016; Nghiem et al., 2026).

Sustainability outcomes were assessed using indicators relating to energy efficiency, environmental protection, resource efficiency, and overall urban liveability. These dimensions are consistent with established urban sustainability assessment frameworks that incorporate environmental performance, resource use, energy, social conditions, and liveability as dimensions of SUD (Leach et al., 2017; Shamaee et al., 2024; Alzaim et al., 2024). The International Telecommunication Union (ITU) framework similarly incorporates environmental quality, energy efficiency, resource management, and social dimensions within the assessment of smart sustainable urban performance (Kim, 2025; Esteban-Narro et al., 2025). Within the present framework, sustainability is considered alongside climate resilience, recognizing that sustainable urban systems should not only improve environmental and resource performance but also maintain essential services and adapt to changing climatic conditions.

Inclusivity was evaluated through perceptions of equitable access to urban services, digital inclusion, accessibility, and participation in urban governance and decision-making. These dimensions reflect the social components of smart sustainable cities, where equitable access to ICT, information, services, and opportunities for participation is considered important for SUD (Kim, 2025; Esteban-Narro et al., 2025). Inclusivity is therefore treated as an enabling condition because technological and adaptation interventions may generate uneven outcomes when access to digital infrastructure, information, services, and decision-making processes is unequal. Citizen satisfaction was measured through indicators relating to perceived service quality, accessibility, responsiveness, and transparency in service delivery. These indicators provide an outcome-oriented assessment of residents' perceptions of urban service performance and are consistent with service-performance and urban liveability approaches (Shamaee et al., 2024; Alzaim et al., 2024). Citizen satisfaction consequently provides a resident-level perspective for assessing whether improvements in technological and institutional capacities are reflected in perceptions of urban service provision.

Following variable operationalisation, the study employed a sequential analytical framework in which each research objective was addressed using an appropriate analytical technique and generated outputs that informed subsequent stages of the investigation. Table 1 summarizes the research objectives, analytical approaches, and corresponding target outputs, thereby establishing a transparent methodological link between the study objectives and the empirical procedures used to address them. Overall, the combined measurement and analytical framework provides an empirical basis for examining how AUSD, AUS, CCI, UR, ES, and UI interact in shaping more inclusive, resilient, and responsive SUE in Southwestern Nigeria. The approach also ensures that the interpretation of the findings remains directly connected to the study's conceptual framework and research objectives.

TABLE 1 Summary of research objectives; analytical approach and proposed target output.

Research objective	Analytical approach	Proposed target output
RO1. To assess the effectiveness and perceived performance of AUSD.	Descriptive analysis of AUSD dimensions.	AUSD performance assessment, identifying strengths and gaps across five service domains.
RO2. To assess the level of AUSD within SUE.	Descriptive assessment of AUSD.	Assessing AUSD such as UR, infrastructure adequacy, PGM, CCI, and UI challenges.
RO3. To identify and empirically validate the underlying dimensions and interrelationships of AUSD.	(i) Principal Component Analysis (PCA) and (ii) Pearson's Chi-square analysis.	Empirically validating the five dimensions of AUSD structure and their interrelationships.
RO4. To determine the relative effects and contributions of AUSD to promote inclusive and RSUE.	Multiple regression analysis.	Determination of AUSD predictive model, demonstrating the relative contribution and predictive importance of the five dimensions.
RO5. To evaluate USS; UI Assessment Across the Eight Case Study Cities in Southwestern Nigeria.	(i) Descriptive statistics, (ii) One-way ANOVA and Tukey HSD Post-hoc analysis; (iv) Communalities analysis; (v). UI assessment and spatial visualization.	(i) Validated AUSD factor structure, confirming that all five dimensions substantially contribute to explaining AUSD performance; (ii) Comparative USSD assessment, demonstrating statistically significant spatial differences among the eight cities; and UI Scores across Southwestern cities in Nigeria.

4 Materials and methods

4.1 Description of the study area and justification for case selection

The study was conducted in eight cities in South-Western Nigeria: Ado-Ekiti, Lagos, Ibadan, Ogbomoso, Ile-Ife, Abeokuta, Akure, and Osogbo (Figure 2). The study sites were between 6°N to 9°N and 2°E to 6°E in latitude and longitude, respectively. It includes one megacity, Lagos, with an estimated population of 21 million and two large cities, Ibadan and Abeokuta, with populations of 1 and 5 million, respectively. Apart from that, the study sampled two medium-sized cities, Osogbo and Ado-Ekiti, with populations of 0.5–1 million, and one small city, Ogbomoso, and Ile-Ife, with populations less than 0.5 million. The selected cities differed in developmental status, administrative functions, commercial values, and infrastructural facilities for assessing the variations in the respondents' perceptions toward AUSD. Additionally, the eight study cities were selected using a criterion-driven, purposive case-selection strategy informed by the principles of purposeful and maximum-variation sampling (Patton, 2002; Palinkas et al., 2015). This approach was considered appropriate because it enabled the selection of cases that could provide relevant and diverse insights into the research questions. The selection was not intended to achieve statistical representativeness of the wider population; rather, it was designed to capture meaningful variation in urban characteristics relevant to the study objectives (Patton, 2002; Palinkas et al., 2015). Maximum-variation case selection further facilitates the examination of a phenomenon across cases that differ substantially in characteristics considered relevant to the research problem, thereby enabling a broader understanding of patterns and contextual differences across the selected cities (Seawright and Gerring, 2008).

The selection criteria were established a prior to ensure meaningful variation in the urban contexts within which AUSD are experienced and evaluated. In the first instance, urban scale and population-related development pressures were considered. The selected cities represent different levels of urban development, ranging from the highly urbanized Lagos metropolitan area and major regional centers such as Ibadan and Abeokuta to medium-sized administrative and educational centers, including Akure, Ado-Ekiti, and Osogbo, as well as smaller urban centers such as Ile-Ife and Ogbomoso. This variation is relevant because differences in urban scale, population pressure, and development intensity may influence demand for infrastructure, housing, mobility, public services, digital connectivity, and other adaptive urban systems. The diversity of urban contexts therefore provides a basis for examining how AUSD are perceived and experienced under different levels of urban development pressure (Patton, 2002; Palinkas et al., 2015; Seawright and Gerring, 2008). In addition, functional and administrative diversity was considered to capture differences in the roles and service demands of the selected cities. The cases include major commercial, educational, administrative, cultural, and service centers, thereby providing varied contexts for assessing AUSD, inclusivity, and sustainability. The differences in infrastructure, digital connectivity, technological development, and smart-city initiatives were considered to capture variation in adaptive service capacity. The geographical and socio-economic diversity was incorporated to reflect contextual differences that may shape urban development and residents' perceptions. Together, these criteria support comparative analysis across contrasting urban contexts, consistent with previous case-selection approaches (Henderson, 2002; Dodman et al., 2023). Finally, data accessibility and research feasibility were considered to ensure that the selected cities could support effective survey administration and provide sufficient contextual information for meaningful comparison. These practical considerations are consistent with purposive case-selection principles when explicitly aligned with the study objectives (Palinkas et al., 2015; Seawright and Gerring, 2008). Accordingly, the eight cities were not intended to be statistically representative of all cities in Southwestern Nigeria; rather, they were purposively selected to maximize contextual variation and facilitate

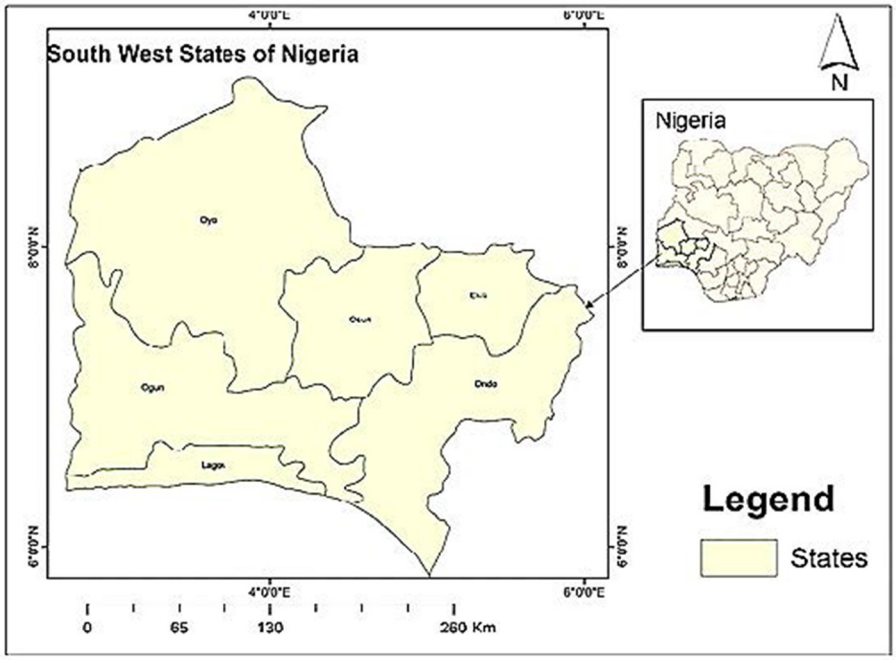


FIGURE 2
Case study areas' map. Source: Grace et al. (2023).

comparison of respondents' perceptions of AUSD across different urban settings (Kara et al., 2026; Başegmez and Dogan, 2025).

4.2 Quantitative survey and study's participants

This study adopted a quantitative cross-sectional survey design to examine respondents' perceptions of AUSD, UR, RE, and USS across selected cities in Southwestern Nigeria. A structured questionnaire was developed based on the research objectives and relevant literature. In addition to demographic and location information, the questionnaire comprised three main sections addressing: (i) the effectiveness and level of AUSD; (ii) key dimensions of AUSD, including RE, UI, PGM, ID, and CCI; and (iii) respondents' USS, and perceptions of UI. All measurement items were assessed using a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree, consistent with established quantitative approaches for measuring perceptions and relationships among urban development constructs (Bibri and Krogstie, 2020; Meijer and Bolívar, 2016; Creswell, 2012).

Before statistical analysis, all returned questionnaires underwent a systematic data-quality screening procedure based on predefined eligibility and response-validity criteria. Responses were excluded where they exhibited substantial incompleteness, duplicate submissions, failure to satisfy the study eligibility requirements, or clear inconsistencies and invalid response patterns. This screening was conducted consistently across all responses before the final analytical dataset was established. The procedure was intended to minimize potential sources of response bias and measurement error while ensuring that only sufficiently complete, eligible, and internally consistent responses were included in the analysis. The use of predefined screening criteria also provided a transparent and reproducible basis for determining the final sample and was informed by established methodological guidance on survey data screening and quality control.

The study population comprised residents/citizens and relevant professionals and stakeholders involved in, or directly affected by, urban planning, infrastructure development, smart city initiatives, and AUSD across the six states of Southwestern Nigeria. The professional and stakeholder participants included urban planners, architects, civil engineers, environmental managers, transportation specialists, ICT professionals, housing experts, energy managers, government officials, and academics whose professional responsibilities relate to urban development and service provision. Residents were also included to provide direct user-based perspectives on urban service accessibility, inclusivity, responsiveness, digital access, and citizen satisfaction. The inclusion of both residents and professionals/stakeholders was intended to provide complementary perspectives on the technological, institutional, infrastructural, social, and experiential dimensions of smart and climate-resilient urban development.

Because a comprehensive sampling frame covering the diverse population of residents, professionals, and stakeholders relevant to the study was not available across the six states, non-probability snowball sampling was employed to facilitate participant recruitment. This approach is particularly useful for reaching geographically dispersed and specialized participant groups that were difficult to identify through conventional probability sampling methods (Kaluarachchi, 2021). Initial participants were approached through relevant professional

associations, government agencies, universities, community and social networks, and other established institutional and professional contacts. Participants were subsequently invited to share the online questionnaire with other eligible individuals within their respective networks. This recruitment strategy enabled the study to incorporate both professional/stakeholder expertise and residents' experiential perceptions, thereby providing a broader empirical basis for examining UI, citizen satisfaction, AUSD, CCI, and UR outcomes. To ensure transparency regarding the limitations of the sampling strategy, the study recognizes that snowball sampling is a non-probability technique and therefore does not guarantee statistical representativeness of the wider population of Southwestern Nigeria. Accordingly, the findings are interpreted as reflecting the perceptions of the surveyed respondents rather than as population-wide estimates. The socio-economic characteristics of the participants further demonstrate the diversity of the respondents, including the participation of residents alongside professionals and other relevant stakeholders.

4.3 Urban inclusivity assessment and spatial analysis

UI is defined as the degree to which society and its members can equally access and participate in cities' services and resources regardless of their economic status, gender, age, disability, ethnicity, and location (Rigon and Broto, 2021; Adeboyejo et al., 2022). In other words, it presents the extent to which AUSD delivers smartly integrated solutions that enable all population groups to equally benefit from emerging urban environments and engage in the ongoing sustainable development process notwithstanding their socio-economic characteristics (Bibri and Krogstie, 2020). Similar to prior research, UI conceptualization incorporates elements such as digital inclusion, access to essential services and transportation, the level of sustainability, and AUS for vulnerable and disadvantaged groups (Townsend, 2013). Therefore, the UI assessment relied on the respondents' views on the accessibility and level of satisfaction with urban services, fairness, and digitalisation to align with the goals of Sustainable Development Goal (SDG) 11 and the New Urban Agenda (Rigon and Broto, 2021). Specifically, the Urban Inclusivity Index (UII) was determined by six (6) key indicators identified during the questionnaire and fieldwork stages, including (i) accessibility to services and public transport, (ii) the level of digitalisation, (iii) accessibility to other services, (iv) fairness, (v) the overall satisfaction with AUSD, and (vi) availability of urban services. These indicators were selected based on the smart city inclusion literature (Bibri and Krogstie, 2020; Rigon and Broto, 2021; Townsend, 2013).

Before conducting the analysis, all indicators were normalized using min-max normalization so that the different scales used would not affect the final results. Following normalization, equal weighting (16.7% per indicator) was adopted because no empirical evidence or policy guidance justified assigning differential importance to individual indicators. The normalized indicator values were subsequently aggregated using a weighted arithmetic mean to obtain a composite UII for each city, which was then transformed into a 1–10 scoring scale, where 1 indicates very low inclusivity, and 10 indicates very high inclusivity. The obtained index values were verified by comparing them with qualitative data from the field survey and the participants' responses. This allowed ensuring that the scores correctly represent the observed state of affairs in the cities. The coordinates of the eight cities were imported from the database and visualized in the ArcGIS 10.8 software to confirm their accuracy (Bajjali, 2023). This step was necessary to ensure that the correct locations were used for the subsequent steps of the analysis conducted at the municipal level. Using the Southwestern Nigeria Base Map geographic information system, a geographical database was created, in which the eight cities were visualized as points using their latitude and longitude. The value of the UII score for each city was visualized using the scale property. As a result, the procedure produced a set of geographic data containing the survey results related to inclusiveness scores positioned at their actual locations, forming the basis of the next step (Yap and Biljecki, 2023; Tang et al., 2025).

The final stage involved the categorical visualization of UII across the eight observed cities. The UII scores were classified into three categories: low inclusivity (1–4), moderate inclusivity (5–6), and relatively high inclusivity (7–10). Each city was displayed as an individual point symbol positioned according to its actual geographic coordinates and assigned to its corresponding inclusivity category. No interpolation or continuous surface estimation was applied between the observation points, thereby avoiding the assumption that inclusivity levels were measured in areas where no observations were collected. The resulting categorical city-level map therefore represents only the (8) eight empirically assessed locations. This approach provides a transparent and methodologically appropriate visualization of spatial disparities in UII and supports the identification of cities requiring targeted policy and planning interventions for more equitable, resilient, and SUD across Southwestern Nigeria (Rigon and Broto, 2021).

4.4 Data collection and data analysis procedures

Data were collected electronically from 1st April to 31st August 2025, resulting in 502 questionnaires. The questionnaires were screened for incomplete data and irrelevant responses. Questionnaires with identical responses were excluded. Those with extreme values that showed little time put into completing them were also excluded. Finally, the data were analyzed against the inclusion criteria to select eligible participants. Eligible participants were professionals working in the urban planning, infrastructure, environmental management, ICT, transportation, housing, architecture, engineering, and allied sectors in Southwestern Nigeria. Only questionnaires with complete substantive responses and sufficiently consistent response patterns were retained for analysis. Following the screening process, 100 questionnaires were excluded because of incomplete or inconsistent responses, duplicate submissions, excessive missing data, or failure to meet the eligibility criteria. The final dataset therefore comprised 402 valid questionnaires, representing an effective usable response rate of 80.1%. The valid responses were subsequently categorized

according to respondents' state of residence, such as Lagos, Ogun, Oyo, Ondo, Osun, and Ekiti and professional discipline to facilitate geographical and subgroup comparisons during the analysis. This classification was undertaken at the analytical stage and did not constitute an additional sampling procedure (Creswell, 2012; Kaluarachchi, 2021).

The final sample of 402 respondents provided an adequate dataset for the planned statistical analyses. Data were analyzed using the Statistical Package for the Social Sciences (SPSS), Version 22 (Hashmi and Mohanty, 2025). Descriptive statistics, including frequencies, percentages, mean, and standard deviation, were generated to summarize the respondents' characteristics and perceptions toward AUSD. The variables were analyzed using Pearson correlation analysis. A multiple linear regression model was estimated to determine the degree of association between the AUS characteristics and the sustainability outcomes and UII. One-way Analysis of Variance (ANOVA) was performed to compare the respondents' perception and satisfaction with AUS across the selected cities. Statistical significance was assessed at $p < 0.05$. The resulting quantitative analyses provided the basis for the subsequent Results and Discussion section, where the statistical findings are presented and interpreted in relation to relevant and recent international literature. This approach enabled the study to examine patterns and associations in AUSD while recognizing the cross-sectional and perception-based design.

5 Results and discussion

To ensure the internal consistency and reliability of the survey instrument, Cronbach's alpha was computed for each construct. The results indicated moderate to high levels of reliability, with alpha coefficients ranging from 0.759 to 0.913. These values exceed the commonly recommended minimum threshold of 0.70, indicating satisfactory internal consistency of the measurement scales used in similar applications of Cronbach's alpha (Nunnally and Bernstein, 1994; Tavakol and Dennick, 2011). The obtained coefficients therefore support the reliability of the scales used to assess AUSD systems, citizen satisfaction, sustainable development outcomes, and UI. Construct validity was tested through an Exploratory Factor Analysis (EFA) using Principal Component Analysis (PCA) with Varimax rotation, which is a common method for uncovering the underlying structure of interrelated survey measures and grouping them into components. The initial EFA was run to determine the number of factors for the subsequent analysis. The sampling adequacy was found to be adequate for the analysis since KMO was 0.823, which is higher than the recommended 0.6 (Cronbach, 1951; Nunnally and Bernstein, 1994). Bartlett's Test of Sphericity was also statistically significant ($\chi^2 = 2{,}417.34$, $p < 0.001$), indicating that there were sufficiently high inter-item correlations for factor analysis to be performed (Kaiser, 1974; Bartlett, 1950). Also, convergent validity was established by retaining items with factor loadings equal or greater than 0.5 (Bartlett, 1950; Costello and Osborne, 2005), whereas discriminant validity was achieved by the absence of significant cross-loadings (Costello and Osborne, 2005; Hair et al., 2019). In furtherance to this, multiple linear regression models were then estimated to explore the study's research question, which investigated the association between AUSD indicators and sustainability in smart city development. Before interpreting the findings, the assumptions for linear regression were checked to ensure that the correct model was used and that the regression results were reliable and valid (Williams et al., 2013; O'Brien, 2007).

Visual inspection of the partial regression plots and scatterplots was used to evaluate the linearity of relationships. Histograms were also examined alongside the Shapiro–Wilk test for normality for the residuals, and the plot of standardized residuals against predicted values was used to check homoscedasticity. No extreme deviations were found for any of the assumptions. The independence of errors was assessed using the Durbin–Watson test, where a value close to 2 indicates that there is little to no autocorrelation (Williams et al., 2013; Durbin and Watson, 1950). It was found that Durbin-Watson statistics ranged between 1.75 and 2.10 (O'Brien, 2007). Collinearity was checked using VIF statistics, and a value lower than 3 indicates that there is no correlation between the predictors (Hair et al., 1998). The analysis also showed that there were no significant outliers using Cook's Distance and Leverage analysis (Williams et al., 2013; Cook, 1977). Overall, the statistical analysis was appropriate for the research design, and regression assumptions.

5.1 Respondents' socio-economic and professional characteristics

The socio-economic and professional characteristics of the respondents are presented in Figure 3. The diversity of the respondents therefore provides an important basis for understanding how different stakeholders perceive the effectiveness, responsiveness, and inclusiveness of AUSD across the selected cities in Southwestern Nigeria. As shown in Figure 3a, 57% of the respondents were female, while 43% were male. Although the difference between the two groups is insignificant, the representation is relatively good for both categories. This is an essential observation because access to urban infrastructure and services such as transport, housing, digital technologies, electricity, water, and leisure-time services could be different for different population groups. In this regard, the slight imbalance between genders does not affect the representation of opinions in the study. The modern understanding of smart and sustainable cities emphasizes the importance of considering not only innovative opportunities but also social aspects such as accessibility and inclusiveness. Therefore, taking into account respondents' gender is essential for obtaining a more comprehensive perspective on whether AUSD can meet the needs of different population groups. This assumption was supported by several scholars (Meerow et al., 2016; Sharifi, 2016; Nghiem et al., 2026).

According to Figure 3b, 81% of respondents were married, while 19% were single. The domination of married people is also essential information about the studied population sample. A married person has a broader range of urban services and infrastructure components because they have to consider the needs of family members when making decisions related to housing, transportation, healthcare, power, water, security, and others. At the

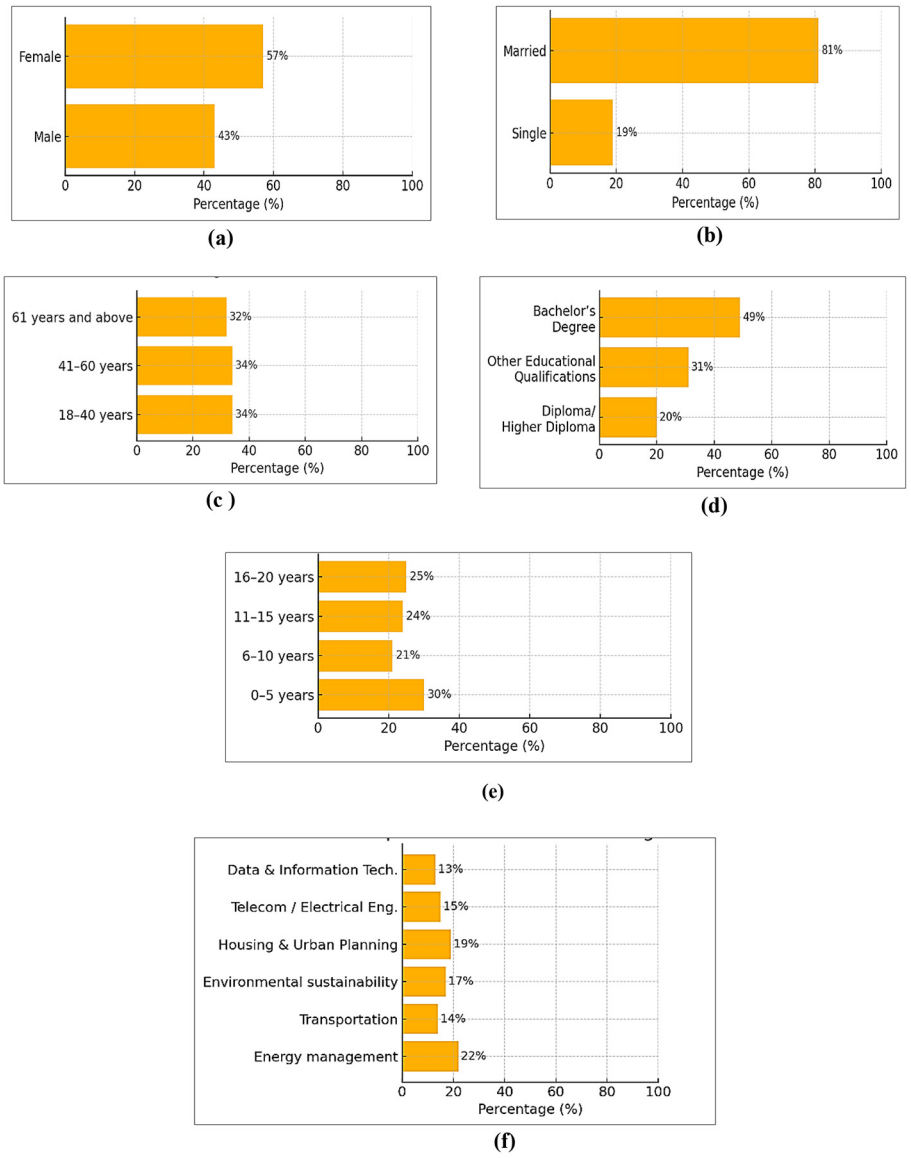


FIGURE 3
Respondents' Socio-economic and Professional Characteristics: **(a)** respondents' gender; **(b)** respondents' marital status; **(c)** respondents' age classifications; **(d)** respondents' educational qualification; **(e)** respondents' years of experience; **(f)** respondents' professional background. Source: Developed by the authors.

same time, this nuance does not influence the perception of AUSD's advantages and opportunities directly. Nevertheless, it is essential to keep in mind that marital status affects the respondents' opinions about urban services' quality and access to them. In addition, this characteristic helps identify other social traits of the studied population sample.

The age distribution as represented by Figure 3c was relatively balanced among the three categories. Therefore, the number of respondents aged between 18 and 40 years accounted for 34%, those aged between 41 and 60 years also accounted for 34%, and those aged 61 years and older comprised 32%. This balance is advantageous to the study because it captures the views of younger, middle-aged, and older respondents. Each of these groups is likely to differ in their expectations and levels of interaction with digital technology and AUSD. For example, the younger group is more likely to be conversant with newer digital technologies and applications. In contrast, the more mature respondents are more likely to provide their views and expectations in relation to their extensive experience in urbanization, city developments, and the provision of key services and infrastructure. Such an advantage is particularly pertinent to SUD. While digital technologies can improve service efficiency and responsiveness, unequal access to digital infrastructure and differences in technological literacy may create barriers for certain population groups, as reinstated by (Bibri and Krogstie, 2020; Ahvenniemi et al., 2017; Agboola and Irgin Uzun, 2026). In this vain, smart and inclusive cities has therefore increasingly emphasized the importance of human-centered approaches that ensure technological innovation does not contribute to new forms of exclusion. The balanced age profile of the present sample

consequently provides an opportunity to capture perspectives from respondents with potentially different levels of technological familiarity and experience of urban development.

Figure 3d presents the educational qualifications of the respondents. The results indicate that 49% held bachelor's degrees, 31% possessed doctoral qualifications, while 20% had diploma or higher-diploma qualifications. Overall, the sample was relatively highly educated, which is consistent with the purposive sampling strategy adopted for the study. Respondents were selected from relevant professional and technical fields because the assessment of AUSD involves complex issues relating to smart technologies, infrastructure systems, urban planning, ES, and UR. The relatively high level of educational attainment may therefore enhance the capacity of respondents to provide informed and experience-based assessments of the issues examined. The respondents also differed considerably in terms of their professional experience, as seen in Figure 3e. This population comprised the largest category of respondents (30%) with 16–20 years of professional experience. They were followed by respondents with 11–15 years of professional experience (25%), 6–10 years (24%), and 0–5 years (21%). The relatively even distribution of respondents across professional experience categories indicates that the study considers both well-established and more recent areas of expertise. The former is reflected in respondents' professional experience of more than 10 years, while the latter is captured by the 0–5-year category. In particular, the respondents with extensive professional experience are likely to have a comprehensive understanding of the evolution of infrastructure provision, governance systems, planning processes, and the overall urban development process. By contrast, the respondents with less professional experience may bring a fresh perspective into the discussion of emerging technologies, recent digital innovations, and contemporary approaches to urban development. Such a combination of perspectives is crucial to the current study, as the smart city solutions explored in AUSD benefit from both institutional knowledge and innovation-driven approaches (Meerow et al., 2016; Sharifi, 2016; Nghiem et al., 2026; Townsend, 2013). The professional experience of the sample thus serves as another factor differentiating the respondents based on their exposure to urban development and technological change.

The interdisciplinary composition of the respondents, shown in Figure 3f, provides further support for the suitability of the sample. Data and Information Technology represented the largest professional group, accounting for 22% of respondents, followed by Transportation (19%), Housing and Urban Planning (17%), Telecommunication and Electrical Engineering (15%), ES (14%), and Energy Management (13%). This distribution is particularly relevant to the objectives of the study because AUSD involve multiple interconnected systems and cannot be adequately assessed from a single disciplinary perspective. As reinstated by (Bibri and Krogstie, 2020; Albino et al., 2015; Agboola, 2026); SUD increasingly depends on the integration of information and communication technologies, real-time data systems, transportation infrastructure, energy management, environmental planning, and institutional governance. The professional diversity of the respondents reflects the multidisciplinary nature of contemporary urban challenges. Participants from ICT and telecommunications provided perspectives on emerging digital technologies, while transportation and urban planning professionals contributed expertise on mobility and land-use systems. Environmental and energy specialists provided insights into resource management, environmental impacts, and sustainability. This multidisciplinary representation therefore supports a broader assessment of AUSD and its implications for SUD.

5.2 The adaptive urban service delivery

In connection with research objective one, respondents' perceptions of the AUSD are presented in Figure 4. Respondents' perceptions of the integration of smart technologies into smart public infrastructure ranged from $M = 3.85$ to 4.15, while selected resilience-related infrastructure, including energy and mobility systems, recorded mean scores from $M = 3.76$ to 4.35, as presented in Figure 4a. Emergency response systems and inclusive urban planning also received relatively favorable assessments, with the latter ranging from $M = 3.92$ to 4.15. However, several respondents held negative or neutral views on the system's accessibility and affordability, indicating mixed opinions about the benefits SUD can bring. Figure 4b below presents respondents' perceptions of resource efficiency. According to the findings, the respondents had positive perceptions of the contribution of smart systems to improved energy and water management and waste management, with a mean score ranging from $M = 3.74$ to 4.15. Similarly, indicators relating to ES recorded positive ratings, ranging from $M = 3.90$ to 3.98, particularly in relation to carbon reduction, renewable energy, and environmental management.

The results for ES, presented in Figure 4c, indicate generally favorable perceptions among respondents. The assessed indicators recorded relatively positive mean scores, ranging from approximately $M = 3.90$ to 3.98, indicating that respondents generally perceived the sustainability measures favorably. Overall, the mean values, which are close to 4.00, suggest a generally positive assessment of ES, efforts across the study locations. Figure 4d presents respondents' assessments of QoL. Unlike the preceding dimensions, the results reveal more mixed perceptions. Urban mobility recorded a relatively high mean score ($M = 4.16$), indicating favorable perceptions of this aspect of urban life. In contrast, access to important facilities received comparatively low ratings, ranging from $M = 2.73$ to 3.05. Finally, Figure 4e presents the results relating to the application of AUSD. Overall, respondents expressed generally positive perceptions of the effectiveness of several adaptive service interventions. Waste management and traffic control or transport-related services received favorable ratings, with mean scores ranging from $M = 3.80$ to 4.08. However, renewable energy integration recorded a substantially lower mean score ($M = 2.53$), indicating comparatively limited perceived effectiveness or implementation of this service area.

The descriptive findings on AUSD across the five assessed areas, such as integration of smart technologies, resource efficiency, ES, QoL, and the application of AUSD, indicate both areas of relative strength and continuing service gaps. Answering

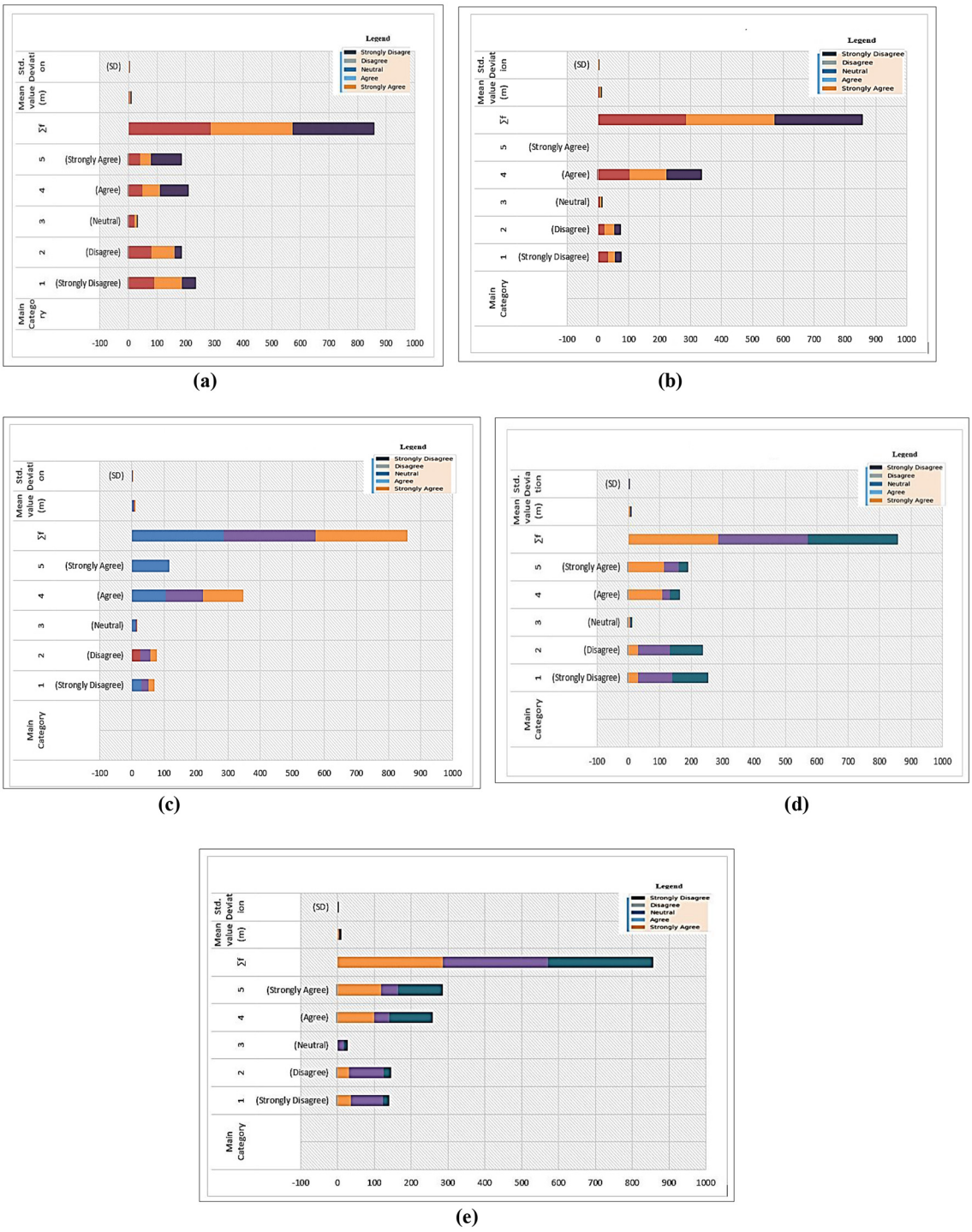


FIGURE 4
The adaptive urban services delivery. **(a)** integration of smart technologies; **(b)** resource efficiency; **(c)** environmental sustainability; **(d)** quality of life; **(e)** applications of AUS. Source: Developed by the authors.

research objective 1; the results suggest that technology-enabled urban interventions could be a good way to improve service efficacy and urban functionality, although the improvements are not consistent across the service areas. A positive view of the role of technology in urban development was also reported in previous studies (Agboola and Irgin Uzun, 2026; Yang et al., 2020). In particular, the current finding of improved performance in terms of efficiency and connectivity was supported by the evidence from the literature (Yang et al., 2020). The results also indicate that smart technologies could contribute to more effective management of energy and water resources. This result is comparable to the previous results (Yang et al., 2020; Bi et al.,

2023), which demonstrate the possibility of achieving higher efficacy through smart management. Finally, the study confirms the significance of reducing operational costs, which was also found in (Bi et al., 2023; Lai, 2022), thus supporting the cost-effectiveness of smart technologies as a tool for sustainable urban development.

The results relating to ES, similarly indicate that AUSD can contribute to improved environmental performance. Perceived reductions in carbon emissions and more efficient resource utilization are consistent with previous evidence concerning the role of smart technologies in supporting lower-carbon urban development (Lai, 2022; Moglia et al., 2018; Abdelkarim et al., 2023). The inclusion of renewable energy sources and improvement in urban greening were also positively associated with environmental benefits of sustainable and climate-responsive urban development (Alotaibi et al., 2024; Folke et al., 2003; Rammel et al., 2007; Moglia et al., 2018; Abdelkarim et al., 2023). However, the relatively low assessment of renewal energy suggests that the development and implementation of these technologies still require more efforts. In turn, the results confirm the role of AUS in urban liveability and QoL. Indeed, comparably high evaluations of urban mobility and responsive transportation services indicate smart growth's potential to enhance access to urban centers, reduce traffic intensity, and improve overall living conditions (Anthony Jnr, 2025; Sosunova and Porras, 2022; Agboola et al., 2024). In a similar vein, the positive trends in terms of waste management and other responsive services highlight the ability of adaptive urban systems to improve the comfort of everyday life. At the same time, the low and inconsistent perception of the availability of different facilities and services demonstrates that the responsiveness of technological infrastructures does not always translate into equal opportunities and access.

Altogether, the results highlight the relevance of developing a context-specific and comprehensive view of AUSD. The results of the study show that smart infrastructure, urban mobility, natural resources, waste management and selected resilience services are relative strengths, whereas renewable energy, affordability, technology access and access to key facilities are areas in need of improvement. This pattern underlines the limited perspective of simply pursuing technology adoption for its own sake; rather, the smartness or otherwise of the city depends to a considerable extent on how far technological solutions are embedded in supportive infrastructure, accessible to all and underpinned by appropriate institutional and planning frameworks. The results therefore have significant implications for urban policymakers and planners. AUSD requires enhanced investment in such areas as renewable energy, smart and green infrastructure, and technologies supporting the improved operation of key urban services as well as addressing the identified gaps in technological adoption and accessibility to ensure the benefits of smartness are distributed across society. The results therefore provide empirical evidence of the potential of AUSD to underpin improved efficiency and support more environmentally sustainable and liveable cities, but also highlight the need for integrated approaches to address current deficits in a range of key services.

5.3 Adaptive urban services delivery within smart urban environments

The results in Figure 5 are connected with the research objective 2. In general, there is a positive attitude toward the five dimensions, but they differ in terms of respondents' perception. Figure 5a demonstrates the participants' perceptions of UR. This suggests that the respondents acknowledge the role of resilience in AUSD. In particular, UR processes such as energy and mobility received positive mean scores from $M = 3.53$ to 4.09. As for the inclusiveness dimension, Figure 5b illustrates that respondents gave medium-positive scores from $M = 3.88$ to 4.71. It can be suggested that the inclusiveness dimension and its processes have some influence on decision-making in urban development. As for the processes related to PGM, Figure 5c demonstrates that respondents gave medium scores from $M = 3.90$ to 3.98. In particular, the adaptive housing process was positively acknowledged by the participants. At the same time, it should be noted that responses varied across the indicators, which means that the current approaches to PGM are not fully effective. In particular, the adaptive housing process was positively acknowledged by the participants. Indicating that the current approaches to PGM are not fully effective. As for Figure 5d, it demonstrates the participants' perceptions of infrastructure, where smart infrastructure and upgrading had the highest mean scores from $M = 3.85$ to 4.15. It should also be noted that the scores for transportation were lower compared to other processes, implying that respondents perceive transportation as less prioritized than other infrastructure-related processes. Finally, Figure 5e demonstrates that the CCI-related items received high mean scores, suggesting that participants acknowledge the impact of climate change on AUSD. However, there were some variations across the processes related to extreme weather conditions, where urban heat had mean scores from $M = 3.48$ to 3.70.

The obtained results contribute to fulfilling research objective two as they confirm that the attributes of AUSD depend on the city's ability to withstand, adapt to, and respond to emerging demands while ensuring the continuity of critical services. Overall, resilience emerged as the most critical component, supporting the idea that cities need the capacity to adapt and respond to environmental, socio-economic, and institutional disruptions to promote their sustainability. This result resonates with resilience theories that emphasize the importance of adaptive capacity in promoting urban sustainability (Ogunseye et al., 2022; Agbalagba and Wasurum, 2026; Toukabri and Mohamed Youssef, 2023). In addition, emergency response systems were also a significant contributor to AUSD, which is consistent with previous studies (Meerow et al., 2016; Townsend, 2013). This finding highlights the importance of responsive governance in building community resilience to disasters, pandemics, and other disturbances.

UI was also revealed as an essential component of AUSD. A strong correlation between perceived accessibility, digital inclusion, participatory governance, and citizen satisfaction with AUSD performance suggests that the focal role of SUD is determined by the extent to which its benefits are distributed. This finding aligns with the studies by Bibri and Krogstie (2020); Auwalu and Bello (2023), which highlight equity in service provision, affordable

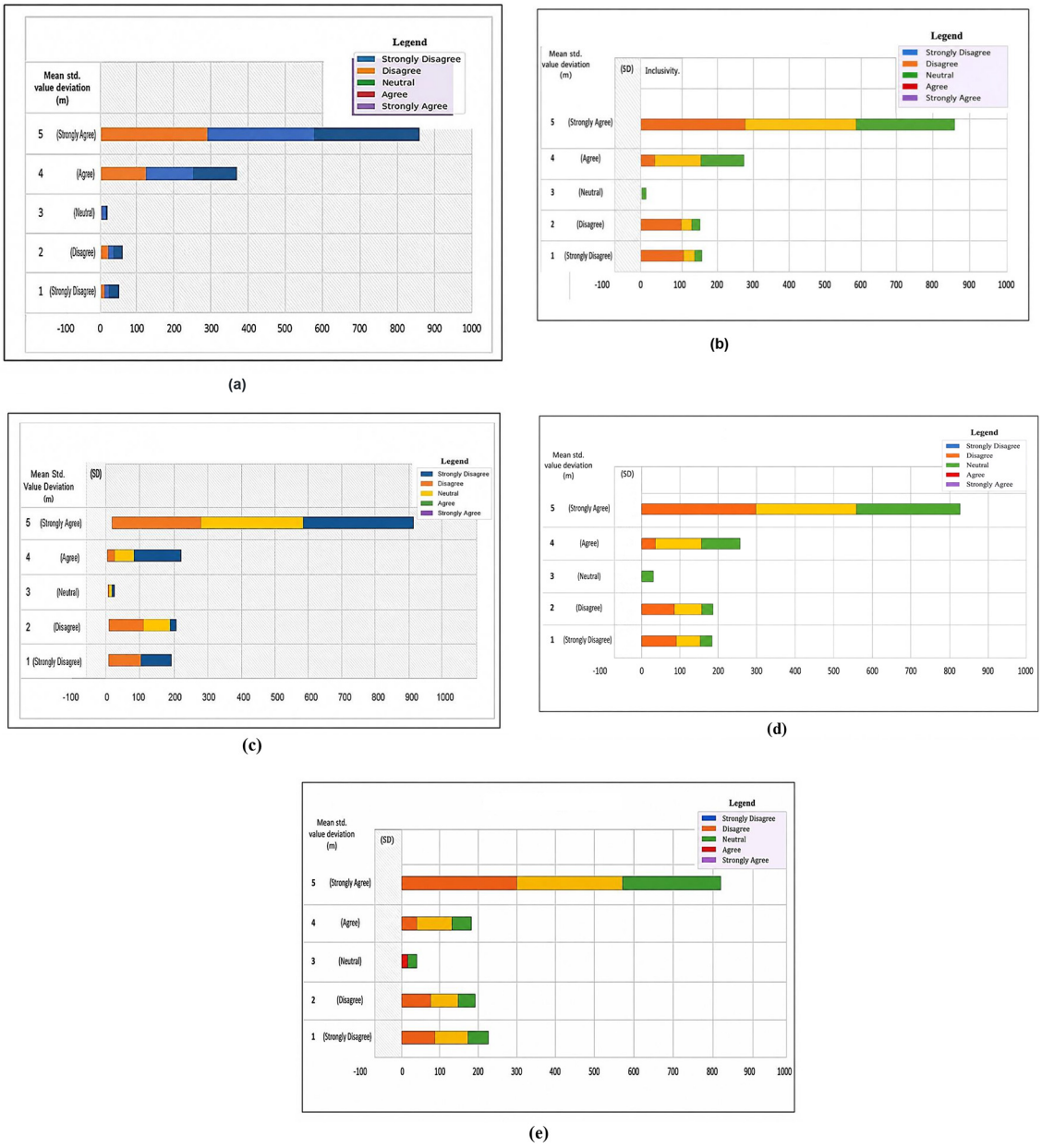


FIGURE 5
Adaptive urban services delivery variables: **(a)** resilience; **(b)** inclusivity; **(c)** population growth management; **(d)** infrastructure demands; **(e)** climate change impacts. Source: Developed by the authors.

housing, and digital inclusion as critical aspects of sustainable urban development. The same study notes the importance of participatory planning, which adds credibility to the argument on the transformative potential of inclusive approaches in urban policy (Toukabri and Mohamed Youssef, 2023; Hussain and Naqvi, 2025; Dano et al., 2020). Thus, the analysis demonstrates that inclusivity should be embedded in the core of AUSD design, not viewed as an afterthought. PGM and the level of infrastructure development also emerged as critical urban assets, with respondents associating housing provision, informal settlement replacement schemes, and universal access to public utilities and smart infrastructure with AUSD's ability to respond to urbanization challenges effectively. The emphasis on infrastructure resonates with the findings by (Rigon and Broto, 2021; Agboola et al., 2024; Auwalu and Bello, 2023), which identify adaptability as a key priority in post-pandemic urban development.

Furthermore, the analysis emphasizes the centrality of CCI as a component of AUSD. The relevance of climate-responsive planning and design, flood management, and climate-adaptive construction technologies illustrate the increasing incorporation of environmental considerations in urban service planning. This finding reflects research highlighting the benefits of climate-sensitive design to enhance environmental performance and mitigate urban heat-related risks (Doussard et al., 2024), as well as

prior studies advocating integrated strategies for flood management and other climate-related hazards (Folke et al., 2003; Nghiem et al., 2026; Agbalagba and Wasurum, 2026). The inclusion of climate-resilient construction technologies and green infrastructure further corroborates studies demonstrating the capacity of sustainable construction approaches and nature-based interventions to lower urban vulnerability and improve environmental quality (Hussain and Naqvi, 2025). The study's findings therefore build upon prior smart city and UR research (Meerow et al., 2016) through its empirical assessment of the significance of technological, institutional, social, and environmental pillars in context of Southwestern Nigeria.

5.4 Principal component structure and interrelationships of adaptive urban services delivery

The Principal Component Analysis (PCA) was performed to explore the data dimensionality of the factors impacting AUSD relative to research objective 3. According to Table 2 below, the first component (PC1), UR, was characterized by such indicators as AUS ($\beta = 0.781$), emergency response systems ($\beta = 0.743$), and energy and transport resilience ($\beta = 0.420$) with a positive loading. This component had an eigenvalue of 1.67 that explained 13.9% of the variance. The second component (PC2), UI, had an eigenvalue of 1.98 that explained 16.5% of the variance. It was represented by inclusive planning ($\beta = 0.612$), digital access equity ($\beta = 0.510$), and affordable services ($\beta = 0.400$). The third component (PC3), PGM, had an eigenvalue of 2.54 that explained 21.2% of the variance. It was primarily represented by urban planning efficiency ($\beta = 0.730$), with adaptive housing ($\beta = 0.667$) and informal settlement reduction ($\beta = 0.580$) being secondary indicators. The fourth component (PC4), ID had an eigenvalue of 1.99 and explained 17.8% of the total variance. The component comprised transportation infrastructure ($\beta = 0.681$), energy infrastructure ($\beta = 0.644$), infrastructure adequacy ($\beta = 0.626$), and communication and smart infrastructure ($\beta = 0.610$). Finally, the fifth component (PC5), CCI, emerged as the component explaining the largest proportion of variance (26.8%), with an eigenvalue of 3.21. The component was characterized by strong loadings for flood management ($\beta = 0.830$), climate-resilient materials ($\beta = 0.780$), and urban heat reduction ($\beta = 0.648$).

To investigate if there are significant associations between respondents' categorical (Likert-scale) responses and key AUSD, Pearson's Chi-square (χ^2) test of independence was carried out. The relationships among the variables were examined; while statistical significance, *Cramer's V* was computed to determine the strength of the observed associations. Before the analysis, the assumptions of the Chi-square test were verified, with all expected cell frequencies exceeding the recommended minimum threshold. As presented in Table 3, statistically significant associations were identified across all tested variable pairs. Strong and statistically significant relationships were observed between UR and emergency response systems ($\chi^2 = 48.27$, $df = 16$, $p < 0.001$), CCI and flood management systems ($\chi^2 = 71.83$, $df = 16$, $p < 0.001$), UI and access to digital technologies ($\chi^2 = 56.84$, $df = 16$, $p < 0.001$), and ID and public utility reliability ($\chi^2 = 53.69$, $df = 16$, $p < 0.001$). Furthermore, PGM demonstrated a statistically significant association with informal settlement reduction ($\chi^2 = 31.45$, $df = 16$, $p = 0.013$).

The PCA method revealed the five-dimensional structure of the AUSD, including UR, UI, PGM, ID, and CCI. The fact of their separation indicates that AUSD emerges in the context of the interaction of social, institutional, demographic, infrastructural, and environmental influences. This result is consistent with the findings of previous UR and smart city studies, which identified a set of factors that determine the ability of a city to respond to contemporary issues and challenges, which go beyond the mere provision of technological and physical infrastructure (Meerow et al., 2016; Agboola et al., 2024; Ogunseye et al., 2022). The first component, resilience, reflects the ability of urban systems and service providers to withstand disturbances, respond rapidly, effectively, and recover their basic service functions to maintain critical urban processes. The fact that UR has appeared as a separate dimension confirms previous research findings and the initial understanding of the UR concept, according to which it embodies the notion of preparedness, adaptive capacity, response, and recovery (Başegmez and Dogan, 2025). Moreover, as previous studies have shown, UR requires a coordinated effort, as well as the involvement of responsive infrastructure and the ability to quickly adapt service provision processes in response to environmental and socio-economic disturbances (Meerow et al., 2016; Townsend, 2013). Thus, the present result highlights the importance of ensuring UR as a priority for AUSD provision, particularly in the context of rapid urbanization, which often aggravates the impact of disturbances on the existing capacities of urban systems.

The study reveals that accessibility of urban services, citizen participation, and digital inclusion emphasized in (Bibri and Krogstie, 2020; Dano et al., 2020) are critical sustainability indicators that appear to exacerbate the challenges of unequal access to new technologies and digital services (Toukabri and Mohamed Youssef, 2023; Brown and Ikiriko, 2025; Haruna et al., 2026). The infrastructure needs stand out as proof that the provision, sufficiency, and adaptability of technology infrastructure are crucial aspects of AUSD as established (Meerow et al., 2016; Agboola et al., 2024). The factor loadings for this component were found to be high, pointing to the fact that respondents related infrastructure needs to the overall capacity of their city to deliver reliable and comprehensive services. In Southwestern Nigeria, increasing urbanization brings about the need for better infrastructure development in transportation, energy, water, housing, and digital technology. At this juncture, the results of the PCA revealed a five-factor structure that justified the integration of the variables used in this study. The five factors were resilience, inclusiveness, population growth, infrastructure needs, and CCI. These factors were found to explain respondents' assessment of AUSD in a way that demonstrated that their perception of the variables used was consistent with the theoretical framework. The factors identified reveal that the variables used were not randomly grouped but instead were related aspects of the urbanization process. With these factors, it becomes possible to explore the role of AUSD in promoting smart cities in Southwestern Nigeria.

TABLE 2 Summary of the principal component analysis (PCA) results.

Component	Construct	Variables	PCA loading (β)	Eigenvalue/% variance explained	Key loading pattern	Interpretation
PC1	Urban resilience (RE)	Emergency response systems	0.743	1.67/13.9%	Moderate positive loadings	Represents the capacity of urban systems and services to withstand, respond to, and recover from disruptions
		Adaptive urban services	0.781			
		Energy/transport resilience	0.420			
PC2	Urban Inclusivity (UI)	Inclusive planning	0.612	1.98/16.5%	Moderate positive strong loadings	Represents equitable access, participation, and social inclusion in urban service provision
		Digital access equity	0.510			
		Affordable services	0.400			
PC3	Population growth management (PGM)	Urban planning efficiency	0.730	2.54/21.2%	Strong positive loadings	Represents the capacity of urban planning and housing systems to accommodate demographic growth and reduce associated pressures
		Adaptive housing	0.667			
		Informal settlement reduction	0.580			
PC4	Infrastructure demands (ID)	Infrastructure adequacy	0.626	1.99/17.8%	Moderate positive loading	Represents the adequacy and adaptability of essential urban infrastructure to meet increasing service demands
		Energy infrastructure	0.644			
		Transportation infrastructure	0.681			
		Communication/smart infrastructure	0.610			
PC5	Climate change impacts (CCI)	Flood management	0.830	3.21/26.8%	Strong positive loadings	Represents the capacity of urban systems to anticipate and respond to climate-related hazards and environmental stresses
		Climate-resilient materials	0.780			
		Urban heat reduction	0.648			

$N = 402$.

The model shown in Figure 6 is a citizen-centered model of how AUSD can be leveraged to promote urban sustainability. One of the benefits of the proposed model is that it is adaptive. The model will encourage resiliency in cities through adaptation to the pressures such as urban hazards, disruptions to urban structures, and shifts in demographics. The model will also ensure sustainable

TABLE 3 Chi-square test of association between key adaptive urban service delivery variables.

Variable pair	χ^2	*df*	*N*	*p*-statistic	Cramer's V statistic	Strength of association	Interpretation
Resilience × emergency response systems	48.27	16	402	<0.001**	0.347	Moderate	A statistically significant association exists between perceived UR and emergency response systems.
Inclusivity × access to digital technologies	56.84	16	402	<0.001	0.376	Moderate	Digital accessibility is significantly associated with perceptions of UI.
Population growth management (PGM) × informal settlement reduction	31.45	16	402	0.013	0.279	Small to moderate	PGM is significantly associated with reductions in informal settlements.
Infrastructure demand × public utility reliability	53.69	16	402	<0.001	0.365	Moderate	Reliable public utilities are significantly associated with the ability to meet growing ID
Climate change impacts (CCI) × flood management systems	71.83	16	402	<0.001	0.423	Relatively strong	Effective flood management systems are strongly associated with CCI initiatives.

$N = 402$.** $p < 0.05$.

cities through the provision of social services such as housing, digital technology, transportation, and accessibility to enhance the voice and choices of all citizens. Additionally, the model is focused on climate-resilient development through the adoption of renewable energy, energy-efficient technologies and systems, climate-resilient infrastructures and buildings, environmentally friendly technologies and systems, sustainable urban transport, and sustainable management of resources. In this way, the model will help reduce greenhouse gases and provide urban areas with cleaner environments. Furthermore, the model supports low-carbon urban development, and hence contributes toward achieving SDG 11. The model also supports other SDGs such as 7, 9, 13, and 17 through clean energy, resilient infrastructures, mitigation of CCI, and global partnerships, respectively.

5.5 Adaptive urban service delivery dimensions in promoting urban inclusivity and resilience

For Research Objective 4, the multiple regression results presented in Table 4 indicate that all five predictor variables were positively and significantly associated with respondents' evaluations of AUSD, with all relationships statistically significant at $p < 0.001$. Among the predictors, resilience recorded the strongest standardized coefficient ($\beta = 0.357$, $SE = 0.041$, $t = 7.83$, $p < 0.001$), followed by UI ($\beta = 0.291$, $SE = 0.046$, $t = 6.51$, $p < 0.001$), PGM ($\beta = 0.236$, $SE = 0.043$, $t = 5.84$, $p < 0.001$), ID ($\beta = 0.214$, $SE = 0.047$, $t = 5.11$, $p < 0.001$), and CCI ($\beta = 0.188$, $SE = 0.049$, $t = 4.76$, $p < 0.001$). These results indicate that higher scores on each of the five dimensions were associated with more favorable evaluations of AUSD, with RE showing the strongest association within the model. The multicollinearity diagnostics further indicate that excessive overlap among the predictor variables was unlikely to have substantially distorted the regression estimates. The tolerance values were in the range from 0.301 to 0.493, which is more than the commonly applied minimum of 0.20, while the VIF values were between 2.03 and 3.32, which is less than the commonly applied threshold of 5.0. The communalities were also relatively high, ranging from 0.722 for ID to 0.821 for resilience. Specifically, UR (0.821), CCI (0.804) and PGM (0.785) had the highest communality values, while the UI (0.739) and ID (0.722) were also adequately represented by the extracted component structure. Thus, the results indicate that the retained variables were reasonably well represented in the underlying factor structure.

As summarized in Table 5 below, the regression model had a good fit to the data, as evidenced by the appropriate multiple correlation coefficient of $R = 0.865$. In this case, the coefficient of determination ($R^2 = 0.748\%$) implies that 74.8% of the variance in respondents' evaluations of AUSD is jointly explained by the five hypothesized constructs. The adjusted coefficient of determination remained similarly appropriate (Adjusted $R^2 = 0.744$), suggesting limited reduction in explanatory power after accounting for the number of predictors. The overall regression model was statistically significant, $F_{(5,396)} = 291.63$, $p < 0.001$, indicating that

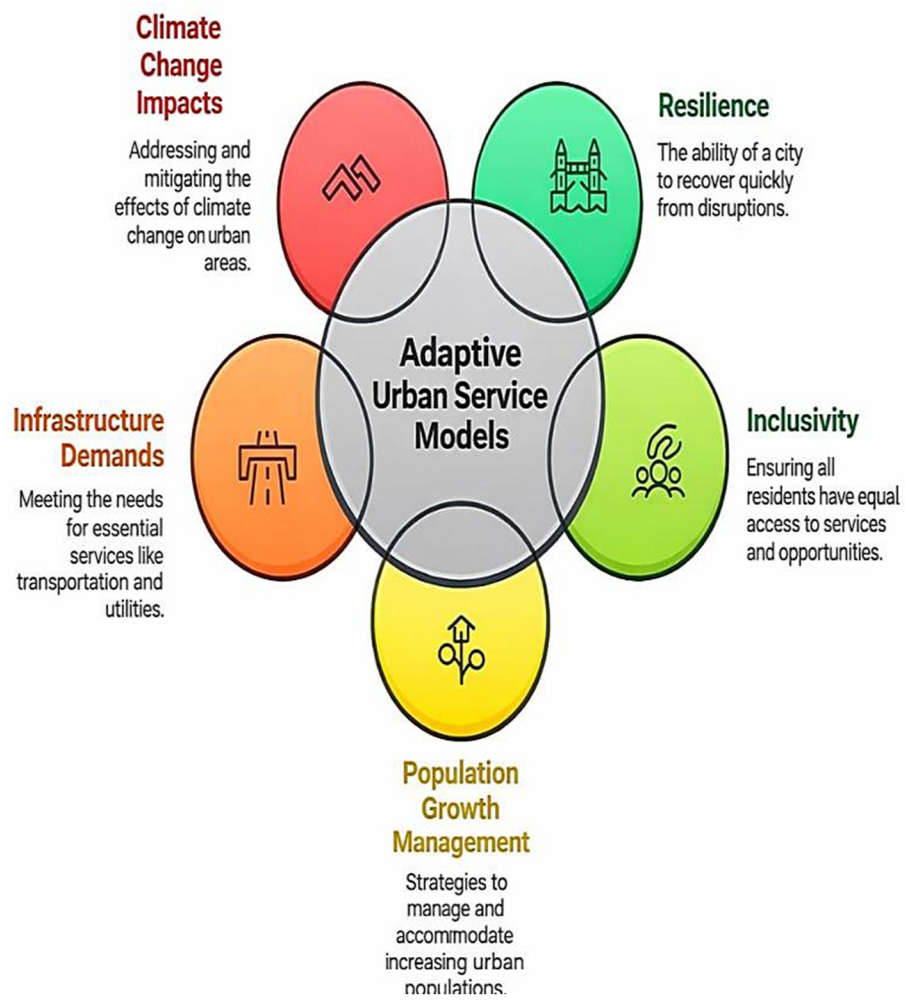


FIGURE 6
Adaptive urban service delivery models and key urban challenges.

TABLE 4 Multiple regression results for adaptive urban service dimensions.

Predictor	Standardized regression (β)	Standard error (SE)	*t*-statistic	Sig. (*p*)	Tolerance statistic	Variance inflation factor (VIF)
Urban resilience (RE)	0.357	0.041	7.83	<0.001**	0.342	2.92
Urban inclusivity (UI)	0.291	0.046	6.51	<0.001**	0.301	3.32
Population growth management (PMG)	0.236	0.043	5.84	<0.001**	0.493	2.03
Infrastructure demands (ID)	0.214	0.047	5.11	<0.001**	0.484	2.07
Climate change impacts (CCI)	0.188	0.049	4.76	<0.001**	0.312	3.21

$N = 402$; $^{**}p < 0.001$.

the five predictors jointly explained a statistically significant proportion of variation in AUSD. In other words, the regression and communalities results provide empirical support for the five-dimensional conceptualization of AUSD, comprising UR, UI, PGM, ID, and CCI. The findings suggest that respondents perceived AUSD as a multidimensional phenomenon shaped by interconnected social, demographic, infrastructural, and environmental conditions rather than by technological capacity alone. This interpretation is broadly consistent with previous smart-city and SUD research, (Taheri et al., 2026; Toukabri and Mohamed Youssef, 2023; Barreira et al., 2023); which emphasizes digital access, affordability, participation,

TABLE 5 Model summary for adaptive urban service delivery dimensions.

Model statistic	Statistic
R	0.865
R^2	0.748
Adjusted R^2	0.744
Standard error of the estimate	0.455
F-value	291.63
Degrees of freedom ($df1$)	5
Degrees of freedom ($df2$)	396
Significance (p-value)	<0.001

$N = 402$.

infrastructure, and urban equity as interconnected components of inclusive urban development.

UR emerged as the strongest predictor in the model, a finding consistent with previous studies (Grace et al., 2023; Taheri et al., 2026) that emphasize the capacity of urban systems to anticipate disturbances, withstand shocks, maintain essential functions, respond effectively, and recover from adverse conditions. This result suggests that respondents perceive effective AUSD as being closely associated with the capacity of urban systems and services to maintain continuity during environmental, infrastructural, and socio-economic disruptions. In the context of Southwestern Nigeria, strengthening resilience therefore requires more than physical infrastructure alone; it also involves developing institutional and operational capacities that can support effective emergency response, maintain essential services, and facilitate timely recovery following disruptive events. Furthermore, another positive association was found between UI and AUSD. Notably, this outcome aligns with studies that indicate that equitable access to services, digital inclusion, affordability, participation, and urban equity are critical elements of sustainable and inclusive urban development (Taheri et al., 2026; Toukabri and Mohamed Youssef, 2023; Barreira et al., 2023). These results suggest that respondents considered the effectiveness of AUSD partially in terms of their accessibility and responsiveness to diverse population groups. Consequently, the findings argue that technological innovation on its own may be insufficient if the benefits of urban services are not available to different social and spatial contexts. The model also incorporates PGM successfully. This is evident from the result as it proves the importance of spatial planning, provision of housing, and coordination of infrastructure development and housing provision (Alabi et al., 2025). In addition, these are in tandem with previous studies such as (Taheri et al., 2026; Albino et al., 2015; Agboola, 2026) that have shown that increased population growth can lead to significant demands for housing, transport, and other services and put an additional strain on the existing utilities. Thus, this result suggests that the consideration of demographic trends and spatial planning principles is a necessary condition for adaptive service provision strategies.

Infrastructure requirements were also significantly associated with AUSD, indicating the importance of sufficient, flexible and responsive physical and technological systems. Transportation, energy, water, communication, drainage and digital infrastructures constitute essential operational foundations, upon which the effective provision of AUSD is built. This interpretation is in line with previous findings (Nghiem et al., 2026; Taheri et al., 2026; Albino et al., 2015; Agboola, 2026), illustrating RE and SUE require ID which accommodates evolving demands while providing essential services. The findings furthermore suggest that investment in digital and smart technologies may need to be complemented by improvements to fundamental infrastructure, in order to allow for the efficacy of technological interventions, especially in rapidly urbanizing regions where service limitations may impede technological efficacy.

Finally, CCI made a positive and statistically significant contribution to AUSD, although its coefficient was smaller than the other predictors. The finding underlines the importance of considering climate-induced stresses, including flooding, extreme temperatures and environmental degradation, in the design of adaptive urban services, in accord with previous findings by (Turner et al., 2026; Agboola et al., 2024; Ogunseye et al., 2022). The relatively small coefficient indicates that the respondents perceived CCI as one part of a multifaceted AUSD rather than an independent determinant for overall service performance. Overall, these findings support the interpretation of AUSD as a multi-faceted construct in which RE, UI, PMG, ID, and CCI act as interwoven dimensions.

The finding is key to considering the implications of climate-related stresses, including flooding, extreme temperatures, and environmental degradation, in the planning and provision of AUSD, as found in the prior work (Turner et al., 2026; Agboola et al., 2024; Ogunseye et al., 2022). The relative smallness of the coefficient implies that respondents perceived CCI as one of the components of the overall adaptive urban service system, rather than an independent determinant for its overall performance. The communalities analysis further supports the retention of the five-dimensional structure, as the observed variables were appropriately accounted for and added to the extracted components meaningfully to the underlying dimensions of the adaptive city delivery. Together with the regression results, the overall analysis provides a basis to retain resilience, inclusivity, PGM, demands of infrastructure, and CCI as the primary dimensions of the analytical model. The identification of the interconnected dimensions is further aligned with the prior smart-city and UR studies (Taheri et al., 2026; Albino et al., 2015; Agboola, 2026; Toukabri and Mohamed Youssef, 2023), which highlight the combined influence of a mix of social, infrastructural, demographic, and environmental factors on urban adaptation and sustainability.

5.6 Assessment of the urban service satisfaction and qualitative assessment of urban inclusivity across the eight case study cities

5.6.1 Assessment of the urban service satisfaction

To address Research Objective 5 concerning USS, the descriptive statistics presented in Table 6 show some variation in respondents' satisfaction with AUSD across the eight selected

TABLE 6 Descriptive statistics of respondents' satisfaction with adaptive urban services delivery.

City	Sample size (*n*)	Mean	Standard deviation
Lagos	70	4.22	0.55
Ibadan	50	3.88	0.53
Akure	53	4.05	0.49
Ado-Ekiti	52	3.91	0.51
Osogbo	50	3.90	0.50
Ile-Ife	40	3.95	0.46
Abeokuta	50	3.89	0.52
Ogbomoso	37	3.91	0.50
Total	402	3.98	0.52

$N = 402$: across selected southwestern nigerian cities.

cities in Southwestern Nigeria. Lagos recorded the highest mean satisfaction score ($M = 4.22$, $SD = 0.55$), followed by Akure ($M = 4.05$, $SD = 0.49$) and Ile-Ife ($M = 3.95$, $SD = 0.46$). The remaining cities recorded relatively moderate mean scores: Ado-Ekiti (M = 3.91, $SD = 0.51$), Ogbomoso ($M = 3.91$, $SD = 0.50$), Osogbo ($M = 3.90$, SD = 0.50), Abeokuta ($M = 3.89$, $SD = 0.52$), and Ibadan ($M = 3.88$, $SD = 0.53$). The aggregate mean of 3.98 ($SD = 0.52$) indicates generally favorable perceptions of AUSD across the surveyed locations. Although Lagos recorded the highest mean, the relatively moderate range of city-level means (3.88–4.22) indicates that the differences in descriptive satisfaction levels were moderate. The *SD*, ranging from 0.46 to 0.55, also indicate relatively limited dispersion in responses within each city.

The one-way *ANOVA* presented in Table 7 indicates that satisfaction with AUSD differed significantly across the eight cities, $F_{(7,394)} = 7.96$, $p < 0.001$. Thus, the null hypothesis that the eight city means are equal was rejected. The *ANOVA* result establishes that at least one city differs significantly from another, but it does not identify the specific city pairs responsible for the overall difference. Accordingly, *Tukey's Honestly Significant Difference* (HSD) test was subsequently conducted to determine which pairwise comparisons reached statistical significance. The *HSD Post Hoc Test* presented in Table 8 was conducted following the significant One-Way *ANOVA* to identify the specific city pairs contributing to the observed differences in USS. The results revealed several statistically significant pairwise differences, indicating that respondents' perceptions of AUSD varied across the selected Southwestern Nigerian cities. Akure recorded significantly higher USS than Osogbo (mean difference = 0.15, $p < 0.001$), Ogbomoso (mean difference = 0.14, $p < 0.001$), Abeokuta (mean difference = 0.16, $p < 0.001$), and Ibadan (mean difference = 0.17, $p = 0.001$). These findings indicate that respondents in Akure reported higher levels of satisfaction with AUSD than respondents in these four cities. Similarly, Lagos showed significantly higher USS than Osogbo (mean difference = 0.32, $p < 0.001$), Ogbomoso (mean difference = 0.31, $p = 0.002$), Abeokuta (mean difference = 0.33, $p = 0.006$), and Ibadan (mean difference = 0.34, $p = 0.018$). The relatively larger mean differences observed for Lagos suggest a comparatively stronger perceived performance of AUSD in Lagos than in these cities.

Further significant differences were identified between Ado-Ekiti and Osogbo (mean difference = 0.01, $p = 0.008$), Ado-Ekiti and Ogbomoso (mean difference = 0.00, $p = 0.041$), and Ile-Ife and Osogbo (mean difference = 0.05, $p = 0.029$). Although the mean differences for these comparisons were small, their statistical significance indicates that the corresponding city-level differences in USS were unlikely to be attributable to sampling variation alone. Overall, the significant comparisons demonstrate that satisfaction with AUSD was not uniform across the study cities. The reported results provide evidence of specific city-level differences in USS, with the most consistent differences involving Akure and Lagos relative to Osogbo, Ogbomoso, Abeokuta, and Ibadan. These findings complement the significant overall *ANOVA* result and demonstrate that variations in perceived AUSD performance occur at the city level across Southwestern Nigeria.

The comparative analysis of USS across the eight case-study cities indicates statistically significant differences in respondents' perceptions. This finding provides empirical evidence relevant to Research Objective 5 and suggests that perceived satisfaction with AUSD is not uniform across Southwestern Nigeria. The *One-Way ANOVA* results confirm that the observed differences in satisfaction between cities are statistically significant, indicating variation in respondents' assessments of urban service provision. Similar differences have been reported in (Adeshina et al., 2024; Agboola and Nia, 2025; Barreira et al., 2023), which associate variations in urban development outcomes with differences in governance capacity, infrastructure investment, service provision, and planning effectiveness. The present findings therefore support the broader observation that urban service experiences can vary considerably between cities within the same regional context. The descriptive results show that Lagos recorded the highest mean satisfaction score, indicating relatively favorable perceptions of AUSD among the respondents surveyed. This result is consistent with (Adeshina et al., 2024; Olaseni and Alade, 2012); that have identified Lagos as a major metropolitan center with substantial investment in infrastructure, digital transformation, and urban development. However, the higher satisfaction score should be interpreted as a perception-based finding rather than direct evidence that Lagos provides moderate services across all dimensions. Akure also recorded a relatively high satisfaction level. This result may be associated with improvements in infrastructure and urban-service provision reported in (Meerow et al., 2016; Ogunseye et al., 2022), although the present cross-sectional study cannot establish that particular investments caused the observed level of satisfaction. Osogbo recorded the lowest satisfaction score, while Ibadan, Abeokuta, Ogbomoso, Ado-Ekiti, and Ile-Ife occupied intermediate positions. These differences suggest variation in how respondents perceive the availability, accessibility, and effectiveness of urban services across the study locations. Researches such as (Meerow et al., 2016; Ogunseye et al., 2022; Olaseni and Alade, 2012) on Nigerian urban development has similarly identified challenges involving infrastructure deficits, transportation, digital access, public utilities, and unequal service provision. These studies provide a useful context for interpreting the differences observed in the present analysis.

TABLE 7 One-Way ANOVA comparing respondents' satisfaction with adaptive urban services delivery.

Source of variation	Sum of squares (*SS*)	*df*	Mean square (MS)	*F*-value	Sig. (*p*-value)
Between cities	12.84	7	1.834	7.96	<0.001
Within cities (error)	90.76	394	0.230		
Total	103.60	401			

Sig. $p < 0.001$.

TABLE 8 *Tukey's HSD Post Hoc* multiple comparisons of mean urban service satisfaction.

Comparison	Mean difference (I–J)	*p*-statistic	95% *CI* lower	95% *CI* upper	Significant
Akure vs. Osogbo	0.15	<0.001	0.43	1.01	Yes
Akure vs. Ogbomoso	0.14	<0.001	0.32	0.89	Yes
Akure vs. Abeokuta	0.16	<0.001	0.25	0.81	Yes
Akure vs. Ibadan	0.17	0.001	0.19	0.74	Yes
Lagos vs. Osogbo	0.32	<0.001	0.32	0.88	Yes
Lagos vs. Ogbomoso	0.31	0.002	0.20	0.76	Yes
Lagos vs. Abeokuta	0.33	0.006	0.13	0.69	Yes
Lagos vs. Ibadan	0.34	0.018	0.06	0.62	Yes
Ado-Ekiti vs. Osogbo	0.01	0.008	0.14	0.74	Yes
Ado-Ekiti vs. Ogbomoso	0.00	0.041	0.02	0.62	Yes
Ile-Ife vs. Osogbo	0.05	0.029	0.04	0.68	Yes

$N = 402$. Across selected Southwestern Nigerian cities.

The *Post Hoc Tukey HSD* analysis provides further detail on the city pairs contributing to the significant overall *ANOVA* result. The results show that Akure had significantly higher USS than Osogbo (mean difference = 0.15, $p < 0.001$), Ogbomoso (mean difference = 0.14, $p < 0.001$), Abeokuta (mean difference = 0.16, $p < 0.001$), and Ibadan (mean difference = 0.17, $p = 0.001$). Lagos also recorded significantly higher USS than Osogbo (mean difference = 0.32, $p < 0.001$), Ogbomoso (mean difference = 0.31, $p = 0.002$), Abeokuta (mean difference = 0.33, $p = 0.006$), and Ibadan (mean difference = 0.34, $p = 0.018$). Additional significant differences were observed between Ado-Ekiti and Osogbo (mean difference = 0.01, $p = 0.008$), Ado-Ekiti and Ogbomoso (mean difference = 0.00, $p = 0.041$), and Ile-Ife and Osogbo (mean difference = 0.05, $p = 0.029$). These findings indicate that the significant spatial variation in USS was concentrated in some cities rather than occurring uniformly across all locations.

The city-level comparisons further indicate that Lagos and Akure generally occupied the higher level of the USS distribution relative to several other cities, particularly Osogbo, Ogbomoso, Abeokuta, and Ibadan. The pattern suggests that respondents in these two cities perceived comparatively higher levels of satisfaction with AUSD. However, the results should not be interpreted as evidence that every difference between the eight cities was statistically significant. Rather, the *Tukey HSD* results demonstrate a selective pattern of significant pairwise differences, with the strongest contrasts involving Akure and Lagos. The observed variation perhaps reflect differences in perceived infrastructure provision, institutional capacity, urban planning effectiveness, and service delivery across the study locations, as corroborated by (Meerow et al., 2016; Ogunseye et al., 2022). The findings overall indicate that satisfaction with AUSD varies across the selected cities, as emphasized by (Townsend, 2013; Sosunova and Porras, 2022; Olaseni and Alade, 2012) that the importance of digital infrastructure, emergency preparedness, transportation, public utilities, and climate-responsive planning could shape the quality and inclusiveness of urban environments.

5.6.2 Qualitative assessment of urban inclusivity across selected cities

A qualitative evaluation of UI across the selected cities in Southwestern Nigeria was undertaken between 1st April and 31st August 2025, using the UII to answer Research Objective 5. According to Figure 7, Akure reported the highest inclusivity score (7), signifying a relatively positive performance on the dimensions included in the index. The relatively better performance could be linked to the better urban development, service provision and digital progress in the city. Previous studies such as (Meerow et al., 2016; Agboola et al., 2024; Ogunseye et al., 2022) have identified infrastructure, institutional capacity, digital connectivity and accessibility of urban services as key determinants of inclusive and resilient urban development. Osogbo, Ado-Ekiti, and Ile-Ife reported moderate UII scores ranging from 5 to 6. This outcome indicates an average performance on the dimensions included in the UII. The outcome is similar to previous studies such as (Agbalagba and Wasurum, 2026; Toukabri and Mohamed Youssef, 2023), suggesting that though improvements in infrastructure and service accessibility have occurred across the cities, they are not uniform and the differences in digital access could

affect the inclusiveness of urban development. The average scores reported in these cities therefore highlight the need for continued investments in AUSD, accessible infrastructure, digital inclusion and participatory planning. In contrast, the cities of Ibadan, Lagos, Abeokuta, and Ogbomoso were characterized by low inclusiveness, as revealed by the scores of 3 to 4. This implies that these cities have low performance on the indicators used to measure inclusiveness. In the literature, studies such as (Auwalu and Bello, 2023; Hussain and Naqvi, 2025; Dano et al., 2020) reveal that fast urbanization in Nigerian cities contributes to the inability to provide adequate infrastructure, housing, transportation, and public services and causes ecological degradation, which results in inequality in access to services within these cities. Therefore, the fact that these cities had low scores in our study is an indication that they face greater challenges in providing services comparable to other cities that had higher scores.

The findings are especially surprising for Lagos as it is the commercial hub of Nigeria and is highly urbanized and therefore faces the challenge of congestion and inequality in accessing services as revealed by the studies of (Hussain and Naqvi, 2025; Dano et al., 2020; Brown and Ikiriko, 2025). This could explain why Lagos has a lower score compared to other cities in Nigeria. The low performance of Lagos, Ibadan, Abeokuta, and Ogbomoso can be attributed to the inability to provide adequate infrastructure and public services and the ecological degradation that has been documented in studies such as (Auwalu and Bello, 2023; Dano et al., 2020; Haruna et al., 2026). For example, the review of the literature revealed that Ibadan urbanizes very fast and faces greater challenges in providing infrastructure and services to its fast-growing urban population (Auwalu and Bello, 2023; Haruna et al., 2026). This finding can help explain the low inclusiveness score of Ibadan compared to other Nigerian cities. Overall, the qualitative assessment established that there are significant differences in the UI of the selected Southwestern Nigerian cities. The variations found are in line with previous studies (Agboola et al., 2024; Ogunseye et al., 2022; Agbalagba and Wasurum, 2026; Toukabri and Mohamed Youssef, 2023), that report the importance of considering the overall infrastructure, accessibility, digital connectivity, institutional governance, and social capital in achieving inclusive development. Thus, the findings support the need for smart-city development and management to consider the inclusiveness of the given processes in order to ensure that a broad range of opportunities is available in a city (or town) and that people's needs are considered in its development. Moreover, the current findings are aligned with studies (Meerow et al., 2016; Ogunseye et al., 2022; Agbalagba and Wasurum, 2026; Toukabri and Mohamed Youssef, 2023), noting the connection between UR and UI, which is based on a comprehensive consideration of technological, social, institutional, and environmental dimensions.

The observed differences highlight the importance of city-level analysis, as aggregate assessments may mask important variations among individual cities. Urban development strategies should therefore be context-sensitive and responsive to the specific challenges, opportunities, and institutional conditions of each location. Key priorities should include improving adaptive urban services, expanding equitable access to infrastructure, strengthening digital inclusion, and promoting citizen-centered governance. These priorities are particularly relevant to smart-city development in Nigeria and align with Sustainable Development Goal 11, which seeks to make cities and human settlements inclusive, safe, resilient, and sustainable (Barreira et al., 2023). In rapidly urbanizing cities, an inclusive approach is essential for responding to growing demands for urban services while addressing persistent gaps in infrastructure, accessibility, and service provision.

The sensitivity analysis presented in Table 9 examined the robustness of the UII to alternative weighting schemes. In the baseline specification, the six indicators were equally weighted at 16.7% each and compared with entropy-based, PCA-based, and systematically varied unequal weighting schemes. The high similarity across the specifications is consistent with previous composite-indicator research showing that alternative weighting procedures can produce comparable results when indicators represent related dimensions (Chinweokwu Ogborogu et al., 2025; Umar et al., 2024; Olanrewaju and Adegun, 2021; Okosun et al., 2023). The correlations between the baseline UII and the alternative indices exceeded 0.90, ranging from 0.93 for PCA-based weighting to 0.97 for entropy-based weighting. Similarly, Spearman rank correlations exceeded 0.90, indicating that the relative ordering of observations remained largely stable across weighting schemes. This stability supports the robustness of the UII and suggests that its principal findings are not substantially dependent on the choice of weighting procedure, as supported by (Chinweokwu Ogborogu et al., 2025; Umar et al., 2024; Olanrewaju and Adegun, 2021).

The ranking comparison provides additional support for the stability of the baseline specification. Approximately 90% of the observations remained within the same broad performance category under the alternative weighting schemes, while changes in individual rankings were limited. This pattern agrees with previous evidence that moderate changes in indicator weights do not necessarily result in major changes in composite-index classifications, particularly where the indicators are related (Olanrewaju and Adegun, 2021; Okosun et al., 2023). There was also no substantial reversal of the principal pattern observed under the equal-weighted specification. Observations with relatively higher UII scores generally remained relatively higher under the alternative specifications, while those with relatively lower scores tended to remain comparatively lower.

Taken together, these results indicate that the overall pattern captured by the UII is not substantially dependent on the equal-weighting assumption. Although alternative weighting approaches produced some differences in individual index scores and rankings, these variations did not materially change the overall pattern of UII. Retaining equal weighting as the baseline specification is therefore reasonable on the grounds of transparency and interpretability, particularly in the absence of sufficiently strong theoretical, empirical, or policy evidence for assigning greater importance to specific indicators (Chinweokwu Ogborogu et al., 2025; Umar et al., 2024; Olanrewaju and Adegun, 2021). Equal weighting also facilitates the clear communication of each indicator's contribution without introducing additional assumptions about their relative importance. Overall, the UII

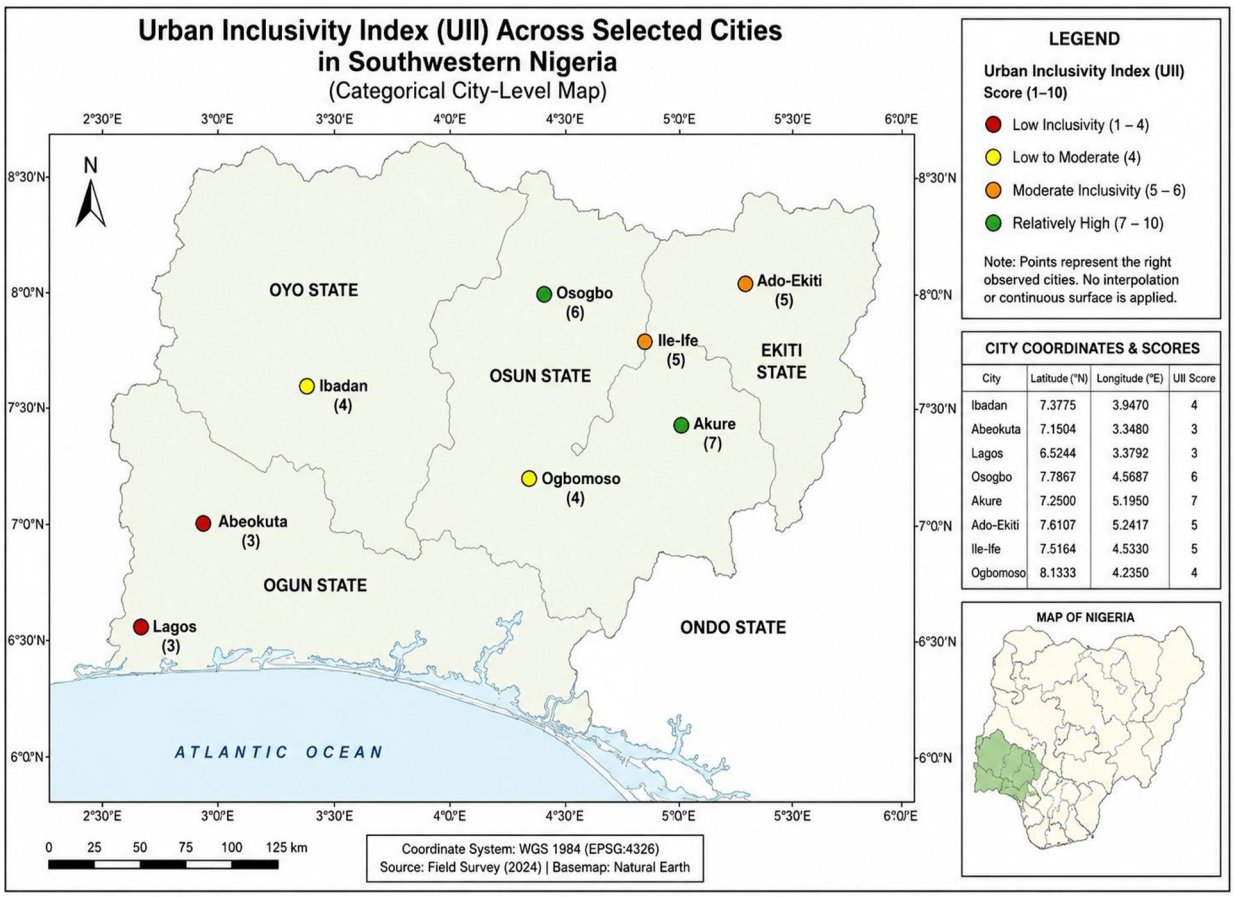


FIGURE 7
Urban-level spatial distribution of urban inclusivity index scores across selected cities in Southwestern Nigeria held between 1st April and 31st August 2025. Inclusivity index ranging 1–10: 1 (very low) to 10 (very high).

TABLE 9 Sensitivity results of the urban inclusivity index to alternative weighting schemes.

Weighting scheme	Description	Correlation with baseline UII	Spearman rank correlation	Observations remaining in same performance category (%)	Overall robustness
Equal weighting (baseline)	Six indicators weighted equally (16.7% each)	1.000	1.000	100.0	Baseline
Entropy weighting	Weights determined according to the discriminatory/information content of each indicator	0.97	0.96	92.0	High
PCA-based weighting	Weights derived from the contribution of indicators to the principal component	0.93	0.92	89.0	High
Unequal weighting	Alternative differential weights assigned across the six indicators, with total weight = 100%	0.95	0.94	90.0	High

suggests that sustainable smart-city development extends beyond the deployment of advanced technologies. Consistent with the principles of Sustainable Development Goal 11 and the New Urban Agenda, the findings highlight the importance of equitable access to urban services, inclusive governance, spatial equity, and adequate infrastructure alongside technological innovation. Addressing gaps

in infrastructure, digital connectivity, and public-service provision may therefore support more UI, RE, and AUSD in Nigerian cities.

6 Conclusions

This study empirically examines perceptions of AUSD's contribution to UI, RE, and sustainability in rapidly urbanizing cities in Southwestern Nigeria. The overall UI mean score was 3.98 (SD = 0.52), indicating generally favorable perceptions of UI among respondents. However, variations across the study locations suggest that the benefits of urban services are not experienced uniformly. The findings further highlight the importance of integrating technology, infrastructure, and responsive service provision in advancing sustainable urban development. Although technological capacity can support inclusive urban development, the observed variations indicate that technology alone may not guarantee equitable outcomes. Effective and AUSD therefore requires accessible infrastructure, responsive institutions, and governance mechanisms that ensure the benefits of technological innovation are distributed more inclusively.

The study also revealed variations in perceptions of USS among respondents. The city mean scores for USS were 3.91, 4.22, 4.05, and 3.95 for Ogbomoso, Lagos, Akure, and Ile-Ife, respectively. The variations in perception of USS (0.31) among the cities indicate differential perceptions of AUSD. The differences in the perception of AUSD may be attributed to variations in infrastructural provisions, institutional frameworks, accessibility, and service quality in the study cities. The findings suggest the need to consider the local differences in promoting urban development. The study's spatial analysis also revealed variations in the level of UI across the study area. Although the overall mean score of the respondents' perception of UI was 3.98, the variations in the mean scores across the cities imply that the respondents perceived differences in urban services' availability and inclusiveness. As a result, policymakers must consider the differential accessibility and adoption of digital technologies, transportation systems, housing plans, health services, social services, and other urban services. As a result, policymakers must prioritize addressing the perceived gaps in infrastructural and service accessibility in the study area.

Achieving inclusive and sustainable urban transformation requires more than the introduction of smart technologies rather depends on equitable access, participatory planning, responsive governance, institutional capacity, and effective public-service provision. The potential contribution of this study on AUSD connects technological development with social inclusion, environmental responsibility, climate-responsive planning, and targeted infrastructure investment. This study also contributed to the development of an integrated, context-sensitive framework linking AUSD with RE, UI, PGM, ID, CCI, and spatial assessment. The evidence from 402 respondents, together with the overall UI score and observed differences between cities, provides a basis for examining these dimensions collectively. In this respect, the framework extends conventional smart-city discussions beyond technological infrastructure, digital innovation, and operational efficiency by giving greater attention to the social, spatial, and adaptive dimensions of AUSD in rapidly urbanizing African contexts. This study also contributes methodologically by combining survey-based assessment, statistical analysis, UI indicators, and GIS-based spatial analysis. The difference between Ogbomoso (3.91) and Lagos (4.22) further illustrates the usefulness of examining UI at the city level, since aggregate measures may obscure differences between locations. However, the proposed framework should be regarded as a context-specific analytical approach rather than a universally validated measure of smart-city readiness or urban performance. Further testing across different settings is needed before its wider applicability can be established.

The generally favorable UI score, together with the observed differences between locations, suggests that technological capacity needs to be complemented by accessible and socially responsive urban services. From a practical and policy perspective, urban planners and policymakers should adopt integrated and place-sensitive approaches that combine equitable digital access, resilient infrastructure, accessible public services, participatory governance, and climate-responsive planning. The 0.31-point difference between the highest and lowest reported UI scores highlights the importance of considering geographical variation when designing urban interventions. Rather than applying uniform smart-city strategies, authorities could prioritize infrastructure, transportation, digital connectivity, service accessibility, and participatory governance according to locally identified needs. Urban monitoring frameworks should also incorporate explicit UI indicators to identify disparities in access to urban services and guide targeted interventions. Such approaches can support more equitable, UR, and SUD while contributing to the objectives of Sustainable Development Goal 11.

Several limitations are noted based on the study's results. The cross-sectional nature of this study is a significant limitation as it prevents the determination of cause-and-effect relationships between variables of interest. Also, the study relied on respondents' perceptions of the phenomenon under investigation. As such, the results reflect the opinions, thoughts, and perceptions of the study participants. The study's findings might not be generalizable to the larger community due to the non-probability sampling technique, and the scope of this research was limited to the Southwestern part of Nigeria. Therefore, the conclusions drawn from this study should be interpreted with caution as they only represent the views of the surveyed proportion of the community.

Future research should build on these findings by adopting mixed-methods approaches that combine quantitative and qualitative evidence, applying probability-based or stratified sampling techniques, and increasing the sample size to improve the representativeness and generalisability of the findings. Longitudinal studies would also be valuable for examining how the identified predictors and outcomes change over time and whether improvements in AUSD are associated with changes in UR, UI, and sustainability. Comparative studies across other Nigerian cities and urban areas in Sub-Saharan Africa could further determine whether the observed relationships remain consistent across different socio-economic, environmental, infrastructural, and institutional contexts. In addition, integrating objective indicators of infrastructure performance, technological capacity, environmental conditions, and service delivery with respondents' perceptions would provide a more comprehensive assessment of AUSD.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the studies involving humans as it involved minimal risk, anonymous data collection, and no vulnerable populations. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

OA: Conceptualization, Methodology, Investigation, Writing – review & editing, Software, Formal analysis, Writing – original draft. MF: Resources, Validation, Conceptualization, Project administration, Writing – review & editing, Visualization, Supervision, Writing – original draft, Funding acquisition.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2026.1916019/full#supplementary-material

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