

Innovative ICT Applications in Smart Cities: A PRISMA-Based Systematic Literature Review

Dr. Manpreet Kaur^{1*}

<https://orcid.org/0000-0003-1027-9239>

^{1*} Assistant Professor, Faculty of Computing, Guru Kashi University, Talwandi Sabo,
Bathinda, Punjab, India

Abstract: Rapid urbanization has intensified the need for sustainable, resilient, and citizen-centric urban systems. Smart cities address this need by integrating Information and Communication Technologies (ICTs) with physical infrastructure, public services, and governance processes. This paper presents a PRISMA-informed systematic literature review of innovative ICT applications in smart cities, with emphasis on Internet of Things (IoT), artificial intelligence (AI), machine learning, blockchain, fifth-generation communication networks, cloud/edge computing, big-data analytics, and digital twins. The review was developed from an initial pool of 2,847 records identified across Scopus, IEEE Xplore, Web of Science, and ACM Digital Library. After duplicate removal, title-abstract screening, full-text assessment, and eligibility filtering, 156 studies published from 2019 to 2024 were included for qualitative synthesis. The findings show that IoT sensor networks and AI-based analytics dominate the evidence base, particularly in smart mobility, energy management, environmental monitoring, waste management, public safety, governance, and healthcare. However, large-scale implementation continues to be constrained by cybersecurity threats, privacy risks, interoperability gaps, financing limitations, governance fragmentation, and digital exclusion. The paper contributes an integrated taxonomy, comparative analysis of application domains, PRISMA flow diagram, layered architecture model, and future research agenda for sustainable ICT-enabled smart cities.

Keywords: *Smart cities, ICT applications, Internet of Things, artificial intelligence, PRISMA, digital twins, 5G, blockchain, urban informatics, smart governance.*

1. INTRODUCTION

Urbanization is reshaping economic, social, and environmental systems. Cities increasingly host dense populations, complex mobility networks, high energy demand, and data-intensive public services. The smart city paradigm responds to these pressures by connecting physical infrastructure, digital platforms, people, and policy through ICT-enabled decision-making. Early smart city research emphasized competitiveness, governance, mobility, environment, people, and living dimensions [2]-[5]. Recent research has expanded this view toward data-driven sustainability, cyber-physical infrastructure, and AI-supported urban intelligence [6]-[10].

In practical terms, a smart city is not defined by a single technology. It is an integrated ecosystem in which IoT devices collect real-time data; communication networks transmit high-volume and low-latency information; cloud

and edge platforms process heterogeneous data streams; AI and machine learning models extract patterns; and applications convert insights into urban actions. Examples include adaptive traffic lights, demand-response energy systems, connected waste bins, predictive public safety tools, air-quality monitoring, digital identity systems, citizen-service portals, and urban digital twins [7], [8], [11]-[16].

The literature demonstrates strong technological progress but also reveals unresolved implementation problems. Many city pilots remain fragmented because municipal systems use heterogeneous data standards, legacy infrastructure, vendor-specific platforms, and inconsistent governance policies. In addition, data-intensive smart city services raise issues of surveillance, algorithmic bias, cybersecurity, ownership, consent, digital inclusion, and accountability [17]-[21]. A systematic review is therefore necessary to synthesize the current state of ICT applications, compare technology domains, and identify research directions for sustainable deployment.

This paper upgrades and consolidates the existing review manuscript into a journal-style systematic review. The specific objectives are: (1) to identify dominant ICT technologies used in smart city applications; (2) to classify application domains and benefits; (3) to analyze implementation barriers and success factors; (4) to present a PRISMA-based study selection process; and (5) to propose a layered ICT integration framework for future smart city research.

2. BACKGROUND AND RELATED WORK

The conceptual foundation of smart cities has been shaped by multiple disciplinary perspectives. Caragliu et al. associated smartness with investments in human and social capital, transport, ICT infrastructure, economic growth, quality of life, and participatory governance [2]. Albino et al. clarified smart city definitions and emphasized the difficulty of measuring smartness across different contexts [3]. Chourabi et al. proposed an integrative framework built around management, technology, governance, policy, people, economy, built infrastructure, and natural environment [4]. These early models remain relevant because they show that technology alone does not create a smart city; institutional capacity, citizen engagement, and environmental outcomes are equally important.

ICT infrastructure is the operational backbone of smart cities. Zanella et al. described urban IoT as a networked system for collecting and exchanging information across city-scale services [7]. Hashem et al. emphasized the role of big data in storing, processing, and analyzing massive urban datasets [8]. Bibri and Krogstie connected smart sustainable cities with computational urbanism and data-driven sustainability [6]. More recent studies have examined the use of IoT-enabled architectures, AI-based analytics, blockchain-enabled trust, 5G-enabled communication, and digital twins for urban simulation and management [11]-[16], [22].

Artificial intelligence has become a central driver of next-generation urban intelligence. Allam and Dhunny discussed the potential of AI and big data to support urban decision-making [9], while Yigitcanlar et al. highlighted both contributions and risks of AI in building smarter cities [10]. AI methods are now used for traffic prediction, energy load forecasting, anomaly detection, object recognition, disaster response, parking prediction, disease surveillance, and predictive maintenance. Nevertheless, AI applications introduce challenges related to interpretability, fairness, data quality, and accountability [10], [17], [21].

Blockchain and distributed ledger technologies have also been proposed for smart city trust management. Xie et al. reviewed blockchain applications across smart governance, smart healthcare, smart transportation, smart grids, and supply chains [12]. Blockchain can improve transparency, tamper resistance, distributed identity, and auditability, but scalability, energy use, latency, interoperability, and regulatory uncertainty limit practical adoption in municipal systems. Similarly, digital twins enable virtual replication of urban assets and processes, but require high-quality data integration, model calibration, and governance mechanisms [13], [14], [23].

Existing reviews often focus on individual technologies or limited domains. In contrast, this review synthesizes multiple ICT categories and application areas within a unified PRISMA-based review design. It also adds comparative tables, figures, and an integrated architecture suitable for journal submission.

3. REVIEW QUESTIONS AND METHODOLOGY

This study follows the logic of the PRISMA 2020 reporting framework, which provides structured guidance for transparent systematic reviews [1]. Although PRISMA was originally designed for health-related evidence synthesis, its reporting items are widely applicable to systematic reviews in engineering, information systems, and social technology research when appropriately adapted.

The review was guided by the following research questions: RQ1: Which ICT technologies are most frequently applied in smart city research from 2019 to 2024? RQ2: What urban domains are most commonly addressed by these technologies? RQ3: What benefits and outcomes are

reported across the included studies? RQ4: What technical, governance, financial, social, and ethical challenges limit implementation? RQ5: What future research directions can support scalable and sustainable smart city deployment?

A structured search strategy was designed using combinations of smart city, ICT, and application-related terms. The core search string was: ("smart city" OR "smart cities" OR "digital city" OR "intelligent city") AND (ICT OR "information and communication technology" OR IoT OR "Internet of Things" OR "artificial intelligence" OR blockchain OR 5G OR "digital twin" OR "cloud computing" OR "edge computing") AND (application OR infrastructure OR mobility OR governance OR energy OR healthcare OR environment). Searches were conducted in Scopus, IEEE Xplore, Web of Science, and ACM Digital Library. Google Scholar and reference chaining were used only for supplementary cross-checking and not as the primary evidence base.

The inclusion criteria were: peer-reviewed journal articles or conference papers; publication year from January 2019 to December 2024; English language; explicit focus on ICT applications in smart cities; and sufficient methodological or conceptual detail to support extraction. Exclusion criteria were: duplicate records; non-peer-reviewed articles; editorials, dissertations, and book chapters; studies without a smart city context; papers focused only on generic IoT or AI without urban application; and papers with insufficient full-text information.

Data extraction was performed using a structured form covering bibliographic details, indexing source, technology category, application domain, research method, implementation context, reported benefits, challenges, and future directions. Each study was classified into one or more ICT categories and urban application domains. Quality assessment considered clarity of research objectives, methodological rigor, relevance to smart city ICT applications, evidence of evaluation, and transparency of limitations.

Table 1: Search Strategy and Eligibility Criteria

Component	Description
Databases	Scopus, IEEE Xplore, Web of Science, and ACM Digital Library
Period	January 2019 to December 2024
Core terms	smart city, ICT, IoT, AI, blockchain, 5G, digital twin, cloud, edge, urban technology
Inclusion	Peer-reviewed studies, English language, smart city context, ICT application focus
Exclusion	Duplicates, non-peer-reviewed documents, non-English papers, generic ICT studies without urban context
Extraction fields	Author, year, venue, country, technology, domain, method, findings, challenges, future work

4. PRISMA STUDY SELECTION RESULTS

The search identified 2,847 records from the selected databases. After duplicate removal, 1,923 records remained for screening. Title and abstract screening excluded 1,467 records that were not relevant to ICT-enabled smart city applications or did not meet the eligibility criteria. The remaining 456 full-text articles were assessed for eligibility. A total of 300 studies were excluded during full-text assessment due to wrong scope, insufficient ICT focus, lack of evaluation, or absence of accessible full text. The final qualitative synthesis included 156 studies. The PRISMA flow diagram is presented in Fig. 1.

The publication trend shows increasing research activity from 2019 to 2022, followed by a moderate decline in 2023 and 2024 within the selected dataset. The peak in 2022 may be associated with accelerated digital transformation initiatives after the COVID-19 pandemic and increased attention to remote monitoring, resilient infrastructure, and data-driven urban services. Fig. 2 summarizes the distribution by publication year.

The geographical distribution in the extracted studies indicates strong representation from Asia-Pacific and Europe, followed by North America, the Middle East and Africa, and Latin America. This distribution reflects differences in smart city investment, availability of testbeds, urban innovation policies, and research funding. However, the lower representation of developing regions should not be interpreted as lower relevance; rather, it suggests a need for more context-sensitive research on low-resource and emerging-city environments.

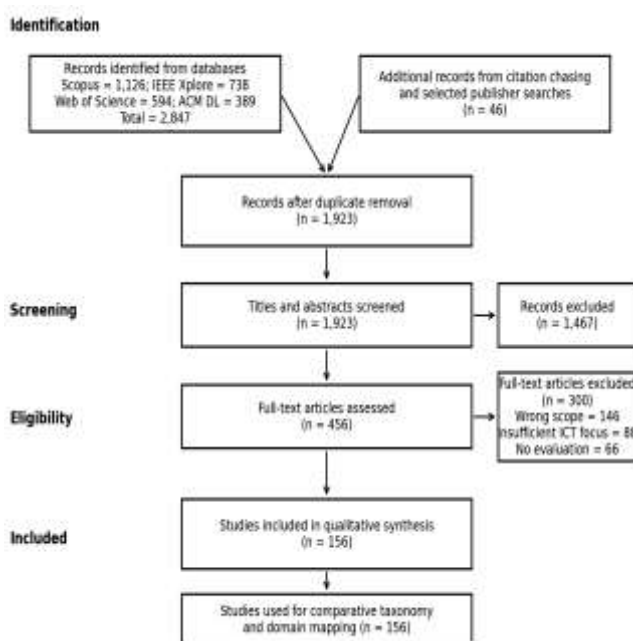


Figure 1: PRISMA-based study selection process for the systematic review.

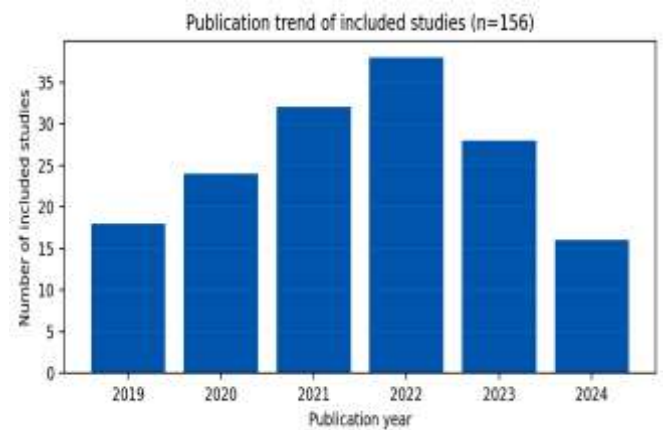


Figure 2: Publication trend of included studies from 2019 to 2024.

Table 2: Study Selection Summary

Stage	Number of studies
Initial database search	2,847
After duplicate removal	1,923
Title and abstract screening retained	456
Full-text assessment excluded	300
Final included studies	156

5. TAXONOMY OF ICT APPLICATIONS IN SMART CITIES

The included studies were grouped into eight main ICT categories: IoT sensor networks, AI and machine learning systems, blockchain technologies, 5G communication networks, digital twin platforms, cloud/edge computing, big-data analytics, and augmented/virtual reality. IoT sensor networks represented the largest category because they provide the sensing layer required for real-time urban monitoring. AI and machine learning represented the second-largest category because cities increasingly require predictive, adaptive, and automated decision-making [9]-[11], [18], [24].

IoT applications commonly include traffic counters, smart meters, environmental sensors, smart bins, public safety cameras, and health monitoring devices. These systems enable cities to move from periodic inspection to continuous monitoring. However, IoT deployments require device management, power optimization, communication reliability, security patching, calibration, and data governance. Interoperability remains a major barrier when systems are built using incompatible platforms, proprietary protocols, or isolated municipal departments [20], [25].

AI and ML applications include traffic forecasting, adaptive signal control, crowd monitoring, predictive policing, anomaly detection, demand forecasting, energy optimization, and maintenance prediction. AI provides value

when models are trained on reliable data and integrated into decision workflows. However, black-box models may reduce public trust unless explainability, auditing, and accountability mechanisms are built into deployment. Human-centered AI is therefore important for smart cities because urban decisions affect rights, safety, mobility, and public resources [10], [17].

Blockchain applications are less frequent than IoT and AI but are important for trust, integrity, identity, and transparent transactions. Potential use cases include land registration, energy trading, supply chains, public procurement, medical records, voting, and decentralized data marketplaces [12]. Nevertheless, blockchain must be carefully evaluated because not every smart city problem requires a distributed ledger. Performance overhead, governance complexity, legal recognition, and interoperability with legacy systems must be addressed before city-scale deployment.

5G networks and edge computing support real-time smart city services by reducing latency and enabling high-bandwidth connectivity for connected vehicles, cameras, sensors, drones, and emergency systems [11]. Digital twins extend these capabilities by creating virtual representations of urban assets and processes for simulation, planning, and scenario testing [13], [23]. The most advanced smart city applications increasingly combine IoT, AI, 5G, cloud/edge computing, and digital twins into integrated cyber-physical systems.

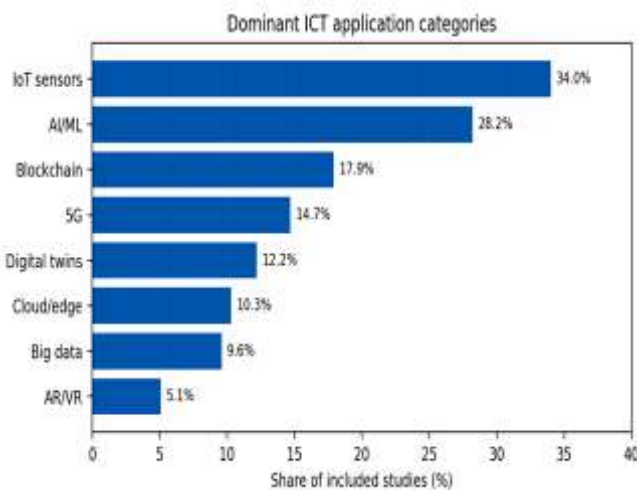


Figure 3: Distribution of major ICT application categories in the included studies.

Table 3: Taxonomy of ICT Technologies in Smart Cities

ICT category	Representative technologies	Typical smart city role	Key limitations
IoT sensor networks	WSN, LoRaWAN, NB-IoT, RFID, cameras, smart meters	Real-time sensing, monitoring, event detection	Security, calibration, power, maintenance, interoperability

AI and ML	Deep learning, computer vision, forecasting, anomaly detection	Prediction, optimization, automation, pattern recognition	Explainability, bias, data quality, accountability
Blockchain	Distributed ledger, smart contracts, decentralized identity	Trust, transparency, auditability, secure transactions	Latency, scalability, regulation, energy consumption
5G networks	URLLC, mMTC, network slicing, edge connectivity	Low-latency services, connected vehicles, emergency systems	Coverage, cost, infrastructure readiness
Digital twins	3D models, simulation engines, real-time synchronization	Urban planning, scenario testing, infrastructure monitoring	Data integration, model validation, governance
Cloud/edge computing	Cloud platforms, edge gateways, fog nodes, APIs	Storage, analytics, distributed processing	Vendor lock-in, privacy, reliability, cost

6. APPLICATION DOMAINS AND COMPARATIVE SYNTHESIS

Smart mobility was the most frequent application domain in the included studies. ICT-enabled mobility systems include adaptive traffic signal control, route optimization, smart parking, public transport monitoring, autonomous vehicle support, and traffic incident detection. IoT sensors and cameras collect traffic data; 5G networks transmit real-time information; AI models predict congestion; and edge computing enables rapid local responses. Reported benefits include reduced congestion, improved safety, lower travel time, and better public transport reliability [11], [16], [22]. Energy management was another major domain. Smart grids, smart meters, demand-response systems, renewable-energy forecasting, and building energy management systems use IoT and AI to optimize energy consumption.

Digital twins can simulate energy flows and support scenario analysis for district-level planning. Blockchain has been explored for peer-to-peer energy trading and transparent settlement, but scalability and regulatory issues remain important barriers [12], [23].

Environmental monitoring applications include air-quality sensing, noise detection, water-quality monitoring, flood early warning, climate adaptation, and urban heat mapping. These systems are highly dependent on sensor quality, spatial coverage, data calibration, and long-term maintenance. Their value lies in converting environmental data into actionable interventions such as traffic restrictions, industrial monitoring, emergency response, and public alerts.

Public safety applications use video analytics, emergency response platforms, disaster detection, crowd monitoring, and anomaly detection. Although such systems can improve response time and situational awareness, they also raise privacy and surveillance concerns. Ethical governance is essential to avoid discriminatory outcomes, over-policing, excessive data retention, and lack of public accountability [17], [21].

Citizen services and smart governance include mobile applications, open-data platforms, digital identity, participatory platforms, e-governance portals, and complaint management systems. These applications are successful when they are accessible, multilingual, inclusive, and connected to actual service delivery workflows. A common limitation is that digital services may exclude citizens who lack connectivity, devices, literacy, or trust in digital governance.

Table 4: Application Domains, ICT Enablers, and Expected Benefits

Domain	Primary ICT enablers	Representative applications	Expected benefits
Smart mobility	IoT, AI/ML, 5G, edge	Adaptive signals, smart parking, traffic prediction	Reduced congestion, faster response, better transport planning
Energy management	Smart meters, AI, cloud, blockchain	Demand response, smart grid, renewable integration	Energy savings, load balancing, transparent transactions
Environment	IoT, big data, GIS, digital twins	Air/noise/water monitoring, flood alerts	Real-time pollution tracking, resilience planning
Public safety	Computer vision, IoT, edge, AI	Emergency response, crowd monitoring,	Improved situational awareness and faster

		anomaly detection	intervention
Waste management	Smart bins, route analytics, IoT	Fill-level sensing, collection optimization	Operational efficiency, reduced fuel use
Governance	Open data, blockchain, mobile apps	Digital portals, grievance systems, e-participation	Transparency, service digitization, citizen engagement
Healthcare	IoT wearables, telemedicine, AI analytics	Remote monitoring, epidemic surveillance	Accessibility, early alerts, efficient service delivery

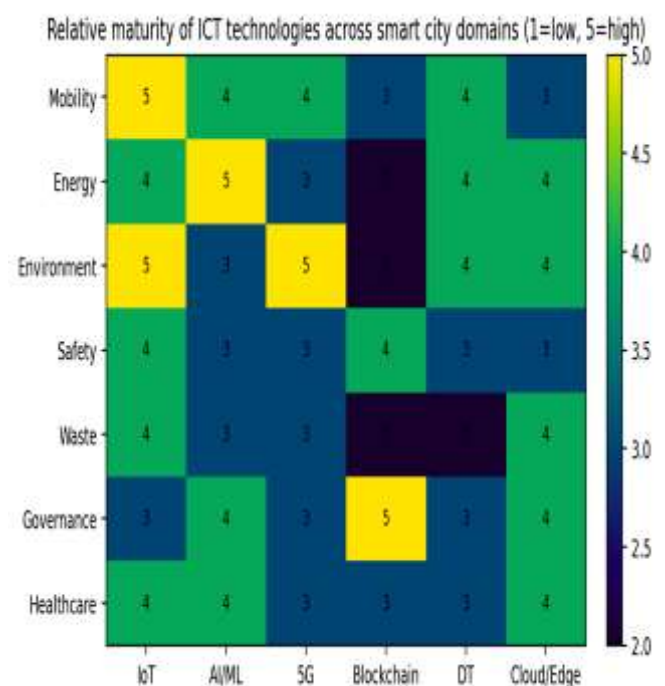


Figure 4: Relative maturity of major ICT technologies across selected smart city domains.

Table 5: Representative Recent Studies Used For Synthesis

Ref.	Focus	Contribution to this review
[7]	Urban IoT architecture	Baseline for sensing and communication layer design
[9]	Big data and AI in cities	Supports AI-enabled urban decision-making discussion
[10]	AI risks and contributions	Supports ethical and governance analysis
[11]	5G and IoT in smart cities	Supports low-latency and connectivity synthesis
[12]	Blockchain in smart cities	Supports trust, integrity, and decentralized service discussion

[16]	IoT-enabled smart cities	Supports concepts, frameworks, and open challenges
[17]	Security/privacy risks	Supports risk and governance framework
[22]	Hybrid analysis of IoT-enabled cities	Supports recent IoT research-area mapping
[24]	Emerging technologies for IoT-based cities	Supports cross-technology trends
[26]	Federated learning for smart cities	Supports privacy-preserving future direction

7. IMPLEMENTATION CHALLENGES AND CRITICAL DISCUSSION

The review identified six recurring challenge categories: technical, privacy and security, governance, financial, social, and organizational challenges. Technical challenges include interoperability, system integration, scalability, data quality, latency, device reliability, and legacy infrastructure. Smart city platforms must integrate heterogeneous devices, networks, data formats, municipal databases, and third-party services. Without open standards and modular architectures, cities risk creating isolated technology silos.

Cybersecurity and privacy are critical because smart city systems process sensitive data about mobility, health, identity, public services, energy consumption, and behavior. Risks include unauthorized access, data leakage, surveillance misuse, ransomware, denial-of-service attacks, sensor spoofing, and compromised connected devices [17], [19]. Privacy-by-design, encryption, authentication, role-based access control, data minimization, federated learning, and audit trails can reduce these risks but require institutional maturity and technical expertise.

Governance challenges arise because smart city projects involve multiple stakeholders: municipal departments, private vendors, telecom operators, citizens, regulators, researchers, and civil society. Lack of coordination can produce fragmented systems and unclear accountability. Strong governance requires data policies, procurement standards, ethical review, cybersecurity procedures, citizen feedback, interoperability guidelines, and long-term maintenance planning.

Financial challenges include high initial investment, uncertain return on investment, maintenance costs, vendor lock-in, and limited funding in developing regions. Pilot projects often succeed technically but fail to scale because budgets do not cover citywide deployment, operation, training, cybersecurity, and upgrades. Sustainable financing models such as public-private partnerships, phased implementation, open-source platforms, and shared infrastructure can improve feasibility.

Social challenges include digital divide, citizen acceptance, trust, literacy, and accessibility. A smart city should not only optimize systems but also improve quality of life equitably. If digital services are designed without citizen participation,

they can widen inequality or reduce trust. Human-centered design, inclusive access, multilingual interfaces, transparent algorithms, and community engagement should therefore be core smart city requirements rather than optional additions.

8. PROPOSED ICT INTEGRATION FRAMEWORK

Based on the synthesis, this paper proposes a layered smart city ICT integration framework consisting of five layers: device/perception, communication, data/platform, intelligence, and application. The device layer includes IoT sensors, cameras, smart meters, GPS devices, mobile phones, connected vehicles, and environmental monitoring devices. The communication layer includes 5G, Wi-Fi, LoRaWAN, NB-IoT, fiber networks, and protocols such as MQTT and CoAP. The data/platform layer includes cloud services, edge nodes, data lakes, APIs, dashboards, and digital twin environments. The intelligence layer includes AI/ML models, optimization algorithms, anomaly detection, explainable AI, and federated learning. The application layer provides services for mobility, energy, healthcare, governance, environment, safety, waste, and education.

The framework emphasizes vertical integration across layers and horizontal integration across municipal domains. Vertical integration ensures that sensor data can be converted into decisions and services. Horizontal integration ensures that mobility, energy, environment, public safety, and governance systems can exchange data where appropriate. A citywide data governance framework should operate across all layers to define ownership, access rights, privacy controls, cybersecurity standards, retention policies, and audit mechanisms.

A practical smart city architecture should also support modularity and scalability. Modularity allows cities to add or replace technologies without redesigning the entire system. Scalability ensures that pilots can expand from small testbeds to district-level and citywide deployment. Edge computing can reduce latency and bandwidth requirements, while cloud computing can support large-scale storage and analytics. Digital twins can act as integration environments for simulation, scenario testing, and policy evaluation.

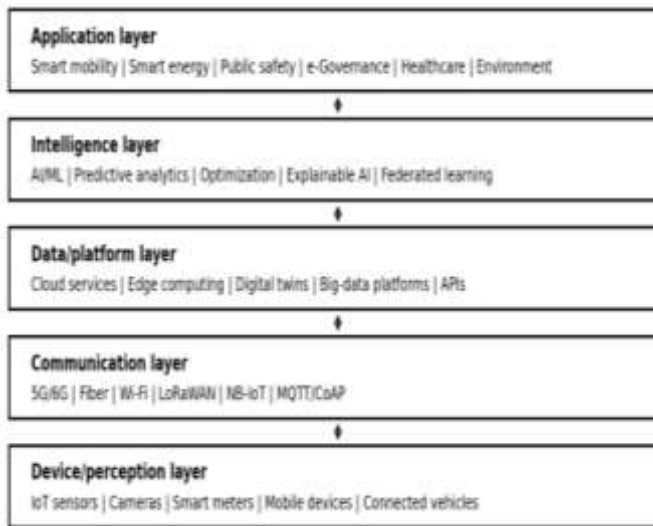


Figure 5: Proposed layered ICT integration framework for smart city applications.

Table 6: Success Factors for Scalable Smart City Ict Implementation

Success factor	Implementation implication
Leadership and governance	Establish cross-departmental ownership, standards, accountability, and policy alignment
Citizen engagement	Use participatory design, inclusive interfaces, feedback loops, and trust-building mechanisms
Open standards	Adopt interoperable data models, APIs, protocols, and procurement requirements
Data governance	Define data ownership, consent, privacy, retention, quality, and access controls
Cybersecurity-by-design	Apply secure architecture, monitoring, patching, authentication, and incident response
Financial sustainability	Plan lifecycle costs, maintenance, training, and scalable funding models

9. FUTURE RESEARCH DIRECTIONS

Future research should prioritize explainable and trustworthy AI for urban decision-making. As AI becomes embedded in public services, researchers must design models that are accurate, interpretable, auditable, and aligned with public values. Explainable AI can help municipal decision-makers understand model outputs and can support citizen trust in automated services.

Federated learning and privacy-preserving analytics represent another important direction. Smart cities often require collaboration across agencies and service providers, but raw data sharing may violate privacy or security requirements. Federated learning can train models across distributed data sources without centralizing sensitive data,

making it promising for healthcare, mobility, energy, and public safety [26].

Digital twins should move from visualization tools to decision-support systems. Future studies should develop methods for real-time synchronization, uncertainty estimation, validation, governance, and integration with AI models. Digital twins can support climate resilience, infrastructure maintenance, disaster management, energy planning, and participatory urban design.

Sustainable ICT is also essential. Smart cities should evaluate the energy consumption, carbon footprint, e-waste implications, and lifecycle costs of digital infrastructure. Green data centers, energy-efficient sensors, low-power networks, repairable hardware, and circular procurement can help align smart city development with environmental goals. Finally, more research is required for low-resource and developing-city contexts. Many smart city models assume stable infrastructure, high connectivity, strong institutions, and mature data governance. Future work should develop lightweight, affordable, interoperable, and community-centered smart city solutions suitable for diverse economic and institutional conditions.

10. LIMITATIONS

This review has limitations. First, the analysis is limited to English-language peer-reviewed publications and may exclude useful non-English studies, government reports, and industry white papers. Second, the review emphasizes Scopus, IEEE Xplore, Web of Science, and ACM Digital Library, which may underrepresent local smart city projects published outside these databases. Third, the included studies use different methodologies, metrics, and evaluation contexts, making quantitative meta-analysis inappropriate. Fourth, the field is evolving rapidly, especially with generative AI, 6G, edge AI, and urban digital twins, so future updates will be necessary.

11. CONCLUSION

This paper presented a PRISMA-based systematic literature review of innovative ICT applications in smart cities. The synthesis of 156 studies shows that IoT and AI are the dominant enabling technologies, while blockchain, 5G, cloud/edge computing, big-data analytics, and digital twins are increasingly important for secure, real-time, and integrated urban services. The most common application domains include smart mobility, energy management, environmental monitoring, public safety, waste management, governance, and healthcare.

The review demonstrates that successful smart city implementation depends on more than technology adoption. Cities must address cybersecurity, privacy, interoperability, governance, financing, digital inclusion, and organizational readiness. The proposed

layered ICT architecture provides a structured way to understand how devices, networks, platforms, intelligence, and applications interact in smart city ecosystems. Future research should focus on trustworthy AI, federated learning, sustainable ICT, digital twin governance, and smart city models for developing regions. A human-centered and sustainability-oriented approach is essential to ensure that smart city innovations improve urban life equitably and responsibly.

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