



## ENHANCING URBAN SUSTAINABILITY THROUGH IOT- ENABLED SMART CITY SOLUTIONS: A COMPREHENSIVE LITERATURE REVIEW

Raji Ibrahim Olayemi<sup>1</sup>, Yousef A. Baker El-Ebiary<sup>2</sup>, Julaily Aida Jusoh<sup>3</sup>

<sup>1</sup>Faculty of Informatics and Computing, Universiti Sultan Zainal Abidin –  
UniSZA, Terengganu, Malaysia.

<sup>2</sup>Faculty of Informatics and Computing, UniSZA, Malaysia.

<sup>3</sup>Faculty of Informatics and Computing, UniSZA, Malaysia.

Email: <sup>1</sup>ibraji12@gmail.com, <sup>2</sup>yousefelebiary@unisza.edu.my,  
<sup>3</sup>julaily@unisza.edu.my

Corresponding Author: **Yousef A. Baker El-Ebiary**

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### Abstract

*The persistent trend of global urbanisation presents a dual challenge: accommodating population growth while addressing significant environmental and social pressures. In response, the 'smart city' concept, underpinned by the Internet of Things (IoT), has become a leading vision for future urban development. This literature review systematically synthesises and critically assesses the existing academic discourse on the relationship between IoT-enabled smart city solutions and urban sustainability. It begins by establishing the conceptual foundations, exploring the evolution of urban sustainability and smart city paradigms, and positioning IoT as a vital enabler of infrastructure. The review then thematically examines the application of IoT across key urban sectors, such as energy, water, mobility, waste, and the built environment, analysing contributions towards sustainability goals, including resource efficiency and emissions reduction. Moving forward, the review also scrutinises a broad body of critical literature, highlighting ongoing challenges related to techno-solutionism, data governance, social equity, and barriers to implementation. Through this synthesis, a notable research gap emerges: a deficiency of integrated, socio-technical frameworks that guide the deployment of IoT solutions to ensure they achieve verifiable sustainability outcomes in an equitable way. The review concludes by emphasising the necessity for future research to shift focus from technological potential assessments to empirical studies of real-world implementation processes and comprehensive impact evaluations.*

**Keywords:** Urban Sustainability, Smart City, Internet of Things (IoT), Sustainable Development Goals (SDGs), Socio-technical Systems, Urban Governance.

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## **I. Introduction**

The 21st century is unequivocally an urban century. Cities, as engines of innovation and economic growth, account for over 70% of resource consumption and greenhouse gas emissions, acting as the primary sites for this development globally [CXV]. This concentration of activity places unprecedented strain on urban infrastructure and ecosystems, endangering the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) [CXV, CIII, CX]. The concept of urban sustainability, broadly defined as development that meets the needs of the present without compromising the ability of future generations to meet their needs [CVIII, C, CXII], has therefore become a central tenet of contemporary urban planning and policy [CIV].

In parallel, the discourse on urban development has been profoundly shaped by the rise of the smart city, a vision of a city that leverages information and communication technologies (ICT) to enhance operational efficiency, information sharing, and the quality of urban services [CIX, CI, CXI]. At the heart of this vision lies the Internet of Things (IoT), a vast network of interconnected sensors and devices that generate real-time data about the urban environment, effectively creating a digital nervous system for the city [CV, CII].

### **The Urban Sustainability Paradigm**

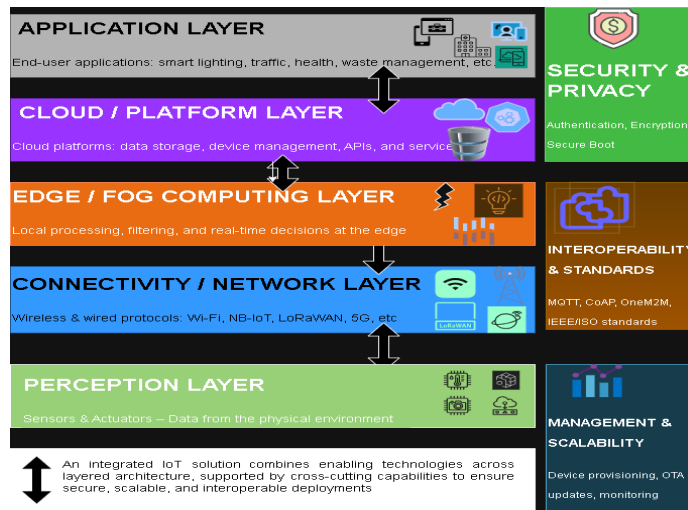
The concept of urban sustainability is multidimensional, traditionally encompassing three pillars: environmental (resource conservation and pollution reduction), social (equity, livability, and public health), and economic (viability and efficiency) [CVI, CXIII, CVII]. More contemporary frameworks, such as the 'urban metabolism' model, conceptualize the city as a complex ecosystem with resource inflows (energy, water, materials) and waste outflows (emissions, solid waste), arguing that sustainability hinges on creating more circular, less resource-intensive metabolic processes [CXIV, V, I]. Furthermore, the concept of urban resilience, which refers to a city's capacity to withstand and recover from shocks and stresses, such as climate-related events, has become integral to the sustainability discourse [IX, III, VII]. A truly sustainable city must therefore be resource-efficient, equitable, and resilient.

### **The Evolution of the Smart City Concept**

Studies have shown evolution in the conceptualization of the smart city. Initial formulations, often labelled "Smart City 1.0," were technology-driven, characterized by large-scale projects led by multinational tech corporations focused on optimizing isolated urban systems [II, X, IV]. This model faced significant criticism for its lack of citizen engagement and potential to create technologically controlled, rather than democratically governed spaces [VI, VIII, LXIV]. In response, scholars proposed more nuanced models. "Smart City 2.0" emphasized a greater role for city governments as leaders and strategists, focusing on utilizing technology to enhance public services and foster citizen engagement [LXI, LXIX, LXV, LXX]. The most recent shift is towards "Smart City 3.0," a citizen-centric model emphasizing co-creation, social inclusion, and the use of technology to empower communities and address issues of equity and justice, see figure 1 [LXII, LXVIII, LXVI, LXIII]. It is within this more holistic and critical framework that the potential of IoT for sustainability must be evaluated.

### The Internet of Things (IoT) as an Enabling Technology

From a technical standpoint, the IoT ecosystem is typically represented as a layered architecture, comprising a perception layer (sensors), a network layer (connectivity), a processing layer (data analytics), and an application layer (services) [LXVII, XXV, XXI, XXIX, XXIII]. This architecture enables the fundamental process of a smart city: sensing the state of the physical environment, communicating this data, analyzing it to derive insights, and acting upon those insights to optimize urban systems [XXVII, XXII]. From a sustainability viewpoint, the value of IoT lies not in the technology itself, but in its capacity to provide the high-resolution, real-time data necessary to manage the complex urban metabolism more effectively than ever before.



**Fig.1.** IoT Enabling Technology and Solution Model

#### Research Problem

Academic and policy literature is replete with optimistic accounts of IoT's potential to address complex urban sustainability challenges [XXX, XXIV, XXVI, XXVIII]. However, a significant disconnect exists between this projected potential and the empirically validated outcomes of real-world deployments. Early smart city models were heavily criticized for their techno-centric, top-down approaches, often driven by corporate actors rather than citizen needs or sustainability principles [LXXXV, LXXXI, LXXXIX, LXXXIII, LXXXVII]. While the discourse has since evolved towards more human-centric models, a critical effort is required to systematically evaluate the evidence, interrogate the underlying assumptions, and identify the key success factors and hidden risks associated with leveraging IoT for urban sustainability.

#### Scope and Objectives

This literature review aims to provide a comprehensive and critical analysis of scholarly research published between 2010 and 2025 on the role of the Internet of Things (IoT) in enhancing urban sustainability. The primary objectives of the review are to:

- I. Establish the conceptual linkages between urban sustainability, smart city paradigms, and IoT architecture.

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- II. Thematically review the application and impact of IoT solutions across key urban systems.
- III. Critically analyse the documented challenges, including technical, ethical, social, and governance issues.
- IV. Identify significant gaps in the current body of knowledge to propose a compelling agenda for future research.

### **Structure of the Review**

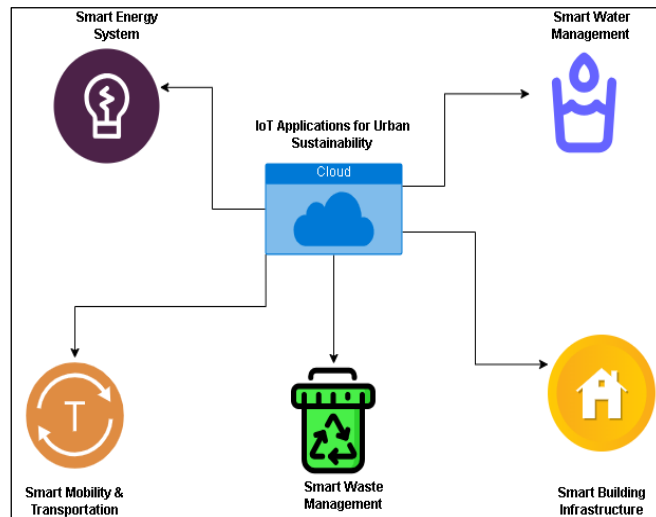
The review is structured as follows: Section 1 provides an introduction to the study. In section 2, the study outlines the conceptual foundations and the thematic analysis of IoT applications in urban sustainability. Section 3 provides a methodology and discusses the critical perspectives and challenges identified in the literature. Section 4 synthesizes the findings to identify the primary research gap. Finally, Section 5 provides a concluding summary.

## **II. IoT Applications for Urban Sustainability: A Thematic Review**

The theoretical convergence of the Internet of Things (IoT), smart cities, and urban sustainability is realized through a diverse array of practical applications that target specific urban systems. By embedding intelligence into the city's physical infrastructure, these IoT-enabled solutions aim to optimize resource use, reduce environmental impact, and improve the quality of urban services (see Figure 2 [LXXXII]). This section systematically reviews the literature across key domains, detailing the role of IoT, presenting findings from relevant studies, and linking these directly to quantifiable sustainability outcomes.

A critical observation emerging from this review is the profound interconnectedness of these systems. While individual applications offer discrete benefits, their broader behavior can be more rigorously understood by conceptualizing urban infrastructures as a multi-layer network  $G = (V, E, \{Ek\})$ , where each layer  $k$  represents a specific urban sector (e.g., energy, transportation, water), and nodes  $V$  correspond to infrastructure components interconnected through intra-layer links  $Ek$ . Interdependencies between sectors are captured through a coupling matrix  $Cij$ , which quantifies the influence of sector  $i$  on sector  $j$  [XC].

Within this framework, the integration of IoT applications can generate compounding sustainability gains through positive cross-sector interactions. However, it also introduces systemic vulnerabilities: disruptions in one layer may propagate across others via inter-layer dependencies, leading to cascading failures. Despite this, the reviewed literature largely treats these systems in isolation, lacking formal representations of interdependencies or empirical estimation of coupling strengths  $Cij$ . Consequently, the dynamics of failure propagation, resilience, and cross-sector trade-offs remain insufficiently understood, with limited application of analytical approaches such as percolation models or network flow analysis.



**Fig. 2.** IoT Application for Urban Sustainability

### Formalizing Interconnectedness

While the literature widely acknowledges the interconnected nature of urban systems, this interdependence is rarely formalized in a way that enables systematic analysis. To address this limitation, IoT-enabled urban infrastructures can be conceptualized as a multi-layer network  $G = (V, E, \{Ek\})$ , where  $V$  represents system components (e.g., sensors, infrastructure nodes),  $Ek$  denotes intra-layer connections within sector  $k$  (e.g., energy, transport, water), and inter-layer dependencies are captured through a coupling matrix  $Cij$ , representing the influence of sector  $i$  on sector  $j$ .

Within this representation, the “interconnectedness” of smart city systems becomes analytically tractable. However, the existing literature largely lacks efforts to define or estimate such coupling structures, resulting in an inability to quantify cross-sector dependencies or evaluate systemic risks. In particular, there is limited investigation of how disruptions in one layer (e.g., energy systems) propagate across other layers (e.g., water supply or transportation), [LXXXIV] despite well-established approaches in network science.

This limitation constrains the assessment of resilience and sustainability, as cascading failures and feedback loops cannot be rigorously analyzed without an explicit representation of interdependencies. From an analytical perspective, the absence of quantified coupling matrices  $Cij$  prevents the application of established methods such as percolation theory, network flow analysis, or robustness simulations to evaluate system-wide behavior under stress [LXXXIV].

### Smart Energy Systems

The energy sector is a primary target for IoT-driven sustainability initiatives. The development of the smart grid is a central theme among scholars, where IoT sensors and smart meters enable two-way communication between utilities and consumers. Studies indicate that this facilitates demand-response programs, reduces transmission losses, and improves the integration of intermittent renewable energy sources [LXXXVI]. Furthermore, IoT-enabled smart street lighting systems have demonstrated

energy savings of 50-70% in numerous pilot projects by dynamically adjusting illumination based on real-time presence detection [LXXXVIII, LXXXIV, XI].

### **Smart Water Management**

Addressing water scarcity and improving water quality are critical components of urban resilience. The literature highlights two main IoT applications in this domain. First, smart water metering provides granular data on consumption patterns, enabling both utilities to manage demand more effectively while encouraging consumers to reduce waste [XIX]. Second, the deployment of acoustic and pressure sensors in water distribution networks for real-time leak detection has been shown to significantly reduce non-revenue water (NRW). Several studies report reductions exceeding 15%, underscoring the substantial efficiency gains achievable through IoT-enabled monitoring [XII, XVIII].

### **Smart Mobility and Transportation**

The Internet of Things (IoT) plays a central role in the development of Intelligent Transportation Systems (ITS). Research demonstrates how data from road sensors and GPS-enabled vehicles can be utilized for dynamic traffic signal control, thereby reducing congestion and associated vehicle emissions [XIV, XVI, XX, XIII]. A significant portion of urban traffic congestion, estimated to be as high as 30% in some cities, is caused by drivers circulating in search of parking spaces [XVII].

The integration of smart parking systems, which guide drivers to available spaces using IoT sensors to provide real-time information on parking availability, has been shown to significantly reduce cruising time, a major contributor to urban traffic congestion and pollution [L, XLIX, XLVIII, XLVII, XLVI]. Collectively, these interventions contribute directly to environmental sustainability by lowering fuel consumption, reducing emissions, and improving urban air quality.

### **Smart Waste Management**

Traditional waste collection systems are particularly inefficient. Empirical studies demonstrate that IoT-enabled waste bins equipped with fill-level sensors can trigger collection requests only when necessary, thereby eliminating unnecessary trips to half-empty bins or failures to collect overflowing ones. This optimization reduces fuel consumption, greenhouse gas emissions, and public health risks [XLV].

IoT-enabled smart waste management systems fundamentally transform this process into a dynamic, data-driven operation. The core technology involves deploying smart bins fitted with ultrasonic sensors that monitor fill levels in real-time [XLIV]. This enables the dynamic routing of sanitation fleets, resulting in substantial reductions in fuel consumption, operational costs, and CO<sub>2</sub> emissions, with reported efficiency gains of up to 40% [XLIII, XLII, XLI, XCV].

In addition, data collected from these systems provides valuable insights into waste generation patterns, supporting the formulation of evidence-based waste reduction policies. A case study conducted in Malaysia validated these benefits, reporting a 20% reduction in truck mileage and an 18% reduction in CO<sub>2</sub> emissions over a 30-day trial period [XCI].

### **Smart Buildings and Infrastructure**

Buildings account for approximately 40% of total energy consumption, largely due to heating, ventilation, and air conditioning (HVAC) systems and lighting. Addressing this energy intensity through the deployment of IoT-driven Building Management Systems (BMS) plays a crucial role in improving energy efficiency and reducing emissions [XCIX, XCIII, XCVII].

For instance, smart HVAC systems can dynamically adjust heating and cooling based on real-time occupancy, as well as pre-cool or pre-heat spaces using predictive occupancy patterns and real-time energy pricing data from the smart grid. These systems rely on a network of sensors to optimize HVAC and lighting operations according to occupancy and environmental conditions, resulting in energy savings of 20-30% [XCII, XCVIII, XCIV].

Beyond energy management, Structural Health Monitoring (SHM) using IoT sensors to monitor bridges and other critical infrastructure, enabling predictive maintenance. This enhances safety, extends asset lifespans, and aligns with circular economy principles by reducing the need for premature demolition and resource-intensive reconstruction [XCVI].

### **Critical Perspectives and Challenges**

Despite the documented benefits of IoT-enabled urban systems, a substantial body of literature presents a critical counter-narrative, highlighting vigorous debates that challenge idealized technological narratives [XXXIV, XXXI]. These critiques are essential for a balanced understanding, as they draw attention to the profound security, social, and ethical complexities associated with transforming cities into pervasive sensing environments [XXXIX, XXXV, XXXIII].

Beyond these concerns, a key limitation in the existing literature is the tendency to treat IoT-enabled systems as static interventions rather than **dynamic, feedback-driven systems**. In practice, many smart city applications, such as intelligent transportation systems or smart grids, operate as **closed-loop dynamical systems**, which can be conceptually represented in state-space form as:  $xt+1=f(xt, ut, wt)$  where  $xt$  denotes the system state (e.g., traffic density, energy load),  $ut$  represents control actions (e.g., signal timing, demand response), and  $wt$  captures exogenous disturbances (e.g., weather conditions, demand fluctuations).

Within this framework, IoT technologies function as sensing and actuation layers that continuously update system states through feedback mechanisms. However, the reviewed literature largely evaluates these systems using before-and-after performance metrics (e.g., efficiency gains), without examining their **temporal evolution, feedback effects, or stability properties**. This omission limits the ability to assess whether observed improvements are sustained over time or whether they lead to unintended dynamics such as demand rebound, control instability, or oscillatory behaviour in adaptive systems.

From a systems perspective, critical challenges such as techno-solutionism, privacy trade-offs, and governance limitations are further compounded by the absence of analyses addressing **system stability and convergence** (e.g., whether  $xt$  remains bounded or converges to a desirable equilibrium). Without incorporating temporal datasets or longitudinal modelling approaches, it remains unclear whether IoT-enabled

interventions produce resilient and sustainable urban outcomes or merely transient performance improvements.

### **Techno-solutionism and Governance Deficits**

A primary critique of the smart city agenda is its tendency towards techno-solutionism, an ideological belief that complex social and political problems can be resolved through technological interventions [XL, XXXII]. Scholars such as Hollands and Greenfield argue that this approach often neglects the underlying political, economic, and structural drivers of urban unsustainability.

Kitchin further contends that the most critical governance questions remain insufficiently addressed, including how urban data are collected and stored, who owns and controls these data, and whose algorithms ultimately shape decision-making processes. Failure to address these governance gaps risks framing smart city initiatives as instruments of private technology corporations, thereby undermining democratic accountability and public interest [XXXVIII, XXXVI, XXXVII].

The absence of clear legal and ethical frameworks governing data collection, consent, and ownership remains a major point of contention. In response, scholars have proposed alternative data governance models, such as data trusts or data commons, that conceptualize urban data as a public asset managed under democratic oversight rather than as proprietary corporate resources [LXXV, LXXI].

### **Data Ethics, Privacy, and Security**

The defining feature of smart cities' pervasive, real-time data collection is simultaneously their greatest vulnerability. The literature raises profound concerns regarding the potential for mass surveillance and the erosion of citizens' privacy, often likening smart cities to panoptic environments of continuous monitoring [LXXIX].

Moreover, the scale and heterogeneity of urban IoT deployments create an exceptionally large attack surface. Many IoT devices, particularly low-cost sensors, possess limited processing power and memory, making the implementation of robust security protocols [LXXIII, LXXVII]. As a result, such systems are vulnerable to cyberattacks, including exploitation within large botnets to launch Distributed Denial of Service (DDoS) attacks capable of disabling critical city services. A successful cyberattack on essential infrastructure, such as a smart grid or water distribution system, could have catastrophic consequences, posing a direct threat to urban resilience and public safety [LXXII, LXXX, LXXIV].

### **The Digital Divide and Social Equity**

While smart city technologies are often promoted as tools for enhancing urban sustainability and quality of life, the literature cautions that, if not designed with equity as a core principle, they may exacerbate existing social inequalities. Urban societies are already structured along lines of socio-economic advantage and disadvantage [LXXVI]. Without deliberate inclusion strategies, smart city initiatives risk reinforcing these divides rather than alleviating them [LXXVIII, LVI].

Access to smart services frequently depends on factors like digital literacy, smartphone ownership, and reliable internet connectivity resources, which are unevenly distributed across the population [LI, LIX, LV, LX]. This creates a digital divide in which the benefits of smart urban systems disproportionately accrue to already privileged groups, while marginalized communities may face exclusion or even harm, for example,

through algorithmic bias in policing, welfare allocation, or service delivery [LII, LVIII, LIII].

**Implementation Barriers**

At a practical level, the literature identifies numerous barriers to the successful implementation of IoT-enabled urban systems. These include high initial deployment costs, limited interoperability between different vendor-specific technologies, shortages of municipal staff with advanced data analytics and cybersecurity skills, and the complexity of designing effective public-private partnerships [LVII, LIV], see table 1.

**Table 1: Summary of Critical Perspectives and Challenges**

Theme	Specific Challenge	Description	Supporting Sources
<b>Governance &amp; Ideology</b>	Techno-solutionism	The belief that complex social/political problems can be solved with purely technological fixes, ignoring root causes.	[LXXXV]
	Governance Deficits	Focusing on efficiency obscures the political questions of data ownership, algorithmic control, and whose interests are being served.	[LXXXIX], [XC], [XCI]
	Corporate-led Governance	Privatization of urban governance, where private tech firms control public data infrastructure, undermines democratic accountability.	[XCIII]
<b>Data, Ethics, &amp; Security</b>	Cybersecurity Vulnerabilities	Hyper-connectivity creates a vast attack surface, making critical infrastructure (grids, water) vulnerable to cyber-physical attacks.	[XCVII], [XCVIII]
	Mass Surveillance & Privacy Erosion	Pervasive data collection from sensors and cameras raises concerns about a "panopticon city" and the loss of civil liberties.	[XCV], [XCVI]
	Data Ownership & Sovereignty	Unresolved legal and ethical questions about who owns and controls the vast amounts of data generated by citizens.	[LXXXIX], [XC], [XCI]
<b>Social Equity &amp; Justice</b>	The Digital Divide	Unequal access to technology, the internet, and digital literacy skills excludes marginalized groups from the benefits of smart cities.	[CI], [CII]
	Algorithmic Bias	AI systems trained on biased historical data can perpetuate and exacerbate societal inequalities in areas such as policing and service delivery.	[CIV], [CV]

	Lack of Citizen Participation	Top-down implementation models that fail to meaningfully involve citizens in the design and governance of smart city projects.	[XXVI]
<b>Implementation &amp; Impact</b>	Rebound Effect	Efficiency gains in one area (e.g., traffic) may lead to increased overall consumption (e.g., more driving), negating benefits.	[CIX], [CX]
	High Costs & Scalability	Significant upfront investment and ongoing maintenance costs are major barriers for municipalities, as is scaling pilot projects city-wide.	

### III. Methodology

This paper constitutes a comprehensive and critical synthesis of a corpus of academic literature, including peer-reviewed journal articles, conference papers, technical reports, and relevant industry analyses. The methodology employed is a structured literature review, designed to systematically map, analyse, and integrate a diverse body of knowledge in order to identify key concepts, trends, and research gaps [CXII]. The review process involved several distinct stages. First, an initial analysis of the selected research materials was conducted to extract foundational definitions, key theoretical frameworks, and empirical findings related to the core themes of urban sustainability, smart cities, and the Internet of Things [XLII].

Second, a thematic analysis was undertaken to categorize the literature according to major application domains (e.g., energy, mobility, waste, water) and critical challenges (e.g., governance, privacy, equity, interoperability) [CXIV]). This approach enabled systematic comparison of findings and perspectives across different sub-fields.

Third, a critical synthesis was performed to move beyond descriptive summarization and to interrogate relationships, tensions, and contradictions within the literature. This involved comparing technology-focused studies that emphasize efficiency and optimization with the critical, socio-technical scholarship that foregrounds ethical, political, and governance concerns. This integrative process directly led to the identification of the primary research gaps, as articulated in the subsequent discussion. By and large, the review was structured to develop a coherent analytical argument, culminating in the proposal of a future research agenda grounded in the identified limitations of the existing body of knowledge.

Lastly, this review adopted a structured measuring and evaluating framework to assess the quality, strength, weaknesses, and relevance of existing literature, to analyse scholarly works on IoT-enabled smart solutions and urban sustainability. For measurement, the study focused on how existing research defines and assesses sustainability through various indicators, levels of analysis, and methodological frameworks. An evaluation of the existing literature was also conducted through a critical examination of conceptual rigor, methodological strength, and empirical validity, particularly in relation to the degree to which efficiency gains support equitable and long-term sustainability outcomes. This paradigm facilitates a systematic comparison across themes, revealing key gaps in existing studies.

## **Synthesis and Identification of the Research Gap**

### **Synthesis of the Literature**

The existing literature presents a complex and often contradictory picture of IoT-enabled urban sustainability. On the one hand, substantial evidence from numerous domain-specific studies indicates that IoT technologies can, in principle, deliver significant improvements in resource efficiency, thereby supporting environmental sustainability objectives. On the other hand, a robust body of critical scholarship demonstrates that these technologies are deeply embedded within complex social and political systems, and their implementation introduces ethical risks and practical challenges that may undermine both social and environmental objectives. A dominant limitation in the literature is the tendency to examine these two dimensions, the technological potential of IoT and its socio-ethical implications, in relative isolation. As a result, insufficient attention is paid to how technological innovation interacts with governance structures, institutional capacity, and long-term sustainability outcomes in practice.

### **The Primary Research Gap**

This review identifies a critical gap at the intersection of these two strands of research: the absence of integrated, empirically grounded socio-technical frameworks for implementing and managing IoT-enabled systems in urban contexts. While many studies focus on what technology can achieve (the technical literature) or on the risks it poses (the critical literature), there is a notable lack of research examining how much systems can be deployed, governed, and adapted in practice to achieve sustainable, equitable, and resilient urban outcomes.

Specifically, the literature reveals deficiencies in the following areas:

- I. **Holistic, Longitudinal Impact Assessments:** In terms of scope, most studies focus on short-term pilot projects or isolated performance metrics (e.g., energy saved) without evaluating long-term system-wide impacts. This includes limited consideration of rebound effects, institutional lock-in, and unintended social consequences.
- II. **Context-Specific Governance Models:** There is insufficient research on governance arrangements, policy frameworks, and citizen engagement mechanisms capable of managing trade-offs between efficiency, privacy, and equity, especially within the diverse institutional and socio-economic contexts of cities in the Global South.
- III. **Actionable Implementation Frameworks:** Urban policymakers and practitioners lack empirically validated, practical frameworks that integrate technological design with adaptive governance, social inclusion, and ethical oversight. This gap constrains the effective translation of IoT innovations into sustained urban sustainability outcomes.

### **Socio-Institutional Outcomes**

This review identifies a critical gap at the intersection of technical performance and socio-institutional outcomes in IoT-enabled smart city systems. To formalize this gap, we conceptualize urban IoT deployments within a joint socio-technical space  $Z = (T, G, S)$ , where  $T$  denotes technical performance metrics (e.g., efficiency, scalability, reliability),  $G$  represents governance variables (e.g.,

regulatory frameworks, data governance, citizen participation), and SSS captures social outcomes (e.g., equity, inclusiveness, quality of life).

Within this multidimensional space, the “integration gap” is defined as the misalignment or weak coupling between these dimensions, which can be empirically examined through the joint distribution  $P(T, G, S)$ . Existing literature, however, predominantly analyzes these dimensions in isolation, with limited attempts to construct datasets or models that enable joint or conditional analysis (e.g.,  $P(S|T, G)$ ,  $P(S \mid T, G)$ ,  $P(S|T, G)$ ). As a result, it remains unclear whether improvements in technical performance systematically translate into positive governance or social outcomes, or whether trade-offs (e.g., efficiency versus equity) emerge in practice.

Specifically, the literature reveals deficiencies in the following areas:

**I. Holistic, Longitudinal Impact Assessments:**

Most studies emphasize short-term pilot evaluations or isolated technical indicators without capturing system-wide, long-term dynamics across TTT, GGG, and SSS. There is limited use of longitudinal or panel data to analyze how relationships within  $P(T, G, S)$  evolve, including rebound effects, institutional lock-in, and unintended social consequences.

**II. Context-Specific Governance Models:**

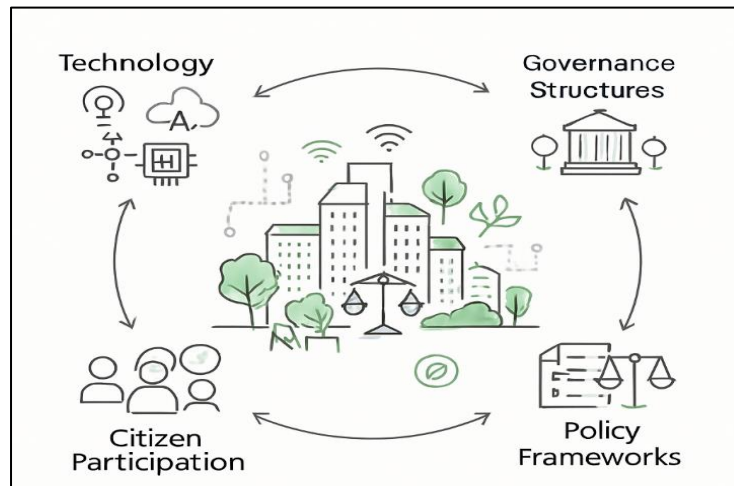
There is insufficient empirical modeling of governance variables GGG and their interaction with technical systems TTT in diverse urban contexts. In particular, cities in the Global South lack datasets and comparative analyses that would allow estimation of how governance structures mediate social outcomes SSS, constraining the ability to evaluate context-dependent trade-offs.

**III. Actionable Implementation Frameworks:**

Urban policymakers and practitioners lack empirically validated frameworks that explicitly integrate and operationalize TTT, GGG, and SSS. Few studies propose measurable indicators or analytical methods (e.g., correlation, regression, or causal inference models) to detect misalignment within  $ZZZ$ , limiting the ability to translate IoT innovations into sustainable, equitable, and resilient urban outcomes.

**Proposed Research Direction**

Therefore, a major priority for future studies is to address this gap by developing and empirically testing socio-technical frameworks for the sustainable and equitable implementation of smart city technologies. Such research should move beyond narrow assessments of technological performance to examine the dynamic interactions between technology, governance structures, policy frameworks, and citizen participation in shaping real-world sustainability results, see figure 3.



**Fig. 3.** Showing the Future smart city research, which integrates technology with governance, policy, and inclusive participation to achieve real-world sustainability

#### **IV. Results and Discussion**

The findings from this literature review suggest that IoT-enabled smart city solutions show a strong and consistent potential for improving operational efficiency and urban sustainability. This is particularly relevant within certain urban sectors such as water, waste management, energy, mobility, and buildings. Across different sectors, empirical evidence consistently demonstrates reductions in energy consumption, measurable efficiency gains, water losses, operational costs, emissions, and traffic congestion. [LXXVIII] These findings further established the role of IoT as a crucial enabling technology for data-driven optimization of urban systems, corroborating past studies which argue that IoT is the digital nervous system of smart cities [XII, XL].

Furthermore, in the built environment and energy industries, research on smart meters, building management systems, and smart grids shows significant efficiency improvements using demand-response mechanisms, real-time monitoring, and predictive control [LXXVI, LXXIX]. Similarly, studies on smart water management indicate that IoT-enabled smart metering and leak detection can sustainably reduce non-revenue water, which in turn leads to a sustainable enhancement of urban resilience [CXV]. In mobility and transport, smart parking applications and IoT-based intelligent transportation systems are reported to reduce emissions and congestion by minimizing cruising time and optimizing traffic flows [LXIII, LXV, LXVIII]. Together, these findings demonstrate the technical effectiveness of IoT interventions, especially in sector-specific implementations and pilot projects.

Despite these positive results reported, several issues appear. A critical assessment indicates that these positive results are significantly confined to short-term, project-level assessments, without sufficient evidence of a broad system sustainability effect. Most of these studies rely on narrow performance metrics, such as emission reductions or percentage energy savings, without accounting for rebound impacts, cross-sectoral interactions, and institutional lock-in [CX]. The result here indicates and aligns with critiques of early smart city models, which emphasize tech optimization while downplaying broader socio-political dynamics [XLVII]. As a result, the literature tends

to overemphasize the power and potential while underexploring the complexity attached to its implementation.

Another major result concerns the emergence and the importance of governance, social equity challenges, and ethical concerns within existing literature. Scholars have consistently demonstrated concerns about the disturbing nature of techno-solutionism, arguing that smart city programs frequently frame complex urban issues as technical problems, as a consequence, creating nuances on their structural and political roots [LXXXVII]. Researchers focusing on data governance have raised unanswered questions surrounding accountability, algorithmic control, and data ownership, raising concerns about how corporate-led smart city models can influence and undermine democratic governance. According to the arguments of these scholars, it is clear that without comprehensive institutional models, IoT deployments risk reinforcing existing power asymmetries rather than promoting inclusive sustainability.

Further results also highlight a persistent imbalance between social sustainability considerations and environmental efficiency. While environmental indicators are often dominant in empirical findings, issues such as privacy, digital exclusion, citizen participation, and cybersecurity are frequently addressed as secondary concerns [XCIX]. Research on the digital divide also shows that access to smart services is unevenly distributed, with the possibility of excluding marginalized groups, triggering urban inequality [CV]. This imbalance raises serious social concerns and limits the extent to which smart city programs can be genuinely considered sustainable within ethical and social contexts.

These findings and analyses converge, providing insight into underlying issues. First, the major limitation of the existing body of research lies not in technological potentials but in socio-technical integration. Second, while IoT technologies can provide measurable efficiency gains, their sustainability outcomes are dependent on the quality of governance, inclusive implementation models, and institutional capacity. The absence of empirically validated and integrated socio-technical models linking IoT deployment with long-term sustainability and governance arrangements presents a crucial gap in current research. Addressing this limitation is crucial for integrating smart city innovations into technologically advanced, yet resilient, equitable, and sustainable cities.

## **V. Conclusion**

This study critically examined the role of IoT-enabled smart city solutions in advancing and promoting urban sustainability. The study finds that IoT technologies have the capacity to optimize efficiency across major urban systems. These include water, energy, mobility, buildings, and waste management. Empirical studies further suggest that reductions in emissions, operational inefficiencies, water losses, and energy consumption reinforce the dominant idea that IoT serves as a major infrastructure that enables data-driven urban management.

The study further highlights that these benefits are overwhelmingly documented across sector-specific, pilot-based projects, which are short-term, limiting their capacity to provide a comprehensive knowledge of system-wide sustainability outcomes, which are long-term. The ethical and social dimensions of sustainability, which encompass citizen participation, data governance, privacy, and equity, are also underexplored and insufficiently integrated into mainstream smart city research. As a consequence, most

of the available literature continues to focus on technological improvement over broader socio-institutional importance.

Critically, scholars have demonstrated that the absence of adequate governance models in IoT-enabled smart city programs risks reinforcing techno-solutionism, digital inequality, and corporate dominance. Further issues, linked to cybersecurity susceptibility, the digital divide, and data ownership, underscore the importance of examining smart cities as socio-technical systems rather than purely technological projects. This suggests that sustainability outcomes are not solely dependent on technological design, but also on the relevance of institutional capacity, governance quality, and inclusive implementation models.

The principal challenge facing smart city development is no longer technological innovation, but socio-technical implementation. The absence of integrated, empirically grounded frameworks linking IoT deployment with governance arrangements and long-term sustainability outcomes constitutes a critical gap in the literature. Addressing this gap requires future research to move beyond efficiency-focused evaluations toward longitudinal, context-sensitive, and governance-aware studies that can ensure smart cities are not only technologically advanced but also equitable, resilient, and sustainable.

Future research should integrate control-theoretic and data-driven approaches to model IoT-enabled urban systems as dynamical processes, enabling the analysis of stability, convergence, and long-term system behavior under varying operational and environmental conditions.

#### **Conflict of Interest:**

There was no conflict of interest regarding this paper.

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