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ICT-Enabled Smart Environment Development: A Systematic Review of Technologies, Functional Roles, and Environmental Outcomes

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ABSTRACT

Information and communication technology (ICT) is increasingly used to address urban environmental challenges, yet evidence on its specific roles in Smart Environment initiatives remains fragmented. This study systematically reviews the technologies, functional roles, and environmental outcomes of ICT-enabled Smart Environment development. A systematic literature search was conducted across six academic databases for studies published from 2020 to 2025. Of 1,879 initially identified records, 30 studies met the eligibility criteria and minimum quality threshold and were synthesized thematically. The findings identify the Internet of Things as the most frequently reported technology, complemented by artificial intelligence, cloud/fog/edge computing, digital twins, blockchain, smart grids, and other digital systems. ICT contributes through six interconnected functions: environmental sensing and monitoring, data integration, intelligent analytics, decision support, resource efficiency, and governance support. The main conceptual contribution is an integrative ICT-enabled Smart Environment framework linking ICT enablers, functional roles, application domains, and environmental outcomes. Although the reviewed studies generally report positive contributions, direct and comparable evidence of environmental improvement remains limited. Future research should evaluate integrated ICT architectures using measurable sustainability indicators.

INTRODUCTION

The accelerating pace of urbanization has given rise to various environmental challenges, such as increased air pollution, high energy consumption, traffic congestion, suboptimal waste management, and pressures on the quality of life for urban residents(Mukherjee & Bairwa, 2025). In this context, the Smart City concept has emerged as a strategic approach to managing cities more efficiently, responsively, and sustainably through the use of digital technology(Bibri & Krogstie, 2020). One key dimension of the Smart City is the Smart Environment, a concept of intelligent environmental management that leverages technology to monitor, control, and improve environmental quality in a sustainable manner(Ullah et al., 2024).

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A Smart Environment is not only about using technology to manage the physical environment, but also encompasses a city's ability to leverage data, sensors, digital infrastructure, and analytical systems to support decision-making(Bibri et al., 2023). Through this approach, city governments and stakeholders can obtain environmental information more quickly and accurately—for example, regarding air quality, energy use, waste management, mobility, green open spaces, and environmental resilience(Attah et al., 2024). Therefore, a Smart Environment is a vital component in efforts to create cities that are not only technologically advanced but also ecologically sustainable and socially inclusive.

Although the use of ICT in Smart Cities has been extensively studied, discussions regarding the specific role of ICT in supporting a Smart Environment remain scattered across various contexts and approaches(Deebak et al., 2020). Some studies focus on the Internet of Things (IoT) for environmental monitoring, while others address digital twins for urban planning, cloud and edge computing for data infrastructure, or AI for predictive analytics(Prasath & Vishnupriya, 2025). This situation indicates that research on Smart Environments remains fragmented based on technology type, application domain, and intended use. Consequently, there is currently no comprehensive overview of how ICT contributes to the development of Smart Environments, which technologies are most widely used, or the extent to which these technologies impact environmental quality.

Furthermore, previous studies have often treated the "Smart Environment" as part of the broader discussion of "Smart Cities," meaning that environmental aspects have not been analyzed in depth. In fact, environmental issues have distinct characteristics compared to other dimensions of Smart Cities because they are directly related to ecological sustainability, resource efficiency, climate change mitigation, and the quality of life for the community(Addas, 2023).

Previous studies have examined ICT-enabled Smart Environment development from different perspectives. (Bibri et al., 2023) primarily focused on the convergence of AI, IoT, and big data for environmentally sustainable smart cities, while (Ullah et al., 2024) emphasized IoT and machine learning in data-centric smart environments. (Jacques et al., 2024) discussed integrated technological solutions for urban management, whereas (Peldon et al., 2024) concentrated specifically on the role of digital twins in smart city development. In addition, (R. U. Islam et al., 2025) approached Smart Environment development primarily from the perspective of future Internet and networking architectures. Although these studies provide important insights, their scopes tend to emphasize particular technological ecosystems, individual technologies, or broader smart city contexts.

Consequently, a comprehensive synthesis that simultaneously connects a broad range of ICT technologies with their functional roles, application domains, and environmental outcomes remains limited. Moreover, previous studies have not sufficiently distinguished between the expected environmental benefits of ICT implementation and environmental improvements supported by direct empirical evidence. To address these gaps, the present review develops an integrative ICT-enabled Smart Environment framework linking technological enablers, functional roles, application domains, and environmental outcomes.

Given these research gaps, this study conducts a Systematic Literature Review (SLR) to systematically examine the role of ICT in supporting Smart Environment development and management. A structured review protocol was employed to ensure that the processes of literature identification, screening, eligibility assessment, quality assessment, and synthesis were conducted systematically and transparently. This review aims not only to summarize previous research but also to develop a conceptual map of the relationships between ICT technologies, their functional roles, application domains, and environmental outcomes.

The novelty of this study lies in the development of a systematic review that classifies the role of ICT in the Smart Environment into several key functions, namely environmental sensing and monitoring, data integration, intelligent analytics, decision support, resource efficiency, and environmental governance. Through this classification, this study is expected to make a theoretical contribution to the development of the Smart Environment literature, as well as a practical

contribution to city governments, technology developers, and policymakers in designing ICT-based environmental management strategies. Specifically, this study aims to answer the following three research questions:

1. How does ICT contribute to the development and management of a Smart Environment?
2. What types of ICT-based technologies are used to support a Smart Environment?
3. To what extent does ICT impact environmental quality in the implementation of a Smart Environment?

This article consists of four sections. The first section presents the background, research gap, novelty, and research questions. The second section explains the Systematic Literature Review (SLR) method, including data sources, search strategy, selection criteria, quality assessment, and data synthesis. The third section presents and discusses the findings on ICT technologies, functional roles, application domains, environmental outcomes, implementation challenges, and the proposed ICT-enabled Smart Environment framework. The final section summarizes the main conclusions, research contributions, limitations, and future research directions.

RESEARCH METHODS

This study employed a Systematic Literature Review (SLR) to identify, evaluate, and synthesize previous studies on the role of Information and Communication Technology (ICT) in Smart Environment development. A structured review protocol was applied to ensure a transparent and systematic process of study identification, screening, eligibility assessment, quality assessment, and final inclusion. The review protocol was designed to address three research questions concerning the functional roles of ICT, the technologies applied, and the environmental outcomes reported in Smart Environment initiatives. The search protocol and eligibility criteria are presented in Table 1.

Table 1. Search Protocol and Eligibility Criteria

Component	Search Protocol and Eligibility Criteria
Review design	This study employed a Systematic Literature Review (SLR) to identify, screen, assess, and synthesize studies on the role of Information and Communication Technology (ICT) in Smart Environment development.
Review objective	The review examined: (1) the functional roles of ICT in Smart Environment development and management; (2) the ICT-based technologies applied in Smart Environment initiatives; and (3) the environmental outcomes associated with ICT implementation.
Data sources	ScienceDirect, Emerald Insight, IEEE Xplore, SpringerLink, Wiley Online Library, and Taylor & Francis Online.
Search date	The searches were conducted between January 1, 2020, and December 31, 2025.
Publication period	Studies published from 2020 to 2025 were considered to capture recent developments in ICT-enabled Smart Environment research.
Search fields	Title, abstract, keywords, and full-text fields were searched where supported by each database. The search syntax was adapted to the technical format of each database.
Search string	(“smart environment” OR “smart city environment” OR “smart sustainable city” OR “urban environment”) AND (“ICT” OR “information and communication technology” OR “digital technology” OR “Internet of Things” OR “IoT” OR “artificial intelligence” OR “cloud computing” OR “fog computing” OR “edge computing” OR “digital twin” OR “blockchain”) AND (“environmental quality” OR “environmental management” OR “sustainability” OR “energy efficiency” OR “waste management” OR “air quality”)

Component	Search Protocol and Eligibility Criteria
Document type	Peer-reviewed journal articles, conference papers, and scholarly book chapters available in full text.
Language	English.
Inclusion criteria	(1) Studies published between 2020 and 2025; (2) studies discussing Smart Environment, smart city environmental management, or ICT-enabled urban environmental management; (3) studies examining ICT-related technologies, such as IoT, AI, cloud/fog/edge computing, digital twins, blockchain, smart grids, sensors, or related digital systems; (4) studies reporting applications, frameworks, models, implementations, or outcomes relevant to environmental management; and (5) studies available in full text.
Exclusion criteria	(1) Studies unrelated to Smart Environment, urban environmental management, or environmental sustainability; (2) studies discussing Smart City without a substantive environmental focus; (3) studies merely mentioning ICT or Smart Environment without explaining technological application, function, or outcome; (4) duplicate records; (5) editorials, opinion papers, non-academic publications, and inaccessible full-text documents; and (6) studies with insufficient methodological or conceptual relevance to the review questions.
Screening process	Records were screened sequentially through title and abstract screening, duplicate removal, full-text eligibility assessment, and final inclusion.
Data extraction and synthesis	Data were extracted regarding publication characteristics, ICT technologies, functional roles, application domains, reported environmental outcomes, and implementation challenges. The included studies were subsequently synthesized using thematic analysis.

The search was conducted across six multidisciplinary and technology-oriented academic databases, namely ScienceDirect, Emerald Insight, IEEE Xplore, SpringerLink, Wiley Online Library, and Taylor & Francis Online. These databases were selected because they provide peer-reviewed studies relevant to smart cities, environmental sustainability, urban management, Internet of Things applications, artificial intelligence, digital infrastructure, and emerging ICT-based solutions. The Boolean search string combined Smart Environment-related terms, ICT-related technologies, and environmental management or sustainability terms. To maintain consistency while accommodating database-specific functions, the search syntax was adapted to each platform.

The search was limited to publications from 2020 to 2025 in order to capture recent developments in ICT-enabled Smart Environment research. Only peer-reviewed journal articles, conference papers, and scholarly book chapters available in full text were considered. Studies were included when they provided substantive evidence regarding ICT technologies, their functions or applications, and their relevance to environmental management or environmental outcomes. Studies were excluded when they addressed Smart City initiatives without an environmental focus, only mentioned ICT superficially, were duplicate records, or did not provide sufficient methodological or conceptual relevance to the research questions.

After the search process, all retrieved records were compiled and screened systematically. Duplicate records were removed before title and abstract screening. The potentially relevant studies were then assessed through full-text reading using the eligibility criteria in Table 1. The final set of included studies was analyzed through thematic synthesis to identify ICT technologies, functional roles, application domains, reported environmental outcomes, and implementation challenges.

Study Selection Process

The study selection process was conducted through sequential stages of identification, screening, eligibility assessment, quality assessment, and final inclusion. In the identification stage,

the systematic search identified 1,879 records from six academic databases using Boolean search strings adapted to the search functions of each database. All retrieved records were compiled, and duplicate records were removed before screening. The remaining records were screened based on their titles and abstracts to exclude studies that were not relevant to ICT-enabled Smart Environment development, environmental management, or the research questions. Potentially relevant studies were subsequently assessed through full-text review using the predefined inclusion and exclusion criteria. Ultimately, 30 studies met the eligibility requirements and minimum quality threshold and were retained for the final thematic synthesis.

Quality Assessment

Before the final synthesis, a quality assessment was conducted to evaluate the methodological clarity, evidence quality, and relevance of the eligible studies. The assessment criteria are presented in Table 2.

Table 2. Quality Assessment Criteria

Code	Quality Assessment Criterion
QA1	The study clearly states its research objective or purpose.
QA2	The study adequately describes its research method or analytical approach.
QA3	The ICT technology and its application context are clearly explained.
QA4	The reported findings or outcomes are supported by sufficient evidence.
QA5	The study provides relevant evidence for addressing at least one research question of this review.

Studies meeting at least four of the five criteria were considered to have sufficient quality for inclusion in the thematic synthesis. The quality assessment showed that all 30 eligible studies met the minimum quality threshold and were therefore retained for the final thematic synthesis.

Data Synthesis

The selected articles were analyzed using thematic synthesis. The synthesis was conducted in three stages. First, each article was categorized based on the type of ICT technology discussed. This classification was used to answer RQ2. Second, the contribution of ICT was mapped into several functional categories, including environmental sensing and monitoring, data integration, intelligent analytics, decision support, resource efficiency, and governance support. This stage was used to answer RQ1. Third, the reported environmental impacts were analyzed to identify how ICT contributes to environmental quality, sustainability, energy efficiency, waste management, and urban resilience. This stage was used to answer RQ3.

Through this synthesis, the study developed a conceptual mapping of ICT-enabled Smart Environment, which connects ICT technologies, functional roles, application domains, and environmental outcomes.

RESULTS AND DISCUSSION

Search Results and Study Selection

The database-adapted Boolean search identified a total of 1,879 records across six academic databases. The total was obtained by summing the records returned by ScienceDirect, Emerald Insight, IEEE Xplore, SpringerLink, Wiley Online Library, and Taylor & Francis Online before duplicate removal and screening. After the records were pooled and assessed using the predefined eligibility criteria, 30 studies were retained and met the minimum quality threshold for the final thematic synthesis. The database-level search results are summarized in Table 3.

Table 3. Search Results

No.	Database	Records Identified	Studies Included
1	ScienceDirect	690	20
2	Emerald Insight	350	5
3	IEEE Xplore	289	2
4	SpringerLink	250	0
5	Wiley Online Library	160	0
6	Taylor & Francis Online	140	3
	Total	**1,879**	**30**

ScienceDirect returned the largest number of records and contributed the largest share of studies retained in the final synthesis. However, these database-level counts indicate search coverage rather than the prevalence or importance of particular Smart Environment topics. The final set of 30 studies was determined through the combined eligibility screening and quality assessment process.

RQ1. ICT Functional Roles in Smart Environment Development and Management

To address RQ1, the findings indicate that ICT contributes to Smart Environment development and management through six interconnected functional roles: environmental sensing and monitoring, data integration, intelligent analytics, decision support, resource efficiency, and governance support. The contribution of ICT to Smart Environment can be grouped into six major functional roles: environmental sensing and monitoring, data integration, intelligent analytics, decision support, resource efficiency, and governance support.

Table 4. ICT Contributions to Smart Environment

ICT Contribution	Description	Example of Technology	References
Environmental sensing and monitoring	Collecting real-time environmental data such as air quality, waste, traffic, and energy usage	IoT, sensors, smart devices	(Hussain et al., 2024)(Salman, 2020)(R. U. Islam et al., 2025)(Mehmood et al., 2025)(Gbadega & Sun, 2022)(S. M. M. Islam & Talukder, 2024)(Ghanbari et al., 2024)(Weck et al., 2023)
Data integration	Connecting data from multiple systems, devices, and urban services	Cloud computing, fog computing, edge computing	(Hussain et al., 2024)(Jacques et al., 2024)(Mehmood et al., 2025)(Salman, 2020)(Van Hoang, 2024)(Giant et al., 2020)
Intelligent analytics	Analyzing data to identify patterns, anomalies, and predictions	AI, machine learning, big data analytics	(Pulari & Jacob, 2025)(Peldon et al., 2024)(Efstratopoulou et al., 2024)(Jacques et al., 2024)(Ghanbari et al., 2024)(Villegas-ch et al., 2024)
Decision support	Supporting policy, planning, simulation, and operational decisions	Digital twin, AI-based decision systems	(Hussain et al., 2024)(Peldon et al., 2024)(Ghanbari et al., 2024)(Terribile et al., 2024)(González et al., 2024)
Resource efficiency	Optimizing the use of energy, water, transportation, and waste management resources	Smart grid, IoT, blockchain	(Gbadega & Sun, 2022)(Ghanbari et al., 2024)(Peldon et al., 2024)(Jacques et al., 2024)(Hussain et al., 2024)(Gbadega & Sun, 2022)(Id et al., 2024)

Governance support	Improving transparency, coordination, citizen engagement, and environmental policy implementation	ICT platforms, smart city systems, digital governance tools	(Mehmood et al., 2025)(Weck et al., 2023)(Jacques et al., 2024)(Peldon et al., 2024)(Gabrys, 2020)(Kumar, 2020)(Jiang et al., 2022)(Jiang et al., 2020)

These findings indicate that ICT acts as the technological foundation of Smart Environment. ICT enables the transformation of conventional environmental management into a data-driven, integrated, and adaptive system.

The selected studies show that ICT is applied in various Smart Environment domains. The most common application areas include waste management, energy management, smart mobility, urban resilience, smart grid, environmental monitoring, smart working environment, smart learning environment, and cultural heritage.

Table 5. Applications of ICT in Smart Environment

Application Domain	ICT Role	References
Waste management	Optimizing waste collection, monitoring waste bins, and simulating waste management models	(Hussain et al., 2024)(Gbadega & Sun, 2022; Ghanbari et al., 2024; Jacques et al., 2024; Mehmood et al., 2025; Peldon et al., 2024)
Energy management	Supporting smart grid, energy efficiency, and prosumer-based energy systems	(Gbadega & Sun, 2022; Hijjawi et al., 2024; Jacques et al., 2024; Mehmood et al., 2025)
Environmental monitoring	Monitoring air quality, environmental changes, and urban conditions	(Gbadega & Sun, 2022; S. M. M. Islam & Talukder, 2024; Mehmood et al., 2025)
Smart mobility	Supporting traffic efficiency, transportation planning, and sustainable mobility	(S. M. M. Islam & Talukder, 2024; Weck et al., 2023)(Salman, 2020)
Urban resilience	Strengthening city capacity to respond to environmental risks and climate-related challenges	(Hussain et al., 2024; Mehmood et al., 2025)
Smart working environment	Improving occupational safety through smart PPE, sensors, and ambient intelligence	(Hussain et al., 2024; S. M. M. Islam & Talukder, 2024)
Smart learning environment	Supporting technology-enhanced learning spaces and ethical AI-based learning systems	(Efstratopoulou et al., 2024; S. M. M. Islam & Talukder, 2024; Pulari & Jacob, 2025; Solera-cotanilla & Álvarez-campana, 2025)
Cultural heritage environment	Creating intelligent cultural spaces through smart technologies and immersive systems	(Jacques et al., 2024; Pulari & Jacob, 2025; Weck et al., 2023)

The results show that Smart Environment is a multidimensional concept. It is not limited to natural environmental monitoring but also includes urban systems, human activities, infrastructure, safety, learning, cultural spaces, and governance. The findings show that ICT plays a strategic role in the development and management of Smart Environment. ICT functions as an enabling infrastructure that allows environmental data to be collected, processed, integrated, and used for decision-making(Gbadega & Sun, 2022). Without ICT, Smart Environment would remain a conceptual approach rather than an operational system(Jacques et al., 2024).

The contribution of ICT can be seen in three main layers. The first layer is the sensing layer, where IoT devices, sensors, and smart devices collect environmental data in real time. The second layer is the processing layer, where cloud computing, fog computing, edge computing, AI, and big data analytics process and analyze the collected data(Gbadega & Sun, 2022; Ghanbari et al., 2024; Jacques et al., 2024; Mehmood et al., 2025; Peldon et al., 2024). The third layer is the decision and governance layer, where digital twin, decision support systems, smart contracts, and digital platforms support policy, planning, coordination, and environmental management(Hijjawi et al., 2024; S. M. M. Islam & Talukder, 2024; Mehmood et al., 2025).

This layered contribution shows that ICT is not only a supporting tool but also a core component of Smart Environment development. ICT enables cities to move from reactive environmental management to proactive and predictive environmental governance.

RQ2. ICT-Based Technologies Supporting Smart Environment

The analysis of the 30 selected articles shows that various ICT-based technologies have been used to support Smart Environment. These technologies include IoT, AI, cloud/fog/edge computing, digital twin, blockchain, smart grid, sensor-based systems, ambient intelligence, big data analytics, and immersive technologies.

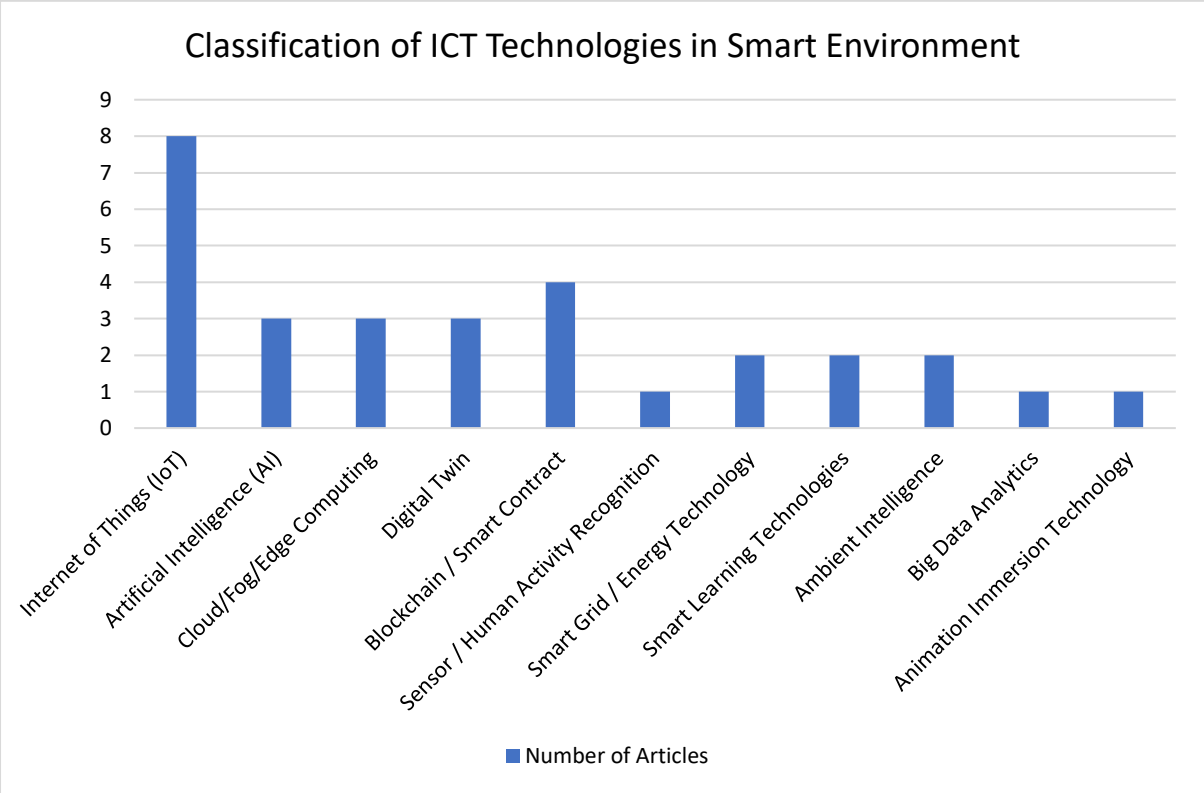

Figure 1. Classification of ICT Technologies in Smart Environment

IoT is the most frequently discussed technology in the selected studies. This finding indicates that IoT plays a central role in Smart Environment because it enables real-time data collection, sensor-based monitoring, automation, and environmental control. IoT is commonly applied in waste management, air quality monitoring, energy efficiency, smart mobility, and urban infrastructure(Hussain et al., 2024)(Salman, 2020)(R. U. Islam et al., 2025)(Mehmood et al., 2025)(Gbadega & Sun, 2022)(S. M. M. Islam & Talukder, 2024)(Ghanbari et al., 2024)(Weck et al., 2023).

AI and machine learning are used to support intelligent analytics, prediction, pattern recognition, and decision-making(Pulari & Jacob, 2025)(Peldon et al., 2024)(Efstratopoulou et al., 2024)(Villegas-ch et al., 2024). Although the number of AI-focused articles is smaller than IoT, AI plays an important role in transforming raw environmental data into actionable insights(Peldon et

al., 2024). Cloud, fog, and edge computing support data processing and storage, especially for large-scale sensor networks that require fast response and low latency(Hussain et al., 2024)(Jacques et al., 2024)(Mehmood et al., 2025)(Salman, 2020).

Digital twin technology is also emerging as an important tool in Smart Environment because it allows cities to simulate, monitor, and evaluate environmental conditions in a virtual environment(Hussain et al., 2024)(Peldon et al., 2024)(Ghanbari et al., 2024). Blockchain and smart contracts are used in specific contexts such as smart energy, electric vehicles, and secure transaction systems(Gbadega & Sun, 2022)(Hussain et al., 2024)(Hijjawi et al., 2024). Ambient intelligence and smart learning technologies show that Smart Environment is not only related to ecological aspects but also to human interaction, safety, learning, and quality of life(Solera-cotanilla & Álvarez-campana, 2025)(S. M. M. Islam & Talukder, 2024)(Efstratopoulou et al., 2024)(Pulari & Jacob, 2025).

IoT was identified as the most dominant technology in the selected studies. This dominance is reasonable because IoT provides the basic capability required by Smart Environment systems: real-time data collection. Environmental management requires continuous information about air quality, waste, energy consumption, mobility, and infrastructure conditions(Hussain et al., 2024)(Gbadega & Sun, 2022; Ghanbari et al., 2024; Jacques et al., 2024; Mehmood et al., 2025; Peldon et al., 2024). IoT enables these data to be captured automatically and transmitted to digital platforms for further analysis.

The dominance of IoT also indicates that current Smart Environment research still strongly depends on sensor-based monitoring(Efstratopoulou et al., 2024; R. U. Islam et al., 2025). However, IoT alone is not sufficient to create an intelligent environment. IoT must be integrated with AI, cloud computing, edge computing, and digital twin technologies to generate meaningful insights and support decision-making(Jacques et al., 2024; Pulari & Jacob, 2025). Therefore, future Smart Environment development should move from isolated IoT implementation toward integrated ICT ecosystems(Giant et al., 2020).

Although IoT is the most frequently discussed technology, other technologies play important complementary roles. AI and machine learning support the analytical capability of Smart Environment by enabling prediction, classification, anomaly detection, and automated decision-making(Ghanbari et al., 2024; Hussain et al., 2024)(Villegas-ch et al., 2024). These capabilities are important for detecting environmental changes, predicting energy demand, optimizing waste management, and improving urban services.

Cloud computing provides scalable storage and processing capacity for large environmental datasets(Jiang et al., 2020, 2022; Mukherjee & Bairwa, 2025). However, cloud-based systems may face latency issues when real-time response is required. Therefore, fog and edge computing become important because they allow data processing closer to the data source(Van Hoang, 2024). This is particularly relevant for environmental monitoring systems that require fast responses, such as air pollution detection, traffic management, and emergency response.

Digital twin technology provides a more advanced capability by creating a virtual representation of urban systems(Gabrys, 2020; González et al., 2024; Kumar, 2020). Through digital twin, policymakers and city managers can simulate environmental scenarios, evaluate policy alternatives, and anticipate the impact of urban changes before implementing them in the real world. This makes digital twin a promising technology for future Smart Environment research and practice.

RQ3. Environmental Quality Outcomes of ICT Implementation

The analysis of selected studies indicates that ICT contributes to environmental quality both directly and indirectly. Direct impacts are found in studies that discuss waste management, energy efficiency, air quality monitoring, and urban resilience(Gbadega & Sun, 2022; Ghanbari et al., 2024; Jacques et al., 2024; Mehmood et al., 2025; Peldon et al., 2024). Indirect impacts are found in studies that discuss smart learning, smart working environments, citizen participation, and urban governance(Hussain et al., 2024; S. M. M. Islam & Talukder, 2024).

Table 6. Environmental Impacts of ICT Implementation

Environmental Impact	Explanation
Improved monitoring capability	ICT enables real-time monitoring of environmental conditions through sensors and connected devices
Resource efficiency	ICT supports more efficient use of energy, waste management systems, and urban infrastructure
Better decision-making	AI, digital twin, and analytics help policymakers make data-driven environmental decisions
Increased urban resilience	ICT supports early detection, simulation, and response to environmental risks
Improved quality of life	Smart Environment technologies support healthier, safer, and more responsive urban living conditions
Sustainability support	ICT contributes to sustainable urban development by integrating environmental data, services, and policies

Although the majority of selected studies suggest positive contributions of ICT, not all studies directly measure environmental quality indicators. Some studies discuss ICT in relation to smart learning, cultural heritage, or working environments, where the environmental impact is indirect(Efstratopoulou et al., 2024; S. M. M. Islam & Talukder, 2024; Pulari & Jacob, 2025; Solera-cotanilla & Álvarez-campana, 2025). Therefore, the impact of ICT on environmental quality should be interpreted based on the context and scope of each study.

The selected studies suggest that ICT can improve environmental quality through monitoring, optimization, prediction, and decision support. In waste management, ICT enables more efficient collection and management processes(Id et al., 2024; Sauer & Seuring, 2023; Terribile et al., 2024). In energy management, ICT supports smart grid, demand response, and energy optimization. In urban resilience, ICT helps cities detect risks, simulate scenarios, and respond more effectively to environmental challenges.

However, the findings also show that not all studies directly measure environmental outcomes. Some studies discuss ICT implementation without providing clear indicators of environmental quality improvement. This indicates an important limitation in the current literature. Many studies assume that ICT contributes positively to the environment, but empirical evidence is still uneven. Therefore, future research should include measurable environmental indicators such as energy consumption reduction, emission reduction, waste reduction, air quality improvement, or resource efficiency improvement.

The implementation of ICT-based Smart Environment faces several challenges. First, technological integration remains a major issue(Addas, 2023; Prasath & Vishnupriya, 2025). Smart Environment systems often involve multiple devices, platforms, data formats, and stakeholders. Without interoperability, ICT systems may operate in isolation and fail to support integrated environmental management.

Second, data privacy and security are important concerns. Smart Environment systems collect large amounts of data from sensors, citizens, vehicles, buildings, and urban infrastructure(Attah et al., 2024; Deebak et al., 2020). If not properly managed, these data may create privacy risks and cybersecurity vulnerabilities.

Third, infrastructure readiness may vary across cities and regions(Bibri et al., 2023; Ullah et al., 2024). Cities with limited digital infrastructure may face difficulties in adopting advanced technologies such as IoT, digital twin, and AI-based analytics. This may create a digital divide between technologically advanced cities and less developed regions.

Fourth, governance and institutional capacity are essential. Smart Environment implementation requires coordination among government agencies, technology providers, communities, and other stakeholders(Bibri & Krogstie, 2020; Hussain et al., 2024; Peldon et al., 2024; Weck et al., 2023). Without clear governance mechanisms, ICT implementation may become fragmented and ineffective.

Proposed Conceptual Framework of ICT-Enabled Smart Environment

Based on the synthesis of selected studies, this review proposes a conceptual framework of ICT-enabled Smart Environment. The framework consists of four interconnected components.

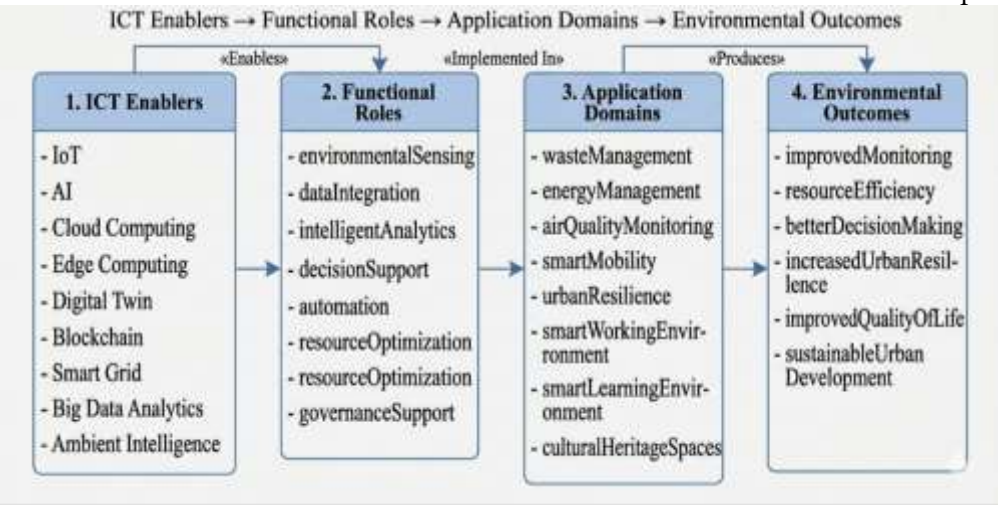

Figure 2. Conceptual Framework of ICT-Enabled Smart Environment

This framework shows that the contribution of ICT to Smart Environment is not direct and linear. Instead, ICT contributes through specific functional roles and application domains before producing environmental outcomes. Therefore, the success of ICT implementation depends not only on the availability of technology but also on how the technology is integrated, governed, and aligned with environmental objectives.

Theoretical Implications

This study contributes to the literature by providing a structured classification of ICT technologies and their roles in Smart Environment. Previous studies often discuss ICT technologies separately, such as IoT for monitoring, AI for analytics, or digital twin for simulation. This review integrates these technologies into a broader conceptual framework that explains how ICT supports Smart Environment development.

The proposed framework also helps clarify the relationship between technology, application, and environmental impact. This is important because Smart Environment research should not only focus on technological adoption but also on how technology produces environmental value.

Practical and Policy Implications

The findings provide several practical implications. For city governments, ICT can be used to support evidence-based environmental policy, real-time monitoring, and integrated urban management. For technology developers, the findings highlight the importance of designing interoperable, secure, and scalable Smart Environment systems. For policymakers, the study emphasizes the need to align ICT investment with environmental objectives, sustainability indicators, and citizen needs.

The results also suggest that Smart Environment initiatives should not focus only on technology deployment. Successful implementation requires governance, stakeholder collaboration, data management, cybersecurity, and continuous evaluation of environmental outcomes.

CONCLUSION

This systematic literature review demonstrates that Information and Communication Technology (ICT) plays a strategic role in Smart Environment development and management through six interconnected functions: environmental sensing and monitoring, data integration, intelligent analytics, decision support, resource efficiency, and governance support. Among the identified technologies, the Internet of Things (IoT) is the most frequently reported, while artificial intelligence, cloud/fog/edge computing, digital twins, blockchain, smart grids, and big data

analytics provide complementary capabilities for data processing, prediction, simulation, optimization, and decision-making. Collectively, these technologies contribute to improved environmental monitoring, resource efficiency, urban resilience, and more evidence-based environmental management.

The main contribution of this study is the development of an integrative ICT-enabled Smart Environment framework that connects ICT enablers, functional roles, application domains, and environmental outcomes within a unified structure. Theoretically, this framework extends previous technology-specific perspectives by explaining the functional pathways through which ICT can generate environmental value. Practically, the framework provides a structured reference for city governments, policymakers, and technology developers to align ICT implementation with specific environmental applications and intended sustainability outcomes.

Nevertheless, the review also reveals that direct and comparable empirical evidence of environmental improvement remains limited, as many studies emphasize technological capabilities rather than measurable environmental outcomes. Future research should therefore evaluate ICT-enabled Smart Environment initiatives using explicit indicators such as energy consumption, emissions, waste reduction, resource efficiency, and response performance. Further studies should also examine the integration of complementary ICT technologies while addressing interoperability, cybersecurity, privacy, infrastructure readiness, governance capacity, and stakeholder collaboration, particularly in developing-country contexts.

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