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Edge Computing for Distributed IoT Data Management in Smart Cities

Shashwat Devan*

School of Computer Engineering, KIIT (Deemed to Be) University, Bhubaneswar -751024, Odisha, India; shashwatdevan549@gmail.com.

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Abstract

As urban areas expand and strive for sustainability, the integration of edge computing with Internet of Things (IoT) is becoming essential for creating smarter, more efficient city systems. IoT devices found in smart cities produce large volumes of data that necessitate swift processing for real-time applications such as energy management, transportation networks, and public safety initiatives. Edge computing fulfills this requirement by decentralizing the processing of data, positioning computation closer to the source of the data, which minimizes latency and reduces bandwidth consumption. This paper examines how edge computing can be utilized for distributed IoT data management, emphasizing its significance in improving the performance of urban infrastructure. Important topics covered include architectural frameworks, implementation strategies, and significant challenges like privacy, security, and scalability. By enhancing the efficiency and reliability of smart city applications, edge computing contributes to greater resilience by distributing processing capabilities throughout the network. Through the use of edge computing, cities can foster more adaptable, responsive, and secure environments, making the best use of resources while enhancing the living standards for their residents.

Keywords: Edge computing, Smart cities, Internet of Things, Fog computing.

1 | Introduction

As urbanization continues to accelerate, cities now accommodate a significant share of the global population, leading to many new challenges. Heightened energy, transportation, healthcare, and public safety demands increasingly strain urban environments. To address these challenges, modern cities are shifting toward becoming "smart cities," where data-driven technologies play a pivotal role in creating sustainable and efficient urban systems.

Corresponding Author: shashwatdevan549@gmail.com
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One of the driving forces behind this transformation is the Internet of Things (IoT). IoT refers to a vast network of interconnected devices and sensors distributed throughout the city, continuously gathering and sharing data to facilitate automated decision-making. These devices can be found in many applications, from traffic management systems and energy grids to wearable health devices and environmental sensors. As cities become more reliant on IoT, they produce vast amounts of data that must be processed and analyzed in real-time to enable fast and effective responses to urban challenges.

However, processing such large volumes of data through traditional, centralized cloud computing frameworks poses several issues. Centralized data processing often leads to latency, bandwidth congestion, and increased pressure on central servers, making it difficult to maintain the responsiveness required for critical smart city functions. This is where edge computing comes into play as a solution for distributed data management in smart cities [1].

Edge computing refers to the practice of processing and storing data closer to the location where it is generated rather than relying solely on centralized data centers. By moving computation closer to the "edge" of the network, edge computing significantly reduces the latency in transmitting data to a central location. This is especially important in smart cities, where real-time decision-making is essential for traffic control, energy management, and public safety systems.

The convergence of edge computing and IoT allows quicker, localized decision-making by analyzing data at the source or within the immediate vicinity. This decentralized approach improves the speed of processing and the efficiency and resilience of smart city infrastructures. For example, real-time traffic data can be analyzed and acted upon directly by traffic management systems at intersections, adjusting signals and redirecting traffic flow without relying on remote servers.

Beyond just faster processing, edge computing also addresses data privacy and security issues. By keeping data processing localized, sensitive information, such as personal health data or surveillance footage, can be handled closer to its origin, reducing the risk of breaches or leaks during transmission. This is especially relevant in smart cities, where a large volume of personal and public data is generated continuously.

Moreover, edge computing reduces the strain on bandwidth, as not all data needs to be sent to the cloud for processing. Only critical or aggregated information might be forwarded to central systems, while routine or less important data can be handled locally. This results in a more scalable and efficient system better suited for handling the growing data volumes of smart city applications.

2 | Literature review

The integration of edge computing and IoT technologies in smart cities has attracted significant attention due to their potential to modernize urban infrastructure, services, and sustainability. Recent studies explore various aspects of these technologies, focusing on their ability to enhance security, improve accessibility, and manage vast amounts of data more efficiently. A key area of interest is the deployment of edge-based sensors for real-time data collection and analysis, which optimizes services such as traffic management, energy grids, and public safety systems [2], [3].

Researchers have also investigated machine learning-based resource allocation strategies designed to optimize the performance of edge computing in IoT environments. These strategies help manage data closer to the source, reducing latency and network strain. Other studies emphasize the importance of Software-Defined Networking (SDN) and energy-efficient designs in edge computing for more scalable and resilient smart city infrastructures [4], [5].

Additionally, the literature addresses challenges such as privacy, security, and the scalability of edge computing systems. Solutions to these challenges are crucial for ensuring the successful implementation of edge computing in smart city projects. The review highlights the need for further exploration of how edge computing can support advanced analytics, improve data processing, and enhance decision-making capabilities at the local level.

Ultimately, ongoing research points toward a future where edge computing is pivotal in building more adaptive, efficient, and secure smart cities.

2.1 | Need and Relevance

The integration of edge computing and IoT technologies has become a transformative force in developing smart cities. As urban populations grow, cities face increasing challenges in infrastructure management, resource efficiency, and sustainability. Edge computing and IoT help tackle these issues by enabling real-time data processing, decentralized decision-making, and optimized resource use at the local level. Recognizing the importance of these technologies is essential for policymakers, urban planners, and researchers seeking to drive digital transformation in urban settings [6].

This chapter explores the role of edge computing and IoT in smart cities, emphasizing their significance for urban development. Beyond technological innovation, these technologies contribute to broader societal objectives, including sustainability, social inclusivity, and economic growth. By adopting edge computing and IoT, cities can reduce energy consumption, mitigate environmental impacts, and improve residents' access to essential services. Additionally, these advancements create opportunities for new business models, entrepreneurship, and innovation within urban areas [7–9].

Objectives:

I. To develop a theoretical framework for understanding the principles of edge computing and IoT and their significance for smart city development.

II. To investigate the practical applications and use cases of edge computing and IoT across various smart city sectors, including transportation, energy management, healthcare, public safety, and environmental monitoring.

III. To analyze the challenges, opportunities, emerging trends, and new technologies while outlining future research directions in edge computing and IoT for smart city initiatives.

3 | Method of Study

The research employed a descriptive approach, relying on secondary data sources to analyze the topic. This methodology allows for an in-depth discussion of the observed challenges and insights related to the subject matter.

Observations

This section delves into the complex relationship between edge computing and IoT within smart city contexts, thoroughly exploring key concepts, technologies, and challenges. The chapter provides a detailed analysis of these technologies' significant role in shaping future smart city development.

Edge computing in smart cities

In smart city environments, edge computing refers to processing data close to its source, near IoT devices and sensors, rather than relying solely on centralized cloud servers. This approach minimizes data latency by enabling computations at the network's edge, thus facilitating real-time analysis, automation, and decision-making. It is particularly valuable for applications like traffic management, where swift responses can significantly impact congestion and mobility.

Table 1. Summarize key information about edge computing and IoT.

Aspect	Edge Computing in Smart Cities	IoT in Smart Cities
Definition	A computing model that processes data near its origin, improving response times.	A network of connected devices and sensors that gather and exchange data for urban efficiency.
Purpose	Enhance speed, data processing efficiency, and real-time decision-making capabilities.	Foster a more interconnected and intelligent city environment, optimizing service delivery.
Benefits	- Lowers data latency. - Enhances system reliability and scalability. - Better bandwidth utilization. - Reduces the need for cloud-based processing.	- Increases operational efficiency. - Streamlines resource management. - Boosts public services. - Supports data-driven decision-making.

Edge computing enhances system reliability by allowing local processing to continue during network disruptions. It optimizes bandwidth use by processing data locally, reducing the volume of raw data transmitted to central servers and lowering costs. Additionally, it bolsters privacy and security by keeping sensitive data close to its origin, minimizing the risks linked to data transfer.

IoT in smart cities

In smart cities, the IoT involves interconnected devices, sensors, and systems that gather, share, and analyze data to improve urban living. This technology enhances services' efficiency, sustainability, and quality by integrating IoT across essential infrastructure like transport networks, utility grids, and public safety. IoT devices act as data sources, enabling real-time monitoring of city operations, environmental conditions, and infrastructure performance. This continuous data flow supports more informed decision-making, automated processes, and adaptive management of city resources .

The main goal of IoT in smart cities is to build a more connected and responsive urban environment that addresses citizens' needs effectively. It facilitates quick responses to changes, such as traffic congestion, through data-driven insights. Furthermore, IoT promotes sustainability by optimizing resource use and reducing the environmental impact of urban operations. These advancements create smart cities that are technologically advanced, resilient, and better equipped to handle future urban challenges.

Architectural frameworks for edge computing and IoT integration

The integration of edge computing and IoT in smart cities relies heavily on architectural frameworks, which play a vital role in organizing and deploying systems. These frameworks offer the necessary guidelines for developing and implementing systems combining edge computing with IoT technologies. Fusing these two technologies is essential for creating efficient and resilient systems that can manage the diverse and dynamic data generated in smart cities. *Fig. 1* represents smart city environments empowered by IoT and Edge Computing.

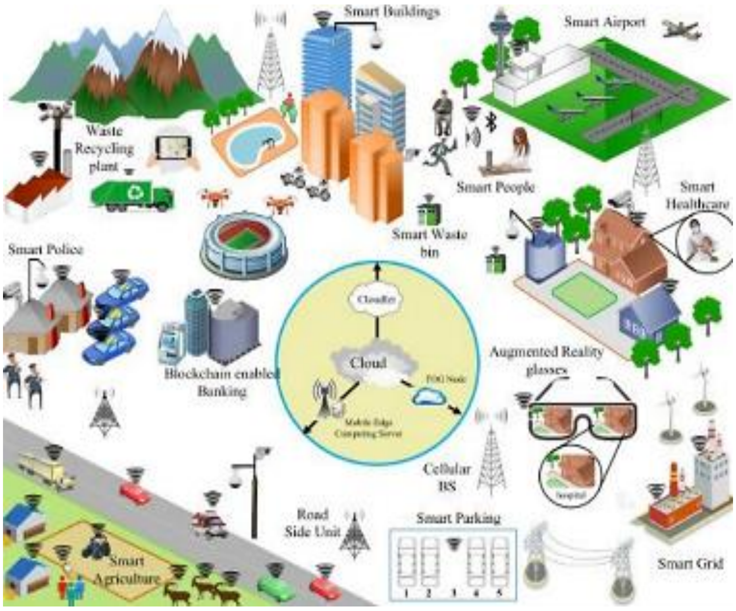

Fig. 1. Overview of smart cities enabled by IoT and edge computing.

Architectures designed for edge computing and IoT in smart cities aim to provide a flexible and scalable infrastructure. By distributing computing tasks across a network, edge nodes are positioned to process data locally, ensuring critical decisions are made using locally processed information. Below are a few widely used architectural frameworks for edge computing and IoT integration [10]:

I. EdgeX foundry: this open-source platform provides a standardized collection of APIs and services for developing edge computing applications.

II. Eclipse kura: a lightweight, Java-based framework that supports IoT application development and maintenance on edge devices.

III. FIWARE: another open-source platform, FIWARE, offers components for developing and managing IoT applications.

IV. Amazon greengrass: a service by AWS that supports the execution of AWS Lambda functions on edge devices.

V. Microsoft azure IoT edge: this service enables deploying and managing IoT applications on edge devices via Microsoft's Azure platform.

VI. IBM watson iot edge: it facilitates setting up and managing cognitive IoT applications on edge devices.

These frameworks are the backbone for developing intelligent, responsive, scalable IoT systems within smart cities. They provide guidelines for resource allocation, device compatibility, and edge machine learning deployment. As smart cities evolve, these architectural frameworks will play a key role in enhancing sustainability, efficiency, and overall quality of life.

Deployment Techniques in Smart Cities

The development of robust deployment strategies is essential to fully leverage the benefits of IoT and Edge Computing in smart cities. One approach involves strategically placing edge nodes across urban areas to ensure data is processed close to its source, reducing latency and enabling real-time decision-making. This strategy is vital for applications like intelligent transportation systems, where fast reactions are critical for traffic optimization. Smart cities can enhance mobility and ensure quick, effective responses to various needs by reducing the physical distance between data processing points and end-users. This flexibility also allows cities to adjust to dynamic demands, promoting scalability and efficient resource allocation across various applications. This hybrid deployment model is key to improving the agility and performance of services in urban environments [11].

Distributed and Mobile Edge Computing

As smart cities and the IoT evolve, distributed edge computing emerges as a pivotal shift in managing data processing. Unlike conventional centralized computing models, where data is routed to distant data centers for processing, distributed edge computing brings computation closer to the data source. This approach leverages servers and edge nodes placed across multiple locations within a network, allowing for real-time data processing and minimizing latency. By processing data locally, edge computing significantly reduces the distance data must travel, improving the responsiveness of critical smart city applications such as traffic management, energy monitoring, and public safety systems. This model creates a more decentralized and flexible architecture, promoting efficiency and scalability in handling large amounts of urban data [12].

In tandem with distributed edge computing, Mobile Edge Computing (MEC) plays a crucial role, especially for applications reliant on cellular networks. MEC pushes computation closer to mobile devices, deploying processing power at the network's edge. This transformation is especially beneficial for mobile apps that require ultra-low latency and high-speed data handling. Autonomous vehicles, augmented reality (AR), and smart surveillance are just a few examples of applications that benefit from MEC. By processing data on mobile devices or local servers rather than centralized cloud systems, MEC reduces latency and improves real-time decision-making, a critical requirement in smart cities with dynamic data needs.

As cities increasingly adopt technologies like 5G, MEC is anticipated to further revolutionize urban infrastructure by enabling smoother, faster, and more efficient data exchanges. This will ensure that smart cities remain responsive, scalable, and adaptable to the growing demands of urban living [13].

Fog computing

In smart cities, fog computing, an advanced form of edge computing, plays a vital role in bridging the gap between IoT devices and the cloud. As a decentralized computing model, fog computing brings intelligence and processing capabilities closer to the network edge, enabling faster data processing directly at IoT devices. It acts as an intermediary between cloud servers and local devices, ensuring quicker responses by minimizing the need for long-distance data transfer. This is particularly important in applications like smart traffic management and urban monitoring, where real-time analytics are essential. Fog computing helps address the specific needs of urban areas, providing an effective solution for real-time data processing while maintaining low latency. Its ability to scale with growing urban data needs ensures that cities can adapt to evolving challenges while reducing reliance on distant centralized systems [14].

Applications and use cases

The integration of edge computing and IoT has led to many applications that directly improve urban living. From traffic management to environmental monitoring, edge computing offers low-latency data processing, enabling real-time solutions. Edge nodes can handle complex tasks like resource allocation, network optimization, and decision-making at the edge of networks, reducing the load on centralized systems. Smart cities benefit from this, as edge computing allows faster, localized solutions, improving everything from waste management to smart parking. With its capacity to scale and adapt, edge computing is becoming a critical infrastructure element for the management and sustainability of urban ecosystems [15], [16].

Intelligent transportation systems

The fusion of edge computing and IoT within smart transportation systems revolutionizes how cities handle dynamic traffic conditions. Sensors embedded in vehicles and roads feed real-time data to edge nodes, which process this information to optimize traffic signals, route planning, and congestion management. By enabling adaptive traffic control, edge computing helps reduce travel times, fuel consumption, and vehicle emissions while contributing to a cleaner environment. As cities grow, the importance of intelligent transportation powered by edge computing will increase, providing better flow and safety on urban roads.

Traffic management

Edge computing in smart traffic management brings significant advancements by processing data close to the source. Through real-time analysis of information gathered by IoT sensors, cities can dynamically optimize traffic signals and manage congestion more effectively. This method reduces delays and improves traffic flow by processing data locally, which is crucial for time-sensitive tasks like rerouting traffic during emergencies or peak hours. Additionally, edge computing enhances traffic systems by predicting potential disruptions and improving overall city logistics [17], [18].

Energy management

Incorporating edge computing with IoT is transforming energy management in smart cities. Systems can monitor and optimize energy distribution and consumption by processing data at the edge in real-time. This results in better demand forecasting, efficient use of resources, and reduction in energy waste. Edge computing empowers cities to optimize energy flow by responding quickly to demand spikes, equipment failures, or changes in usage patterns, leading to more sustainable and efficient energy systems. Moreover, this approach supports the integration of renewable energy sources and smart grids, enhancing overall energy efficiency and lowering operational costs for cities.

Smart grids

IoT devices are pivotal in gathering detailed information on energy consumption patterns, building performance, and grid dynamics in smart cities. These devices continuously feed data to edge computing platforms for real-time processing. This approach improves energy management by reducing waste, adjusting for demand, and optimizing energy distribution. The convergence of edge computing and IoT enhances the resilience and efficiency of urban energy grids, allowing for better resource management and real-time responses to changes in demand. Moreover, smart grids contribute to sustainability goals by using energy more efficiently, reducing overall consumption, and minimizing environmental impact [19].

Environmental monitoring

The combination of edge computing and IoT significantly improves environmental monitoring in smart cities. By processing data closer to its source, edge computing facilitates faster responses to environmental changes, such as air quality or temperature variations. IoT sensors collect real-time data on pollutants, water levels, and other key environmental metrics, while edge devices process this information locally, enabling quick decisions and actions. This local processing reduces reliance on centralized systems, ensuring that relevant data is addressed promptly. Edge computing allows for earlier detection of environmental hazards, enabling more proactive management of pollution or natural disasters and helping cities respond more effectively to environmental challenges.

Air quality and environmental sensors

Edge computing has enhanced the efficiency of air quality monitoring by integrating IoT sensors to track pollutants and contaminants in real-time. These sensors provide data on air quality, which is processed locally, allowing for rapid analysis and action, such as adjusting traffic flow or alerting the public to hazardous conditions. By processing data at the edge, cities can react faster to air quality issues, improving public health and safety. This approach improves air quality monitoring systems' performance and enables greater scalability as cities continue to grow and experience increased environmental pressures.

Healthcare

Edge computing and IoT integration are revolutionizing healthcare systems within smart cities. IoT devices collect real-time data from medical equipment, wearable devices, and sensors, which edge computing processes locally. This quick processing of health data enables faster decision-making in critical situations, such as patient monitoring or emergency responses. Edge computing also reduces the need for data to travel long distances, improving system reliability and enhancing patient care by ensuring real-time access to vital health metrics. These systems are key in developing more personalized and responsive healthcare services, improving the overall quality of medical care provided in smart city environments.

Patient monitoring and telemedicine

Integrating edge computing and IoT in smart city environments has significantly enhanced patient monitoring and telemedicine systems. Wearable devices and medical sensors now capture real-time data on patients' health metrics, such as vital signs and other indicators. This data is analyzed locally through edge computing, reducing latency and enabling immediate insights. In patient care, this allows medical practitioners to quickly access crucial information regarding a patient's condition. This real-time data supports more proactive medical interventions and facilitates personalized treatment plans, ensuring that healthcare can be responsive and tailored to individual needs.

Video surveillance and crime prevention

Edge computing and IoT are transforming smart city video surveillance systems by bringing intelligence closer to the network's edge. IoT-enabled cameras, strategically placed in high-risk areas and key public locations, can now analyze video feeds locally. This decentralization significantly reduces latency and allows real-time detection of suspicious behavior, which improves security and surveillance effectiveness. By enabling more efficient allocation of security resources, these smart systems help law enforcement agencies prevent criminal activity and respond more quickly to potential threats. As a result, smart cities are becoming safer by integrating these advanced technologies, which enhance video surveillance capabilities and improve overall crime prevention efforts.

Emergency response

In emergency scenarios, where every second is critical, combining IoT and edge computing vastly improves response times in smart cities. By processing data locally at the network's edge, vital information from IoT devices—such as accident data or environmental hazards—can be processed in real-time. This minimizes delays, allowing emergency services to act swiftly and with accurate information. Edge computing also enables predictive analytics, helping emergency systems respond more efficiently by anticipating potential crises. Through real-time insights and advanced decision-making capabilities, smart cities can deploy emergency resources effectively, saving lives and ensuring a more coordinated response to disasters or accidents.

Challenges

Numerous challenges and concerns must be addressed for the successful and sustainable integration of groundbreaking technologies like edge computing and the IoT in smart cities. The interoperability of various systems and devices within the smart city framework poses a significant issue. The diversity of communication protocols and standards makes it difficult to ensure that edge computing and IoT applications work seamlessly together. To resolve this, unified frameworks and protocols are required to enable smooth interoperability, thus simplifying integration and fostering effective collaboration between systems and devices.

Public trust in the security and privacy of smart city infrastructure is another critical concern. Employing robust encryption techniques, access restrictions, and strict privacy policies is essential to building this confidence. Cities must balance leveraging cutting-edge technology with ensuring it aligns with privacy laws and regulations while considering its financial implications and sustainability.

Some of the major challenges include

I. Security and privacy: As edge computing and IoT applications proliferate in smart cities, protecting the gathered data becomes crucial. The information comes from multiple devices, making it essential to maintain strong privacy policies and data security measures. Balancing privacy protection with service improvements presents a challenge.

II. Privacy regulations and data security: The complex landscape of data security regulations, such as GDPR, requires strict adherence. Smart cities must ensure their systems are designed to safeguard citizens' privacy while maintaining security audits and robust data protection mechanisms.

III. Scalability: As smart cities evolve, their systems must scale effectively to accommodate the growing number of devices and data traffic. This requires infrastructure capable of supporting increased demand for connectivity and data processing.

IV. Infrastructure requirements: Building the necessary infrastructure to manage the massive amounts of data IoT devices generate is a significant challenge. Ensuring the seamless flow of data while avoiding bottlenecks requires careful planning.

V. Cost of network infrastructure: Developing the network infrastructure for edge computing and IoT is expensive. Substantial investments are needed to construct high-speed, low-latency networks capable of handling large volumes of data generated by IoT devices. Cities must consider the long-term financial feasibility of such initiatives and explore various funding sources.

4 | Discussion

When examining the previously mentioned challenges related to integrating edge computing and IoT in smart cities, several critical factors emerge: 1) ensuring smooth interoperability among the different systems and devices within the smart city infrastructure remains a major hurdle. Research has revealed significant issues related to the inconsistency of communication protocols and standards between devices, highlighting the need for standardized frameworks to enable effective cooperation and seamless integration, 2) building public trust in the security and privacy of smart city infrastructure is paramount. Given the sensitivity of the data being processed, security and privacy must be safeguarded with robust encryption, strict access controls, and adherence to privacy regulations. Scalability is important as smart cities expand to accommodate more IoT devices. The infrastructure must handle growing data volumes and the increasing number of connected devices.

Deploying edge computing and IoT applications demands an infrastructure that can cope with the additional load generated by vast amounts of data. Planning for this expansion requires thorough analysis to ensure the infrastructure is cost-effective and sustainable. Furthermore, the financial aspects of developing such infrastructure, including the need for high-speed networks to handle the surge in IoT data, must be carefully assessed. Cities must explore different funding options and perform long-term sustainability evaluations to ensure the infrastructure's effectiveness.

Another crucial aspect is the role of IoT in improving sustainability and responsiveness within urban environments. By integrating IoT, artificial intelligence, and data analytics, cities can optimize resource use and implement environmentally friendly policies, reducing carbon emissions and minimizing energy consumption. The ability of connected sensors and devices to facilitate better decision-making extends to areas like waste management, transportation, and energy use.

Looking to the future, smart cities must prioritize sustainability, innovation, and inclusivity in their designs. Technology should support participatory governance and collaborative efforts, encouraging innovation and improving living standards through a multi-disciplinary approach.

4.1 | Suggestions and Future Directions

The future of smart cities looks promising as technological advancements continue to reshape urban spaces globally. These cities have the potential to significantly enhance efficiency, sustainability, and responsiveness to their residents' needs by incorporating edge computing, artificial intelligence, and the IoT. Real-time data analysis from interconnected systems will improve decision-making in public safety, energy efficiency, and traffic management. Intelligent infrastructure, such as smart power grids, autonomous vehicles, and cutting-edge healthcare technologies, will contribute to better living standards and a more cohesive urban environment.

Additionally, sustainability and resilience will become even more central to the development of future smart cities. Urban areas will increasingly adopt eco-friendly initiatives, using technology to reduce carbon emissions, optimize resource use, and mitigate climate change's impacts. Smart urban planning will incorporate renewable energy sources, innovative waste management techniques, and other environmentally conscious measures. Importantly, these cities will promote more inclusive and participatory governance, making it easier for citizens to engage in decision-making. This will help create cities that are more sustainable and responsive to their inhabitants' needs.

5 | Conclusion

The integration of edge computing and IoT presents a significant opportunity to revolutionize urban development, addressing many of the challenges cities face today while promoting sustainability, efficiency, and resilience. This chapter highlights the critical aspects of implementing edge computing and IoT in smart cities, including infrastructure requirements, architectural frameworks, and security concerns. These technologies have proven vital for transforming urban life, especially in energy management, healthcare, transportation, and environmental monitoring.

However, while these technologies offer numerous advantages, several challenges must be addressed to realize their full potential. Key issues such as infrastructure scalability, security, privacy, and regulatory compliance require detailed planning and strategic thinking. By exploring various deployment methods, such as mobile and distributed edge computing, and developing supportive architectural frameworks like edge clouds, cities can better handle the complexities of integrating these technologies.

In conclusion, the future of smart cities lies in multidisciplinary collaboration across policy, social sciences, and technological innovation. Overcoming obstacles will require improving the capacity of cutting-edge technologies and fostering inclusive, sustainable, and resilient urban environments that elevate the quality of life for all citizens.

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Data Availability

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Consent for Publication

The author has reviewed the final manuscript and provided consent for its publication.

Ethics Approval and Consent to Participate

This study did not involve human participants, animals, or identifiable personal data. The research is based on a review and analysis of existing scientific literature; therefore, ethical approval and informed consent to participate were not required according to institutional and international research ethics guidelines.

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