*REDVET - Revista electrónica de Veterinaria* - ISSN 1695-7504
Vol 24, No. 4 (2023)
http://www.veterinaria.org
Article Received: 01/05/2024 Revised:03/06/2024 Accepted: 01/07/2024

# A REVIEW ON WIRELESS SENSOR NETWORKS FOR SMART CITY APPLICATIONS

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**Abstract**
*Wireless Sensor Networks (Wsns) Are A Pivotal Technology For Smart Cities, Enabling Real-Time Monitoring, Data-Driven Decision-Making, And Efficient Management Of Urban Infrastructure. This Review Examines The Evolution, Architectures, And Applications Of Wsns Across Domains Such As Traffic Management, Environmental Monitoring, Energy Systems, Water Supply, And Public Safety. The Study Also Highlights The Integration Of Wsns With Iot, AI, And Cloud Computing, Which Enhances Scalability, Predictive Analytics, And Operational Efficiency. Challenges Such As Energy Consumption, Network Scalability, And Security Vulnerabilities Are Discussed, Along With Potential Solutions And Future Research Directions. The Review Provides Insights Into Designing Sustainable, Resilient, And Intelligent Smart City Systems Powered By Wsns.*

**Keywords:** *Wireless Sensor Networks (Wsns), Smart Cities, Internet Of Things (Iot), Real-Time Monitoring, Urban Infrastructure*

## 1. Introduction

The rapid growth of urban populations has accelerated the development of smart cities, which use technology to improve urban living, manage resources efficiently, and support data-driven decision-making. Wireless Sensor Networks (WSNs) are a key technology for smart cities, enabling real-time monitoring of traffic, environment, energy, and public safety. WSNs consist of distributed sensor nodes that sense, process, and transmit data wirelessly, forming the backbone of urban sensing systems.

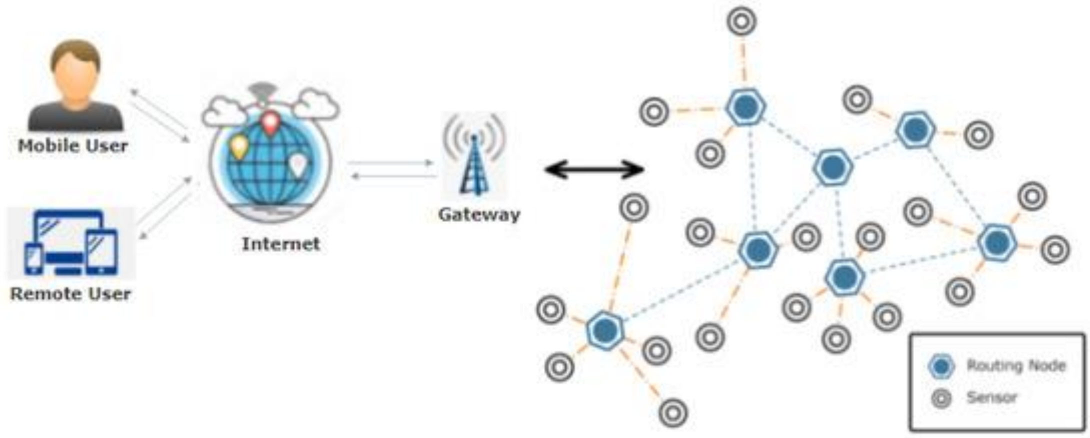


Fig 1: Wireless Sensor Network Design
Source: https://www.mdpi.com/1424-8220/22/6/2087

WSNs integrated with the Internet of Things (IoT) allow continuous monitoring and remote analytics. Kandris et al. (2020) highlight their role in scalable and reliable data collection, while Jaladi et al. (2017) show their effectiveness in environmental monitoring. However, challenges such as energy efficiency, network scalability, and security remain. Muruganandam et al. (2018) note that managing energy consumption is crucial, which can be expressed as:

$$E_{total} = E_{tx} + E_{rx} + E_{proc} \qquad (1)$$

Where Etx, Erx, and Eproc the energies for transmission, reception, and processing.

This review examines WSNs in smart city applications, their architectures, challenges, and future research directions, providing insights into building efficient, sustainable, and secure urban systems.

### 1.1 Aim and objectives

The aim of this study is to review the role, applications, architectures, and challenges of Wireless Sensor Networks (WSNs) in smart cities, with a focus on their integration with IoT, AI, and cloud-based systems to enhance urban sustainability, efficiency, and real-time decision-making.

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**Objectives**

1. To examine the key applications of WSNs in smart city domains, including traffic management, environmental monitoring, energy systems, water supply, and public safety.
2. To analyze the architectures, communication protocols, and design considerations that support efficient, scalable, and reliable WSN deployments.
3. To identify the challenges and limitations of WSNs in urban environments, such as energy efficiency, security, and network scalability.
4. To explore the integration of WSNs with IoT, AI, and cloud computing for enhanced real-time monitoring, data analytics, and intelligent urban management.
5. To highlight future research directions and potential solutions for building sustainable, resilient, and secure WSN-based smart city systems.

## 2. Review of literature

| Author(s) | Year | Aim | Objectives | Scope | Key Findings |
|---|---|---|---|---|---|
| **Ahmed** | 2020 | To analyze security and privacy issues | Identify threats and countermeasures | Secure WSN architectures | Lightweight security mechanisms are necessary |
| **Aid et al.** | 2019 | To model smart traffic congestion control | Use ML with sensor data | Urban traffic systems | ML improves congestion prediction and control |
| **Bangotra** | 2020 | To improve routing in healthcare WSNs | Apply machine learning to routing | Healthcare monitoring networks | ML-based routing increased network lifetime and reliability |
| **Du** | 2016 | To study WSNs in water distribution monitoring | Detect leaks and inefficiencies | Smart city water networks | Early fault detection improves water management |
| **Hashim et al.** | 2019 | To review WSN applications in smart cities | Classify domains and challenges | Smart city applications | Integration and scalability are major deployment issues |
| **Jaladi et al.** | 2017 | To study environmental monitoring using IoT-based WSNs | Analyze sensing, data transmission, and IoT integration | Air, water, soil monitoring | IoT-enabled WSNs improve real-time monitoring and decision-making |
| **Jamil et al.** | 2015 | To develop a smart environment monitoring system using WSNs deployed on vehicles | To monitor urban pollution levels and environmental parameters | Vehicular-based WSNs for smart cities | Mobile WSNs effectively monitor pollution and support dynamic, large-area environmental sensing |
| **Kafi et al.** | 2013 | To study the use of wireless sensor networks for urban traffic monitoring | To analyze traffic monitoring applications and propose suitable WSN architectures | Urban traffic systems in smart cities | WSNs enable real-time traffic data collection; hierarchical architectures improve scalability and reliability |
| **Kamal** | 2020 | To study IoT adoption in e-learning | Assess benefits and constraints | Higher education institutions | IoT enhances learning but needs infrastructure investment |
| **Kandris et al.** | 2020 | To present an updated survey of WSN applications | Review recent architectures, protocols, and applications | Healthcare, smart cities, industry | Energy efficiency, scalability, and security remain critical challenges |
| **Karray et al.** | 2018 | To develop an IoT-based WSN for pipelines | Monitor leaks and pipeline health | Water infrastructure | Real-time monitoring reduces water loss |
| **Kiani & Amir** | 2018 | To develop smart irrigation using WSNs | Optimize irrigation scheduling | Precision agriculture | Significant water savings and improved crop productivity |

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|---|---|---|---|---|---|
| **Mehmood** | 2019 | To enhance WSN security | Propose context-aware intrusion detection | WSN security systems | Improved detection accuracy with fewer false positives |
| **Murugananda m et al.** | 2018 | To survey WSN design challenges for IoT | Identify constraints and design issues | IoT-based WSN systems | Power consumption and interoperability are major limitations |
| **Ramson et al.** | 2016 | To survey WSN applications | Categorize application areas | General WSN domains | Application-specific design is essential for efficiency |
| **Rashid & Rehmani** | 2015 | To review WSN use in urban areas | Identify applications and issues | Urban infrastructure | Traffic, surveillance, and environment dominate urban use cases |
| **Sahar** | 2018 | To design a smart waste bin monitoring system | Automate waste-level detection | Urban waste management | Reduced manual effort and improved waste collection efficiency |
| **Saleem et al.** | 2019 | To review IoT-aided smart grid systems | Analyze technologies and architectures | Smart grid and energy systems | IoT enhances grid efficiency but raises security concerns |
| **Singh et al.** | 2020 | To address scalability in WSNs | Propose scalable architectures | Smart city WSN deployments | Scalability is essential for dense urban sensing |
| **Thondoo et al.** | 2020 | To examine transport planning in small cities | Assess mobility and infrastructure needs | Developing-country cities | Sensor-based planning supports sustainable transport |

**2.1 Research gap**
Despite significant advancements in Wireless Sensor Networks (WSNs) for smart city applications, several gaps remain. Most existing studies focus on individual domains such as traffic management, environmental monitoring, or energy systems, with limited research on fully integrated, multi-domain WSN deployments. Challenges related to energy efficiency, network scalability, and secure data transmission are often addressed in isolation, rather than through comprehensive frameworks that consider the interplay between different urban systems. Additionally, while AI and IoT integration show promise, there is a lack of standardized approaches for optimizing real-time data analytics across heterogeneous networks. Finally, the long-term sustainability, cost-effectiveness, and resilience of large-scale WSN implementations in dynamic urban environments remain underexplored, highlighting the need for holistic research that bridges these technical and operational gaps.

**3. Evolution of Wireless Sensor Networks**
Wireless Sensor Networks (WSNs) have evolved significantly since their inception, driven by the growing need for automated monitoring and data collection in diverse domains. Initially developed for military and industrial applications, WSNs have expanded into environmental monitoring, agriculture, healthcare, and smart city systems. Advancements in microelectronics, wireless communication, and energy-efficient protocols have enabled WSNs to become smaller, more reliable, and more energy-conscious, supporting large-scale deployments with minimal maintenance.
A typical WSN consists of sensor nodes, communication modules, power sources, and a central base station. Sensor nodes detect physical parameters such as temperature, humidity, or motion, and transmit this data wirelessly to the base station for processing and analysis. Sahar (2018) demonstrated this architecture in a smart waste bin monitoring system, where nodes detect bin levels and send notifications to waste management authorities, optimizing collection schedules. Similarly, Kiani & Amir (2018) implemented WSNs for precision agriculture, where sensor nodes monitor soil moisture and environmental conditions to automate irrigation, illustrating the flexibility of WSN architectures across domains.

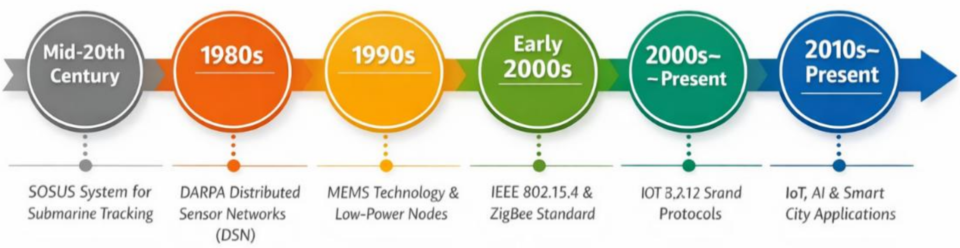

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Fig 2: Evolution of Wireless Sensor Networks
Source: Created in Ms. Word
In healthcare, WSNs have been enhanced with machine learning algorithms for intelligent routing and context-aware operations. Bangotra (2020) proposed an opportunistic routing protocol for healthcare WSNs, improving data delivery and network lifetime. Mehmood (2019) integrated context-aware intrusion detection within WSNs, highlighting the importance of security in sensitive applications.
WSNs rely on specialized communication protocols to ensure reliable data transmission while conserving energy. Common protocols include Zigbee, IEEE 802.15.4, LoRaWAN, and Bluetooth Low Energy (BLE), which are chosen based on factors such as range, power consumption, and data rate. The evolution of these protocols has enabled WSNs to support scalable, heterogeneous networks in applications ranging from urban infrastructure to healthcare monitoring. Integration with IoT standards further enhances interoperability and real-time analytics, allowing WSNs to form the backbone of smart, connected systems.

**4. Role of Wireless Sensor Networks in Smart Cities**
Wireless Sensor Networks (WSNs) are a foundational technology for smart cities, enabling real-time monitoring, automation, and data-driven decision-making across urban infrastructure. They provide continuous data collection from critical systems such as traffic management, water supply, energy grids, environmental monitoring, and public safety. WSNs allow city administrators to optimize resource usage, reduce operational costs, and enhance service quality.
Ramson et al. (2016) highlighted the versatility of WSNs in urban applications, showing that they can monitor traffic flow, detect infrastructure faults, and track environmental parameters. Similarly, Rashid & Rehmani (2015) emphasized that WSNs support intelligent urban systems, including smart transportation, street lighting, and pollution monitoring. Du (2016) demonstrated the practical impact of WSNs by deploying them in water distribution networks, enabling early leak detection, efficient water management, and reduced wastage.

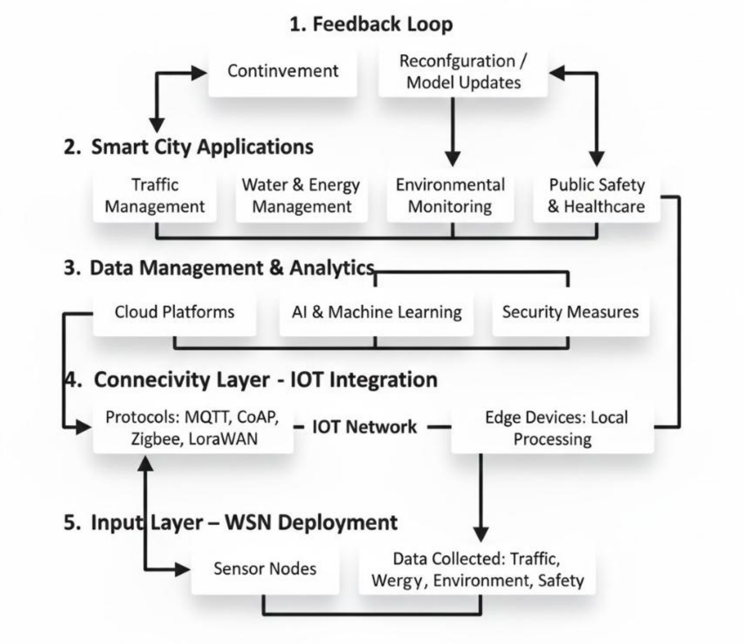


Fig 4: Role of Wireless Sensor Networks in Smart Cities
Source: Created in Ms. Word
Security and privacy are critical considerations in urban WSN deployments. Ahmed (2020) noted that protecting sensitive data, preventing unauthorized access, and ensuring network integrity are essential for maintaining trust and reliability in city services. Without robust security, the effectiveness of WSN-based urban infrastructure can be compromised.
The integration of WSNs with the Internet of Things (IoT) and cloud platforms enhances their functionality and scalability in smart cities. IoT provides seamless connectivity between distributed sensor nodes, while cloud computing enables data storage, real-time processing, analytics, and remote monitoring. This combination allows cities to implement predictive maintenance, automated control, and intelligent decision-making across multiple sectors.
Kamal (2020) demonstrated the potential of IoT-enabled WSNs in higher education, where sensor-based monitoring systems improved resource management and operational efficiency—a concept directly applicable to urban infrastructure. In smart cities, WSN-IoT-cloud integration allows traffic sensors to communicate with centralized control systems, water pipelines to report pressure changes, and environmental sensors to detect pollution levels in real time.
A key metric for evaluating such integrated systems is network lifetime, which measures how long the WSN remains operational without maintenance:

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$$\text{Lnetwork} = \min\left(\frac{Ei}{Pi}\right), i = 1,2, \ldots \ldots N \qquad (2)$$

Where:

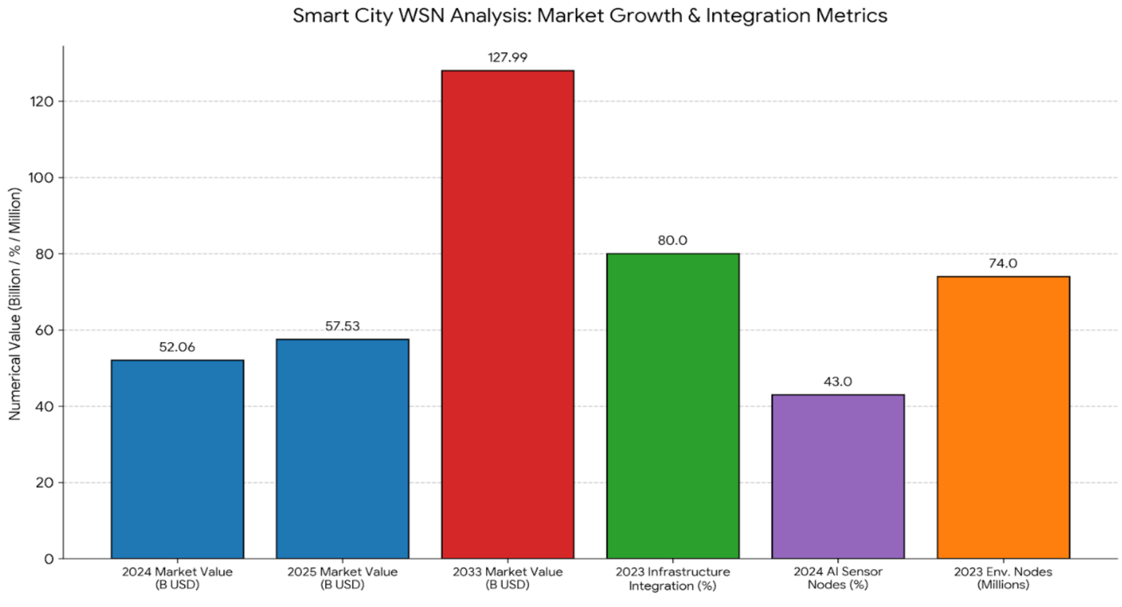
- Lnetwork = network lifetime
- Ei = initial energy of node iii
- Pi = average power consumption of node iii
- N = total number of nodes

Optimizing energy consumption and connectivity in IoT-integrated WSNs ensures continuous monitoring, reliability, and sustainability of smart city operations.

Table 1: Role of Wireless Sensor Networks in Smart Cities
Source: https://www.marketgrowthreports.com/market-reports/wireless-sensor-networks-wsn-market-109104

| S. No. | Aspect / Role in Smart Cities | Numeric Data / Statistics | Impact / Explanation |
|---|---|---|---|
| 1 | Global WSN Market Value (2024) | USD 52.06 billion | Size of the global wireless sensor networks market, reflecting broad adoption including smart city applications (traffic, environment, utility monitoring). |
| 2 | Projected Market (2025) | USD 57.53 billion | Expected growth in WSN demand for smart infrastructure, IoT, and real-time monitoring systems in cities. |
| 3 | Future Market (2033) | USD 127.99 billion | Rapid expansion suggests increasing integration of WSNs in urban services (transport, waste, energy, public safety). |
| 4 | Smart City Integration in Projects (2023) | >80% of smart city infrastructure projects used sensor-based systems | Indicates widespread sensor adoption for energy efficiency, traffic optimization, and safety in urban planning. |
| 5 | AI-Enabled Sensor Nodes (2024) | 43% of new WSN solutions incorporate AI/edge processing | Shows increasing sophistication of sensor networks to support real-time decision making in smart city operations. |
| 6 | Environmental Monitoring Deployment (2023) | ~74 million WSN nodes globally (environmental use) | Reflects large-scale sensor use for pollution, air quality, and environmental health monitoring in urban settings. |

Fig 5: Role of Wireless Sensor Networks in Smart Cities




The data highlights the rapid growth and widespread adoption of Wireless Sensor Networks (WSNs) in smart cities. The global WSN market is projected to increase from USD 52.06 billion in 2024 to nearly USD 128 billion by 2033, reflecting the rising demand for smart infrastructure and real-time monitoring systems. Over 80% of smart city projects in 2023 already rely on sensor-based systems, demonstrating their critical role in traffic management, energy efficiency, and public safety. Additionally, the integration of AI and edge computing in 43% of new WSN solutions indicates that these networks are becoming increasingly intelligent, capable of supporting real-time decision-making. The deployment of approximately

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74 million sensor nodes worldwide for environmental monitoring underscores the scale at which WSNs are contributing to urban health and sustainability initiatives.

**5. Key Smart City Applications of WSNs**

Wireless Sensor Networks (WSNs) are increasingly integral to the development of smart cities, enabling real-time monitoring and management of various urban systems. By collecting and transmitting data on environmental conditions, traffic, waste, water supply, energy, and public health, WSNs support efficient decision-making, resource optimization, and improved quality of life. The table below summarizes key applications of WSNs in urban settings and their benefits.

| S. No. | Application | Description / Function | Key Benefits / Findings | Reference |
|---|---|---|---|---|
| 1 | Environmental Monitoring | Sensors monitor air quality, noise, temperature, pollution. | Continuous monitoring; quick response to hazards; pollution reduction; sustainable urban planning. | Hashim et al. (2019) |
| 2 | Smart Transportation & Traffic Management | Sensors in roads, traffic signals, vehicles collect data on vehicle density, speed, congestion. | Predict congestion; optimize traffic flow; improve road planning; reduce delays. | Aid et al. (2019); Thondoo et al. (2020) |
| 3 | Smart Waste Management | Sensors in waste bins monitor fill levels and alert collection centers. | Reduce operational costs; improve collection efficiency; maintain cleaner urban environment. | Singh et al. (2020) |
| 4 | Smart Water Supply & Pipeline Monitoring | Sensors monitor water pressure, flow, leaks in pipelines. | Early leak/fault detection; reduce water loss; prevent service interruptions; improve resource management. | Karray et al. (2018) |
| 5 | Smart Energy & Smart Grid Systems | Sensors track energy consumption, detect faults, enable predictive maintenance. | Optimize energy distribution; load balancing; improve efficiency of urban energy systems. | Hashim et al. (2019) |
| 6 | Healthcare & Public Safety | Sensors monitor patient vitals, track emergencies, support rapid response. | Improve healthcare services; enhance emergency management; real-time situational awareness. | Singh et al. (2020) |

**6. Data Management and Analytics in WSN-based Smart Cities**

Wireless Sensor Networks (WSNs) are essential for real-time data collection in smart cities, enabling continuous monitoring of urban infrastructure such as energy grids, traffic systems, water supply networks, and environmental conditions. Sensor nodes capture data and transmit it to central servers or cloud platforms, where it is processed for actionable insights. Saleem et al. (2019) highlight that real-time analytics allows city administrators to detect anomalies, optimize operations, and respond proactively to urban challenges.

The efficiency of data collection can be represented by the data rate formula:

$$R = \frac{N.S}{T} \qquad (3)$$

Where:

- R = Data rate (bits/sec)
- N = Number of sensor nodes
- S = Size of data packet (bits)
- T = Time interval for data transmission

This formula helps planners estimate the volume of data generated by WSNs and design appropriate storage and processing strategies.

The integration of machine learning (ML) and artificial intelligence (AI) into WSNs significantly enhances the ability to analyze large datasets, predict trends, and optimize urban operations. For example, in smart grids, ML algorithms can forecast energy consumption, detect faults, and support load balancing. Saleem et al. (2019) emphasize that AI-enabled WSN analytics allows smart cities to implement predictive maintenance, adaptive traffic management, and automated resource allocation, making urban systems more efficient and resilient.

By combining real-time data with ML models, WSNs not only provide monitoring but also enable intelligent decision-making in energy management, transportation, environmental control, and public safety.

**7. Security and Privacy Issues in WSN-based Smart Cities**

Wireless Sensor Networks (WSNs) in smart cities face multiple security threats and vulnerabilities due to their distributed nature, resource constraints, and often unattended deployment. Common threats include:

- **Data interception and eavesdropping** – unauthorized access to sensitive information transmitted by sensors.
- **Node tampering and physical attacks** – sensors deployed in public areas are vulnerable to manipulation or destruction.
- **Denial of Service (DoS) attacks** – attackers can flood the network, disrupting normal operations.
- **False data injection** – compromised nodes can send incorrect data, leading to faulty decision-making.

Kafi et al. (2013) highlighted that WSNs deployed for urban traffic monitoring are particularly susceptible to data integrity and availability issues, which can compromise traffic control systems. Similarly, Jamil et al. (2015) noted that environmental monitoring systems on vehicles face risks of data tampering and unauthorized access, threatening pollution management and urban safety applications.

**Security Mechanisms and Solutions**

To address these vulnerabilities, various security mechanisms are implemented in WSNs, including:

- **Encryption and secure communication protocols** – ensuring data confidentiality during transmission.
- **Authentication and access control** – verifying legitimate nodes and preventing unauthorized access.
- **Intrusion detection systems (IDS)** – monitoring network behavior to detect anomalies or attacks.
- **Fault-tolerant and resilient routing protocols** – maintaining network functionality even when nodes are compromised.

Both Kafi et al. (2013) and Jamil et al. (2015) emphasized that lightweight security solutions are necessary for resource-constrained sensor nodes while maintaining network reliability. Integrating these security measures helps smart cities protect sensitive data, maintain operational continuity, and enhance citizen trust in IoT-enabled urban systems.

## Conclusion

Wireless Sensor Networks (WSNs) have emerged as a cornerstone technology for smart cities, enabling real-time monitoring, data-driven decision-making, and efficient resource management across diverse urban systems. From traffic and environmental monitoring to energy management, water supply, and public safety, WSNs provide scalable and flexible solutions that enhance urban sustainability and quality of life. The integration of WSNs with IoT, cloud computing, and AI further strengthens their capabilities, allowing predictive analytics, intelligent automation, and continuous system optimization. Despite challenges such as energy constraints, scalability, and security vulnerabilities, ongoing research and innovative designs are addressing these issues, paving the way for more resilient, efficient, and secure smart city infrastructures. Overall, WSNs play a critical role in transforming urban environments into intelligent, sustainable, and responsive ecosystems.

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