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Lightweight IoT Architectures for Integrated Smart Waste and Smart Sewage Monitoring in Smart Cities: A Systematic Literature Review

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Abstract: ***The rapid growth of smart city initiatives has increased the need for intelligent, scalable, and energy-efficient environmental monitoring systems capable of improving municipal services and supporting sustainable urban development. Smart waste management and smart sewage monitoring are critical application areas where Internet of Things (IoT) technologies enable real-time sensing, remote monitoring, and data-driven decision-making. This paper presents a systematic literature review of lightweight IoT architectures for integrated smart waste and smart sewage monitoring systems. The review analyzes recent advancements in embedded hardware platforms, communication protocols, edge-fog-cloud computing, artificial intelligence, and emerging technologies including TinyML, Federated Learning, Digital Twins, and Green IoT. The findings reveal that although existing solutions demonstrate significant improvements in monitoring efficiency, many remain application-specific and face challenges related to interoperability, scalability, energy management, cybersecurity, and large-scale deployment. To address these limitations, this paper proposes a conceptual unified lightweight IoT architecture that integrates sensing, embedded processing, communication, distributed computing, cloud services, and intelligent analytics within a modular framework. The proposed architecture aims to enhance resource utilization, reduce cloud dependency, support heterogeneous devices, and enable future smart city integration. A qualitative evaluation demonstrates the potential advantages of the framework while highlighting the need for experimental validation through prototype implementation and real-world deployment. This review provides insights into current trends, research gaps, and future directions for developing sustainable, intelligent, and interoperable IoT-enabled environmental monitoring systems.***

Keywords: Internet of Things (IoT); Lightweight IoT Architecture; Smart Waste Management; Smart Sewage Monitoring; Edge Computing; MQTT; TinyML; Smart Cities.

Nomenclature

Table I lists the abbreviations used throughout the manuscript.

Table I: List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
BLE	Bluetooth Low Energy
CoAP	Constrained Application Protocol
DL	Deep Learning
ESP32 / ESP8266	Espressif Wi-Fi/Bluetooth Microcontroller Series
IoT	Internet of Things
LoRaWAN	Long Range Wide Area Network
LPWAN	Low-Power Wide-Area Network
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
NB-IoT	Narrowband Internet of Things
ORP	Oxidation-Reduction Potential
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RQ	Research Question
SLR	Systematic Literature Review
STM32	STMicroelectronics 32-bit Microcontroller Series
TinyML	Tiny Machine Learning
6G	Sixth-Generation Wireless Communication

1. Introduction

Rapid urbanization and the expansion of smart-city initiatives have intensified the demand for intelligent infrastructure capable of monitoring municipal services efficiently. Waste collection and sewage monitoring are among the most resource-intensive public utilities, requiring continuous monitoring, timely decision-making, and efficient resource utilization [6].

Smart waste management and smart sewage monitoring have therefore emerged as key application domains where IoT technologies can improve operational efficiency, environmental sustainability, and public health through real-time sensing and data-driven decision support [1], [2].

The Internet of Things (IoT) enables interconnected sensing devices, embedded controllers, and communication networks to collect, transmit, and process environmental data in real time. Recent advances in low-power embedded systems have further accelerated practical deployments [4].

Lightweight IoT architectures, characterized by energy-efficient hardware, optimized communication protocols, and edge-assisted processing, are increasingly preferred for resource-constrained smart-city deployments [5].

Although numerous studies have investigated IoT-based smart waste management and smart sewage monitoring independently, most existing solutions are designed for specific application scenarios and employ heterogeneous hardware platforms, communication protocols, and software architectures. Consequently, comparing these solutions, identifying common design principles, and evaluating their suitability for large-scale smart city deployment remain challenging. Furthermore, relatively few review studies have focused specifically on **lightweight IoT architectures** that emphasize low-power operation, efficient communication, modular design, scalability, and integrated environmental monitoring.

Another important observation from the reviewed literature is that waste management and sewage monitoring are frequently addressed as separate research problems despite sharing several architectural components, including sensing devices, embedded controllers, communication networks, edge gateways, cloud infrastructure, and intelligent analytics. Developing separate monitoring infrastructures for closely related municipal services increases deployment complexity, operational cost, and maintenance effort. A unified lightweight architecture capable of supporting both applications has the potential to improve interoperability, simplify infrastructure management, and enhance resource utilization within smart city ecosystems.

In addition, rapid technological developments in recent years have introduced several new research directions that have not yet been comprehensively synthesized within a single review. The integration of Edge AI, TinyML, Digital Twins, Federated Learning, Green IoT, blockchain-enabled security, and next-generation wireless communication technologies has significantly expanded the capabilities of lightweight IoT systems. However, the architectural implications, practical challenges, and future opportunities associated with these emerging technologies remain fragmented across the existing literature.

a) *Research Motivation*

The motivation for this review originates from the growing need to consolidate recent developments in lightweight IoT architectures for integrated environmental monitoring. While numerous implementation-oriented studies have demonstrated the feasibility of IoT-enabled waste and sewage monitoring systems, limited attention has been given to systematically comparing their architectural characteristics, identifying common limitations, and proposing a unified conceptual framework. This review aims to bridge this gap by synthesizing recent research, evaluating prevailing design approaches, and highlighting opportunities for developing scalable, energy-efficient, and interoperable monitoring systems suitable for future smart cities.

b) Contributions of This Review

The major contributions of this review are summarized as follows:

- A systematic review of lightweight IoT architectures for smart waste management and smart sewage monitoring published between 2020 and 2026.
- A comparative analysis of sensing technologies, embedded hardware platforms, communication protocols, edge computing techniques, and intelligent analytics adopted in recent research.
- Identification of major research gaps related to scalability, interoperability, energy efficiency, communication overhead, and cybersecurity.
- Proposal of a conceptual lightweight unified IoT architecture integrating smart waste management and smart sewage monitoring within a common modular framework.
- Discussion of emerging research directions involving TinyML, Edge AI, Digital Twins, Federated Learning, blockchain, Green IoT, and future 6G-enabled smart city infrastructures.

2. Methodology

a) *Research Methodology*

This review adopts a **systematic literature review (SLR)** methodology to identify, evaluate, and synthesize recent research on lightweight Internet of Things (IoT) architectures for smart waste management and smart sewage monitoring systems. The review process follows the general principles of the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020)** guidelines to ensure a transparent, structured, and reproducible literature selection process. As this work is an engineering review rather than a medical meta-analysis, PRISMA is used as a methodological framework for reporting the search and selection strategy.

The objective of the review is to provide a comprehensive understanding of recent developments in lightweight IoT architectures, identify prevailing research trends, compare existing technological approaches, analyse current limitations, and propose future research directions for integrated environmental monitoring in smart cities.

b) Research Questions

To achieve the objectives of this review, the following research questions (RQs) were formulated:

RQ1: What lightweight IoT architectures have been proposed for smart waste management and smart sewage monitoring between 2020 and 2026?
RQ2: Which embedded hardware platforms, communication technologies, and computing paradigms are most frequently adopted in recent studies?
RQ3: What are the major limitations of existing lightweight IoT architectures with respect to scalability, energy efficiency, interoperability, communication overhead, and security?
RQ4: Which emerging technologies are likely to influence the future development of lightweight environmental monitoring systems?
RQ5: How can the findings of existing studies be synthesized into a unified lightweight IoT architecture for integrated smart waste and smart sewage monitoring?

Table III: Research Questions Addressed in this Review

No.	Research Question
RQ1	What are the key characteristics and requirements of lightweight IoT architectures for smart city applications?
RQ2	Which communication protocols are most suitable for lightweight IoT systems in smart cities?
RQ3	How are edge, fog, and cloud computing integrated in lightweight IoT architectures?
RQ4	What role do AI and TinyML play in enhancing lightweight IoT systems?
RQ5	What are the existing research gaps and future trends in this domain?

c) Literature Search Strategy

A comprehensive literature search was conducted using internationally recognized digital libraries to identify peer-reviewed journal articles, conference papers, and review articles relevant to the scope of this study.

The primary databases considered include:

- IEEE Xplore Digital Library
- ScienceDirect (Elsevier)
- SpringerLink
- ACM Digital Library
- MDPI Sensors
- Wiley Online Library

The search process employed combinations of the following keywords:

- "Lightweight IoT Architecture"
- "Smart Waste Management"
- "Smart Sewage Monitoring"
- "Smart City IoT"
- "Edge Computing"
- "MQTT"
- "LoRaWAN"
- "NB-IoT"
- "TinyML"
- "Environmental Monitoring"

Boolean operators (AND, OR) were used to refine search results and improve retrieval accuracy.

Table II: Search Strategy and Database Coverage

Database	Keywords Used	Years Covered	Papers Retrieved
IEEE Xplore	IoT, lightweight, smart city, edge, LoRaWAN, MQTT, TinyML, smart waste, smart sewage	2020–2026	[pending]
Scopus	IoT, low-power, edge computing, fog computing, smart waste, smart sewage, AIoT	2020–2026	[pending]
Web of Science	lightweight IoT, smart-city, resource-constrained, LPWAN, TinyML, AIoT	2020–2026	[pending]
ScienceDirect	IoT architectures, waste management, sewage monitoring, edge AI	2020–2026	[pending]
ACM Digital Library	IoT, edge, TinyML, smart city, sustainable IoT	2020–2026	[pending]
Google Scholar	allintitle: IoT lightweight smart city	2020–2026	[pending]

d) Inclusion and Exclusion Criteria

To ensure the quality and relevance of the reviewed literature, predefined inclusion and exclusion criteria were established.

Inclusion Criteria

- Research published between **2020 and 2026**.
- Peer-reviewed journal articles, conference papers, and review articles.
- Studies related to IoT-based smart waste management, smart sewage monitoring, or lightweight IoT architectures.
- Articles discussing embedded systems, communication protocols, edge computing, cloud computing, or intelligent analytics.
- Publications written in English.

Exclusion Criteria

- Duplicate publications.
- Articles unrelated to environmental monitoring.
- Non-peer-reviewed sources, editorials, blogs, and magazine articles.
- Studies lacking sufficient technical or architectural details.
- Publications outside the defined review period unless required for background context.

e) Study Selection Process

The study selection process consisted of multiple stages.

- Identification of potentially relevant studies from selected digital databases.
- Removal of duplicate records.
- Screening of titles and abstracts.
- Full-text assessment for eligibility.
- Final selection of studies satisfying the predefined inclusion criteria.

The overall selection procedure will be illustrated using a PRISMA 2020 flow diagram in the final version of the manuscript.

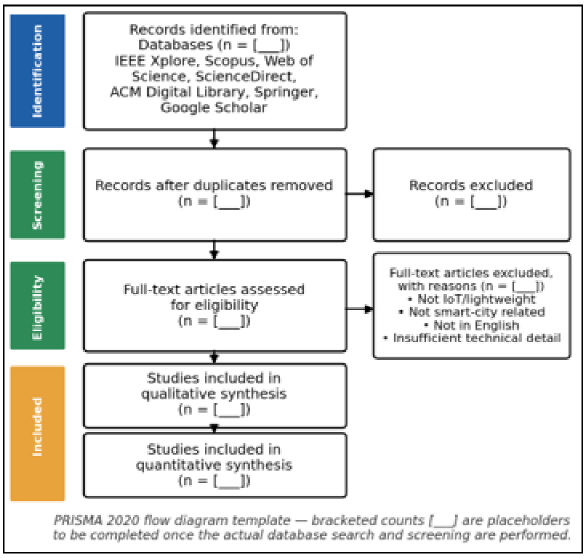

Figure 1: PRISMA-based literature selection process

f) Data Extraction

For each selected publication, relevant technical information was extracted and organized into a structured literature matrix. The extracted information includes:

- Publication year
- Application domain
- Hardware platform
- Sensor technologies
- Communication protocol
- Computing paradigm (Cloud/Fog/Edge)
- Artificial Intelligence techniques
- Major contribution
- Reported limitations

This structured approach facilitates objective comparison among different lightweight IoT architectures.

g) *Quality Assessment*

To improve the reliability of the review, each selected study will be evaluated based on the following quality indicators:

- Technical relevance to the review scope.
- Clarity of architectural design.
- Novelty of the proposed approach.
- Experimental validation or case study.
- Discussion of limitations and future work.

Studies providing comprehensive architectural descriptions and validated implementations will receive greater emphasis during the comparative analysis.

h) *Threats to Validity*

Although every effort has been made to conduct a comprehensive and unbiased review, certain limitations should be acknowledged. First, the review is restricted to publications indexed in selected digital libraries and written in English, which may exclude relevant studies published in other languages or databases. Second, rapidly evolving IoT technologies may result in new developments after the completion of the literature search. Finally, qualitative synthesis inherently involves researcher interpretation; however, the use of predefined research questions, inclusion criteria, and a structured review methodology helps reduce potential bias and improve reproducibility.

i) *Summary*

The systematic methodology adopted in this review provides a transparent framework for identifying, selecting, and synthesizing relevant literature on lightweight IoT architectures for smart waste management and smart sewage monitoring. By employing a structured search strategy, predefined selection criteria, and quality assessment procedures, the review establishes a reliable foundation for the comparative analysis, research-gap identification, and conceptual architecture proposed in the subsequent sections.

3. Literature Review

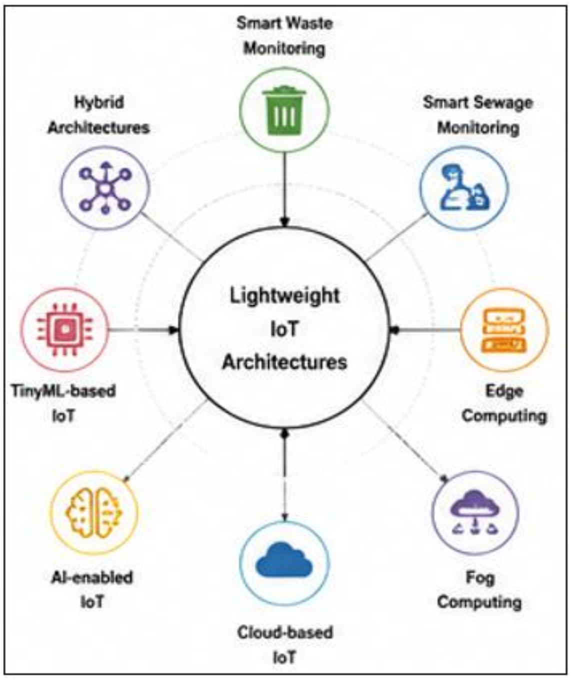

Figure 2: Taxonomy of lightweight IoT architectures discussed in this review.

a) *Evolution of Lightweight IoT Architectures for Environmental Monitoring*

The rapid advancement of Internet of Things (IoT) technologies has significantly transformed environmental monitoring systems over the past decade. Earlier monitoring infrastructures primarily relied on centralized architectures in which sensor nodes transmitted collected data directly to cloud servers for storage and analysis. Although cloud-centric systems enabled remote accessibility and large-scale data management, they frequently suffered from high communication latency, increased bandwidth consumption, greater energy requirements, and limited support for real-time decision making. These limitations became more pronounced in smart city applications where continuous monitoring and immediate responses are essential.

To overcome these challenges, researchers gradually shifted towards **lightweight IoT architectures** that emphasize low-cost hardware, energy-efficient communication, distributed processing, and modular system design. Unlike conventional IoT deployments that depend heavily on cloud computing, lightweight architectures optimize resource utilization by employing embedded microcontrollers with limited computational resources while maintaining acceptable levels of performance, reliability, and scalability. This paradigm has enabled the deployment of practical environmental monitoring solutions suitable for municipal infrastructure with reduced installation and maintenance costs.

Recent developments in embedded hardware have accelerated this transition. Microcontroller platforms such as ESP32, ESP8266, STM32, Arduino, and Raspberry Pi have become popular choices because they provide sufficient computational capability while maintaining low power consumption and affordable deployment costs. Their compatibility with multiple environmental sensors allows researchers to develop flexible monitoring systems capable of measuring waste-bin fill levels, water quality parameters, sewage flow characteristics, toxic gases, temperature, humidity, and other environmental indicators.

Communication technologies have also evolved considerably. Traditional Wi-Fi-based architectures are increasingly complemented by lightweight messaging protocols and low-power wireless communication technologies designed specifically for IoT environments. Protocols such as MQTT and CoAP minimize communication overhead through lightweight message exchange mechanisms, whereas LPWAN technologies including LoRaWAN and NB-IoT enable reliable long-distance communication with significantly reduced energy consumption. The selection of communication technology generally depends on deployment scale, transmission range, latency requirements, network availability, and power constraints.

The emergence of **edge and fog computing** has further influenced the design of lightweight IoT architectures. Rather than transmitting all sensor data to centralized cloud platforms, edge-enabled systems perform preliminary data processing near the sensing devices, thereby reducing network traffic, minimizing communication delays, and improving system responsiveness. Such distributed processing architectures are particularly advantageous for smart waste collection scheduling and sewage anomaly detection, where rapid decision making can improve operational efficiency and reduce maintenance costs.

In recent years, lightweight artificial intelligence has become another important component of environmental monitoring systems. Advances in TinyML, lightweight neural networks, and edge intelligence have enabled resource-constrained devices to perform local prediction, anomaly detection, and classification tasks without relying exclusively on cloud infrastructure. These capabilities contribute to lower communication overhead, improved privacy, enhanced reliability, and more autonomous monitoring systems.

Overall, the evolution of lightweight IoT architectures demonstrates a gradual transition from cloud-dependent monitoring systems toward intelligent, distributed, and energy-efficient architectures that integrate embedded sensing, lightweight communication, edge computing, and artificial intelligence. This evolution forms the technological foundation for modern smart waste management and smart sewage monitoring systems and provides the basis for the thematic literature review presented in the following subsections.

b) IoT-Based Smart Waste Monitoring Systems

Smart waste management has emerged as one of the most actively investigated applications of the Internet of Things (IoT) within modern smart city ecosystems. Rapid urbanization, increasing municipal solid waste generation, and growing environmental concerns have compelled researchers to develop intelligent monitoring systems capable of improving waste collection efficiency while minimizing operational costs. Conventional waste collection strategies generally follow fixed collection schedules without considering the actual fill level of waste bins, resulting in unnecessary fuel consumption, increased labor costs, traffic congestion, and overflowing garbage containers. These limitations have motivated the adoption of IoT-enabled monitoring systems that provide real-time information regarding waste bin status and support data-driven waste collection strategies. Alsayaydeh et al. [1] demonstrated this approach directly, reporting an Arduino/ESP8266-based multi-sensor bin retrofit that, over a 30-day, 12-bin field trial, achieved 85% fill-level accuracy and cut collection-vehicle mileage by 20% through GPS-guided routing.

Recent IoT-based smart waste management systems typically consist of four fundamental components: sensing devices, embedded processing units, communication infrastructure, and cloud or edge-based monitoring platforms. Ultrasonic sensors are widely employed to estimate waste-bin fill levels because of their low cost, simple integration, and reliable distance measurement capabilities. Additional environmental sensors, including temperature, humidity, methane, ammonia, and smoke sensors, are frequently incorporated to detect hazardous conditions such as fire outbreaks, toxic gas accumulation, or decomposition-related emissions. The integration of multiple sensing modalities enhances the reliability of monitoring systems and enables municipalities to respond proactively to environmental risks.

Embedded hardware platforms play a significant role in determining the efficiency and affordability of lightweight IoT architectures. Among the various platforms reported in the literature, ESP32 has become one of the most widely adopted microcontrollers because it integrates Wi-Fi and Bluetooth connectivity while providing sufficient computational capability at low power consumption. Earlier implementations frequently relied on Arduino Uno, NodeMCU (ESP8266), or Raspberry Pi platforms; however, recent studies increasingly favor ESP32 due to its improved processing capability, integrated wireless communication, and support for edge-based applications. The selection of hardware generally depends on deployment cost, available communication infrastructure, computational requirements, and expected battery life.

Wireless communication technologies constitute another critical component of smart waste monitoring systems. Wi-Fi remains a practical solution for short-range deployments in campuses, institutional environments, and residential communities where communication infrastructure already exists. However, city-wide deployments increasingly employ lightweight messaging protocols such as MQTT together with LPWAN technologies including LoRaWAN and NB-IoT to achieve long-distance communication while minimizing energy consumption. MQTT is particularly suitable for lightweight IoT environments because of it publish-subscribe communication model, which reduces communication overhead and supports scalable device connectivity. LoRaWAN enables long-range transmission with minimal power consumption, whereas NB-IoT provides reliable communication through existing cellular infrastructure, making both technologies suitable for municipal-scale deployments.

Cloud computing has traditionally served as the primary platform for storing and analyzing environmental monitoring data. Cloud-based dashboards enable municipal authorities to visualize waste-bin status, monitor historical trends, and optimize collection schedules using centralized management systems. Nevertheless, transmitting all sensor data directly to cloud servers may increase network traffic, communication latency, and operational costs. Consequently, recent research increasingly incorporates edge computing paradigms in which preliminary data processing, filtering, and event detection are performed near the sensing devices before transmitting only relevant information to cloud platforms. This distributed processing approach improves response time, reduces bandwidth utilization, and enhances system scalability.

Artificial intelligence has further expanded the capabilities of smart waste management systems beyond simple monitoring. Machine learning techniques are increasingly applied for waste generation prediction, route optimization, anomaly detection, and intelligent scheduling of collection vehicles. Predictive analytics enables municipalities to estimate future waste accumulation patterns based on historical sensor data, seasonal variations, population density, and user behavior. Route optimization algorithms reduce fuel consumption and operational costs by dynamically selecting efficient collection paths based on the real-time status of waste bins. More recently, lightweight AI models based on TinyML have demonstrated the feasibility of executing intelligent decision-making directly on embedded microcontrollers, thereby reducing cloud dependency while improving system autonomy.

Despite significant technological progress, existing smart waste monitoring systems continue to face several challenges. Energy efficiency remains a primary concern for battery-operated sensor nodes deployed in large-scale outdoor environments. Communication reliability may degrade because of signal interference, network congestion, or infrastructure limitations. Interoperability among heterogeneous sensing devices and communication protocols remains limited, particularly in multi-vendor deployments. Furthermore, many existing implementations prioritize prototype development and small-scale experimental validation, while relatively few studies investigate long-term deployment, cybersecurity, fault tolerance, maintainability, or integration with other smart city services.

Overall, the reviewed literature indicates that smart waste management has evolved from simple sensor-based monitoring systems toward intelligent, distributed, and energy-efficient IoT ecosystems. Contemporary architectures increasingly combine lightweight embedded hardware, low-power communication technologies, edge computing, and artificial intelligence to improve operational efficiency and environmental sustainability. However, achieving scalable, interoperable, and secure deployments suitable for large smart city environments remains an open research challenge, thereby motivating continued investigation into lightweight IoT architectures and integrated municipal monitoring frameworks.

c) IoT-Based Smart Sewage Monitoring Systems

The increasing complexity of urban wastewater management has accelerated the adoption of Internet of Things (IoT)-based monitoring systems capable of providing continuous assessment of sewage networks and wastewater infrastructure. Conventional sewage monitoring primarily depends on periodic manual inspections and laboratory-based water quality analysis, which are often time-consuming, labor-intensive, and incapable of detecting abnormal conditions in real time. Such limitations may result in delayed identification of sewer blockages, wastewater overflow, toxic gas accumulation, equipment failures, and deterioration of water quality. Consequently, municipalities and researchers have increasingly focused on the development of intelligent monitoring systems that support continuous data acquisition, remote supervision, and predictive maintenance. Sundar et al. [2] validated an eight-sensor ESP32 edge node with MQTT reporting and CNN-LSTM contamination classification at a municipal sewage treatment plant, sustaining 98.12% classification accuracy and 99.87% system availability over a 45-day deployment. Forhad et al. [3] similarly reported a PLC-integrated IoT water-quality platform for treatment plants that held a 0.1-0.2 error margin across pH, dissolved oxygen, and TDS while consuming only 29 W.

Modern IoT-enabled sewage monitoring systems generally comprise distributed sensing devices, embedded processing units, wireless communication modules, edge or cloud computing platforms, and visualization dashboards. The distributed deployment of sensing nodes enables continuous monitoring of multiple sewer locations, pumping stations, treatment facilities, and drainage networks, thereby improving operational visibility and reducing the dependence on manual inspection. Real-time data acquisition allows municipal authorities to detect abnormal operating conditions at an early stage and initiate timely corrective actions.

A wide variety of environmental sensors have been employed in recent sewage monitoring applications depending on the intended monitoring objectives. Water quality assessment commonly utilizes pH sensors, turbidity sensors, dissolved oxygen sensors, electrical conductivity sensors, temperature sensors, and oxidation-reduction potential sensors to evaluate the physical and chemical characteristics of wastewater. In addition, ultrasonic sensors and water-level sensors are frequently deployed to monitor sewage flow levels and detect overflow conditions. Gas sensors capable of detecting methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), and other hazardous gases are increasingly integrated into sewage monitoring systems to improve worker safety and enable early warning of dangerous environmental conditions.

Embedded hardware platforms significantly influence the performance and cost of lightweight sewage monitoring systems. Resource-efficient microcontrollers such as ESP32, ESP8266, STM32, and Arduino-based platforms have become widely adopted because they provide sufficient computational capability while maintaining low power consumption and affordable deployment costs. Raspberry Pi-based systems are also employed in applications requiring higher computational performance, image processing, or local data analytics. Recent research increasingly favors ESP32-based platforms owing to their integrated wireless communication capabilities, improved processing performance, and compatibility with multiple environmental sensors.

Reliable communication infrastructure remains a fundamental requirement for large-scale sewage monitoring applications. Wi-Fi-based communication is suitable for localized monitoring environments where network infrastructure is readily available. However, underground sewer networks, remote pumping stations, and geographically distributed wastewater facilities require communication technologies capable of supporting long-distance transmission with minimal energy consumption. Consequently, lightweight messaging protocols such as MQTT and CoAP, together with LPWAN technologies including LoRaWAN and NB-IoT, have emerged as practical solutions for municipal-scale deployments. These technologies improve communication reliability while reducing bandwidth utilization and extending battery life for remote sensing devices.

Cloud computing platforms continue to play an important role in sewage monitoring by providing centralized storage, historical data analysis, visualization dashboards, and remote system management. Nevertheless, transmitting all sensor data directly to cloud servers may increase communication latency and bandwidth consumption, particularly in applications requiring continuous high-frequency monitoring. To address these limitations, recent studies increasingly incorporate edge and fog computing paradigms that perform preliminary data filtering, anomaly detection, and event classification near the sensing devices. Such distributed processing architectures reduce network traffic, improve response time, and enable rapid identification of abnormal events such as sewage overflow, pipe blockage, or sudden deterioration in water quality.

Artificial intelligence and machine learning techniques have further enhanced the capabilities of smart sewage monitoring systems by enabling predictive analytics and intelligent decision support. Machine learning algorithms are increasingly utilized for water quality prediction, anomaly detection, fault diagnosis, predictive maintenance, and trend analysis. Time-series forecasting models assist municipal authorities in estimating wastewater flow patterns and anticipating overflow events during periods of heavy rainfall or increased urban activity. More recently, lightweight artificial intelligence techniques based on TinyML have demonstrated the feasibility of executing environmental classification and anomaly detection directly on embedded microcontrollers, thereby reducing cloud dependency and improving system responsiveness.

Despite considerable progress, several technical challenges continue to limit the practical deployment of IoT-enabled sewage monitoring systems. Sensor reliability may degrade because of prolonged exposure to corrosive wastewater environments, biofouling, and chemical contamination. Wireless communication within underground sewer infrastructure remains susceptible to signal attenuation and intermittent connectivity. Energy management also represents a significant concern for battery-powered sensing nodes deployed in inaccessible locations. Furthermore, cybersecurity, interoperability among heterogeneous devices, standardization, and long-term maintenance continue to receive relatively limited attention in many existing implementations.

Overall, the reviewed literature demonstrates that smart sewage monitoring has evolved from periodic manual inspection toward intelligent, continuously connected, and data-driven monitoring systems. Recent developments increasingly integrate lightweight embedded hardware, low-power communication technologies, edge computing, and artificial intelligence to improve monitoring accuracy, operational efficiency, and environmental sustainability. Nevertheless, the need for interoperable, scalable, secure, and energy-efficient architectures capable of supporting long-term municipal deployment remains an important direction for future research.

d) Lightweight IoT Architectures for Environmental Monitoring

The increasing deployment of Internet of Things (IoT) devices in smart city applications has created a growing demand for lightweight architectures capable of operating under stringent constraints of power consumption, processing capability, memory availability, communication bandwidth, and deployment cost. Environmental monitoring applications such as smart waste management and smart sewage monitoring often involve geographically distributed sensor nodes that operate continuously in resource-constrained environments. Consequently, lightweight IoT architectures have become a preferred design approach due to their ability to provide reliable monitoring while maintaining energy efficiency, scalability, and cost-effectiveness. Kim et al. [4], introducing a dedicated special issue on the topic, frame edge and fog computing as complementary layers that push computation toward constrained IoT infrastructure specifically to meet this kind of power, memory, and bandwidth budget.

A lightweight IoT architecture generally consists of multiple functional layers, including sensing, embedded processing, communication, edge computing, cloud services, and application interfaces. Each layer is designed to minimize computational overhead while ensuring seamless data acquisition, transmission, processing, and visualization. Unlike traditional cloud-centric architectures, lightweight architectures distribute computational tasks across multiple layers, enabling efficient utilization of hardware resources and reducing communication latency.

At the sensing layer, environmental parameters are acquired using low-power sensors specifically selected according to application requirements. Smart waste monitoring systems commonly utilize ultrasonic sensors, load cells, temperature sensors, humidity sensors, and gas sensors, whereas sewage monitoring applications incorporate pH sensors, turbidity sensors, dissolved oxygen sensors, electrical conductivity sensors, water-level sensors, and toxic gas sensors. Since sensing devices often operate in battery-powered environments, minimizing energy consumption through efficient sampling strategies and low-power operation remains an important architectural objective.

The embedded processing layer performs preliminary signal acquisition, sensor interfacing, local control, and communication management. Recent literature demonstrates an increasing preference for resource-efficient microcontrollers such as ESP32, ESP8266, STM32, and Arduino-compatible platforms due to their low power consumption, integrated wireless communication capabilities, and affordable deployment cost. Among these platforms, ESP32 has gained widespread adoption because it combines dual-core processing, integrated Wi-Fi and Bluetooth connectivity, sufficient memory resources, and compatibility with numerous IoT development frameworks. Raspberry Pi-based systems are generally employed in applications requiring higher computational capability, multimedia processing, or local execution of artificial intelligence models.

Efficient communication represents another critical component of lightweight IoT architectures. The selection of communication technology directly influences transmission reliability, network coverage, energy consumption, latency, and deployment cost. Lightweight messaging protocols such as MQTT and CoAP have become increasingly popular because they significantly reduce communication overhead compared with conventional web-based communication mechanisms. MQTT adopts a publish-subscribe communication model that efficiently supports asynchronous data exchange among distributed devices, while CoAP provides a lightweight request-response mechanism suitable for constrained embedded systems. The choice between these protocols depends on application requirements, communication frequency, network topology, and resource availability.

In addition to application-layer communication protocols, low-power wireless networking technologies have significantly improved the scalability of environmental monitoring systems. Wi-Fi remains appropriate for localized deployments where existing communication infrastructure is available; however, large-scale smart city applications increasingly utilize LPWAN technologies such as LoRaWAN and NB-IoT. LoRaWAN offers long-range communication with extremely low power consumption, making it suitable for battery-operated sensor networks deployed across wide geographic areas. NB-IoT provides enhanced reliability and coverage by utilizing existing cellular infrastructure while supporting secure communication and large-scale device connectivity. The selection of communication technology therefore involves balancing transmission range, latency, throughput, network availability, infrastructure cost, and energy efficiency.

Another major evolution in lightweight IoT architectures is the increasing adoption of distributed computing paradigms. Conventional IoT systems typically transmit all sensor data directly to cloud servers, leading to higher bandwidth utilization and increased communication latency. Modern lightweight architectures increasingly integrate edge and fog computing to perform preliminary data filtering, aggregation, anomaly detection, and event processing close to the sensing devices. This distributed processing approach reduces unnecessary data transmission, improves response time, enhances system scalability, and supports near real-time decision making in environmental monitoring applications.

Energy efficiency remains one of the primary design objectives of lightweight IoT architectures. Various optimization techniques have been proposed to extend battery life, including adaptive sensing intervals, sleep scheduling mechanisms, lightweight communication protocols, event-driven data transmission, and efficient power management strategies. Recent research also investigates energy harvesting techniques based on solar power, vibration energy, and hybrid renewable energy sources to support long-term autonomous operation of remote monitoring systems. These approaches reduce maintenance requirements while improving the sustainability of large-scale IoT deployments.

Scalability and interoperability have become equally important architectural considerations as smart city deployments continue to expand. Lightweight IoT architectures are expected to support thousands of heterogeneous sensing devices operating across different municipal services. Standardized communication protocols, modular software architectures, interoperable data models, and service-oriented system design facilitate seamless integration among heterogeneous hardware platforms and cloud services. Nevertheless, interoperability remains an open research challenge because many existing implementations continue to rely on proprietary hardware interfaces and application-specific communication mechanisms.

Security and privacy are increasingly recognized as fundamental requirements for lightweight IoT deployments. Environmental monitoring systems continuously exchange operational information through public communication networks, making them vulnerable to unauthorized access, data tampering, denial-of-service attacks, and device impersonation. However, implementing conventional cryptographic algorithms on resource-constrained embedded devices may significantly increase computational overhead and energy consumption. Consequently, researchers are actively investigating lightweight encryption algorithms, secure authentication mechanisms, blockchain-assisted security frameworks, and privacy-preserving communication techniques specifically designed for constrained IoT environments.

Overall, recent literature demonstrates that lightweight IoT architectures have evolved into modular, distributed, and energy-efficient computing frameworks capable of supporting diverse environmental monitoring applications. The integration of resource-efficient embedded hardware, lightweight communication protocols, LPWAN technologies, edge computing, and intelligent analytics has significantly enhanced the scalability and operational efficiency of smart waste and smart sewage monitoring systems. Despite these advancements, further research is required to improve interoperability, strengthen cybersecurity, optimize energy management, and develop standardized architectural frameworks capable of supporting integrated smart city infrastructures.

Table IV: Summary of Selected Literature (Verified Sources)

Ref.	Year	Domain	Hardware Platform	Communication	Key Contribution	Reported Limitations
[1]	2025	Smart waste monitoring	Arduino/ESP8266, HC-SR04, HX711, DHT22, MQ-135, GPS	Wi-Fi, cloud (Firebase)	Multi-sensor bin retrofit; 30-day, 12-bin trial: 85% fill-level accuracy, 20% less collection mileage	Single-city pilot; no edge processing or AI
[2]	2026	Smart sewage monitoring	ESP32, 8 electrochemical/optical sensors	MQTT, edge (Kalman filter) + CNN-LSTM	45-day municipal STP deployment: 98.12% classification accuracy, 99.87% availability	Deployment-specific tuning; single treatment-plant site
[3]	2024	Water treatment monitoring	PLC + IoT sensor suite (pH, DO, TDS, temp.)	Wired/cloud	0.1–0.2 error margin across parameters at 29 W power draw	PLC-centric design; limited wireless/ LPWAN discussion
[4]	2023	Edge/fog computing for IoT (special-issue editorial)	N/A (survey of contributed works)	N/A	Frames edge/fog as complementary layers for constrained IoT infrastructure	Editorial overview, not a standalone empirical study

[5]	2025	TinyML across smart-city domains	Various microcontrollers (survey of 66 studies)	Mixed; notes LPWAN underused	Systematic review 2019–2024; environmental sensing and waste management represented	Breadth review; limited depth per individual application

e) Edge Computing, Fog Computing, and Artificial Intelligence Integration

The rapid increase in the number of Internet of Things (IoT) devices deployed across smart city environments has significantly increased the volume of data generated by environmental monitoring systems. Conventional cloud-centric IoT architectures require sensor nodes to transmit large quantities of raw data to remote cloud servers for storage, processing, and analysis. Although this approach provides centralized management and scalable storage, it often introduces communication latency, increased bandwidth utilization, higher operational costs, and greater dependence on continuous network connectivity. These limitations have encouraged researchers to investigate distributed computing paradigms capable of processing data closer to the point of generation.

Edge computing has emerged as one of the most promising solutions for overcoming the limitations of cloud-dependent IoT systems. In edge-enabled architectures, computational tasks are executed on embedded devices or nearby gateway nodes before transmitting processed information to cloud platforms. This decentralized processing strategy reduces communication overhead, minimizes response time, and enables near real-time decision-making for environmental monitoring applications. In smart waste management systems, edge computing supports local processing of waste-bin status, event detection, and preliminary route optimization, allowing only relevant information to be transmitted to centralized monitoring platforms. Similarly, smart sewage monitoring systems employ edge processing to detect abnormal water quality conditions, sewer overflow events, or hazardous gas concentrations without requiring continuous cloud communication.

Fog computing extends this concept by introducing an intermediate computing layer between edge devices and cloud infrastructure. Fog nodes aggregate data from multiple sensing devices, perform local analytics, manage communication among distributed devices, and coordinate interactions with cloud services. Compared with purely cloud-based architectures, fog computing reduces network congestion while improving system scalability and fault tolerance. The distributed nature of fog computing is particularly beneficial in large-scale smart city deployments where thousands of heterogeneous sensing devices operate simultaneously across geographically dispersed locations.

The integration of artificial intelligence (AI) has further transformed lightweight IoT architectures by enabling intelligent data interpretation and autonomous decision support. Machine learning algorithms are increasingly incorporated into environmental monitoring systems to analyse historical sensor data, identify hidden patterns, and generate predictive insights. Applications include waste generation forecasting, dynamic collection scheduling, anomaly detection, equipment fault diagnosis, water quality prediction, sewage overflow forecasting, and environmental risk assessment. These capabilities enable municipalities to transition from reactive maintenance toward predictive and condition-based management strategies.

Traditionally, AI algorithms have been executed within cloud platforms because of their computational complexity and extensive memory requirements. However, continuous transmission of sensor data to cloud servers may increase latency and communication costs while raising concerns regarding data privacy and network reliability. To address these limitations, recent research has focused on lightweight artificial intelligence models capable of executing directly on resource-constrained embedded devices. Advances in model compression, quantization, and efficient neural network architectures have made it possible to deploy machine learning models on microcontrollers with limited processing capability.

Tiny Machine Learning (TinyML) represents a significant advancement in this direction by enabling inference on ultra-low-power embedded systems. TinyML frameworks optimize machine learning models for deployment on microcontrollers such as ESP32 and STM32, allowing environmental monitoring devices to perform local classification, anomaly detection, and predictive analysis with minimal computational overhead. By executing inference locally, TinyML reduces communication latency, lowers bandwidth consumption, improves data privacy, and extends battery life through efficient resource utilization. Consequently, TinyML has become an important enabling technology for next-generation lightweight IoT architectures. In a systematic review of 66 TinyML deployments across smart city domains, Trigkas et al. [5] found environmental sensing and waste management already represented among current applications, while flagging LPWAN communication as still underused relative to its potential for this class of device.

The convergence of edge computing, fog computing, and lightweight artificial intelligence has introduced a new paradigm commonly referred to as **Edge Intelligence**. In this architecture, sensing devices continuously collect environmental information, edge nodes perform initial filtering and AI inference, fog nodes coordinate distributed analytics, and cloud platforms provide long-term storage, visualization, and model management. This hierarchical processing framework distributes computational tasks according to available resources, thereby improving overall system efficiency while reducing dependence on centralized cloud infrastructure. Such architectures are particularly advantageous for municipal applications that require continuous monitoring, rapid event detection, and scalable deployment.

Despite these technological advancements, several challenges continue to hinder the practical implementation of AI-enabled lightweight IoT systems. Resource limitations of embedded hardware restrict the complexity of deployable machine learning models. Maintaining model accuracy while minimizing memory usage and computational requirements remains an active research challenge. Furthermore, heterogeneous hardware platforms, inconsistent software frameworks, and the absence of standardized deployment methodologies complicate large-scale implementation. Additional concerns include cybersecurity, secure model updates, privacy-preserving analytics, and the long-term maintenance of intelligent IoT infrastructures operating in dynamic urban environments.

Recent studies also indicate growing interest in complementary technologies such as Digital Twins, Federated Learning, blockchain-assisted security, Green IoT, and future 6G communication networks. Digital Twin technology enables the creation of virtual replicas of physical infrastructure for simulation and predictive maintenance. Federated Learning facilitates collaborative model training without requiring centralized collection of sensitive sensor data, thereby improving privacy while supporting distributed intelligence. Blockchain-based frameworks strengthen trust, authentication, and data integrity within distributed IoT networks, whereas Green IoT emphasizes energy-aware system design and environmentally sustainable operation. Together, these technologies represent the next stage in the evolution of intelligent lightweight IoT architectures for smart city applications.

Overall, the integration of edge computing, fog computing, artificial intelligence, and TinyML has fundamentally reshaped the design philosophy of modern environmental monitoring systems. Rather than relying exclusively on centralized cloud computing, contemporary lightweight IoT architectures increasingly employ distributed intelligence capable of performing real-time analytics, autonomous decision-making, and efficient resource management. These developments significantly improve system responsiveness, scalability, energy efficiency, and operational reliability while establishing the technological foundation for future integrated smart city infrastructures.

f) Literature Synthesis and Research Trends

The comprehensive review of recent literature demonstrates a significant transformation in the design and implementation of lightweight Internet of Things (IoT) architectures for environmental monitoring applications. Although individual studies differ in terms of hardware selection, communication technologies, deployment environments, and application objectives, several common architectural trends have emerged over the past few years. These trends collectively indicate a gradual shift toward intelligent, distributed, scalable, and energy-efficient monitoring systems capable of supporting the evolving requirements of smart cities.

One of the most prominent observations is the transition from traditional cloud-centric architectures to distributed computing frameworks incorporating edge and fog computing. Earlier IoT implementations relied primarily on centralized cloud platforms for data storage, processing, and visualization. While cloud computing remains an essential component for long-term data management and remote accessibility, recent studies increasingly advocate performing preliminary data processing at edge gateways or embedded devices. This architectural evolution reduces communication latency, decreases bandwidth consumption, and improves system responsiveness, particularly in applications requiring real-time event detection such as waste-bin overflow, sewage blockage, hazardous gas leakage, and abnormal water quality conditions.

Another significant trend observed across the reviewed literature is the widespread adoption of lightweight embedded hardware platforms. Resource-efficient microcontrollers, particularly ESP32 and STM32, have become preferred solutions because they offer an effective balance between computational capability, integrated wireless communication, low power consumption, and deployment cost. Although Arduino-based platforms continue to be utilized for educational and prototype implementations, recent studies increasingly employ more capable embedded systems that support advanced networking features and local data processing. Similarly, Raspberry Pi-based gateways are commonly integrated into architectures requiring higher computational performance or local execution of artificial intelligence applications.

Communication technologies have also evolved considerably to accommodate the scalability requirements of smart city infrastructures. Lightweight messaging protocols such as MQTT and CoAP have largely replaced conventional communication mechanisms due to their reduced protocol overhead and suitability for constrained IoT devices. Furthermore, LPWAN technologies, including LoRaWAN and NB-IoT, have become increasingly popular for municipal-scale deployments because they enable reliable long-range communication while maintaining low energy consumption. The reviewed literature suggests that communication technology selection is becoming increasingly application-driven, with researchers considering factors such as transmission range, infrastructure availability, power requirements, network reliability, and deployment cost rather than relying on a single universal solution.

Artificial intelligence has emerged as another defining characteristic of contemporary lightweight IoT architectures. Earlier environmental monitoring systems primarily focused on data acquisition and visualization, whereas modern implementations increasingly integrate machine learning algorithms for prediction, classification, anomaly detection, and intelligent decision support. Predictive waste collection scheduling, water quality forecasting, sewer overflow prediction, and equipment fault diagnosis are among the most common applications reported in recent studies. More importantly, advances in TinyML and model optimization techniques have enabled intelligent inference directly on embedded devices, reducing cloud dependency while improving response time and communication efficiency.

The reviewed studies also indicate a growing emphasis on modular and interoperable system architectures. Rather than developing isolated monitoring solutions for individual municipal services, researchers are increasingly designing reusable architectural frameworks that support heterogeneous sensors, multiple communication technologies, and cloud-independent deployment models. This modular approach facilitates system scalability, simplifies maintenance, and improves interoperability among different smart city applications. Nevertheless, fully standardized architectures capable of integrating waste management, sewage monitoring, water distribution, air quality monitoring, and other urban services remain relatively limited in the existing literature.

Despite considerable technological progress, several recurring research gaps are consistently identified across published studies. Many implementations are validated only through laboratory experiments or small-scale pilot deployments, limiting the understanding of long-term operational performance under real urban conditions. Energy management remains a major challenge for battery-powered sensor nodes operating in remote or inaccessible locations. Similarly, interoperability among heterogeneous hardware platforms, communication protocols, and software frameworks continues to hinder large-scale deployment. Cybersecurity, privacy protection, secure firmware updates, and resilience against communication failures are also insufficiently addressed in many existing implementations. Furthermore, relatively few studies provide comprehensive evaluations considering technical performance together with economic feasibility, maintenance requirements, and sustainability indicators.

Another noteworthy observation is the increasing convergence of emerging technologies with lightweight IoT architectures. Recent research demonstrates growing interest in integrating Digital Twins for virtual infrastructure modelling, Federated Learning for privacy-preserving distributed intelligence, blockchain for secure data management, Green IoT for energy-aware operation, and future 6G communication technologies for ultra-reliable low-latency connectivity. Although these technologies remain at different levels of maturity, their integration has the potential to substantially enhance the scalability, intelligence, and resilience of future environmental monitoring systems.

Based on the synthesized findings, it can be inferred that the future direction of lightweight IoT architectures lies in the development of unified, modular, and intelligent platforms capable of simultaneously supporting multiple smart city services through shared sensing infrastructure, standardized communication protocols, distributed computing, and AI-driven decision support. Such integrated architectures are expected to improve infrastructure utilization, reduce deployment costs, simplify maintenance, and promote interoperability across diverse municipal applications.

The observations presented in this literature synthesis provide the foundation for the comparative analysis discussed in the next section. By consolidating the strengths, limitations, and emerging trends reported across the reviewed studies, the subsequent analysis identifies existing research gaps and highlights opportunities for developing a unified lightweight IoT architecture for integrated smart waste and smart sewage monitoring systems.

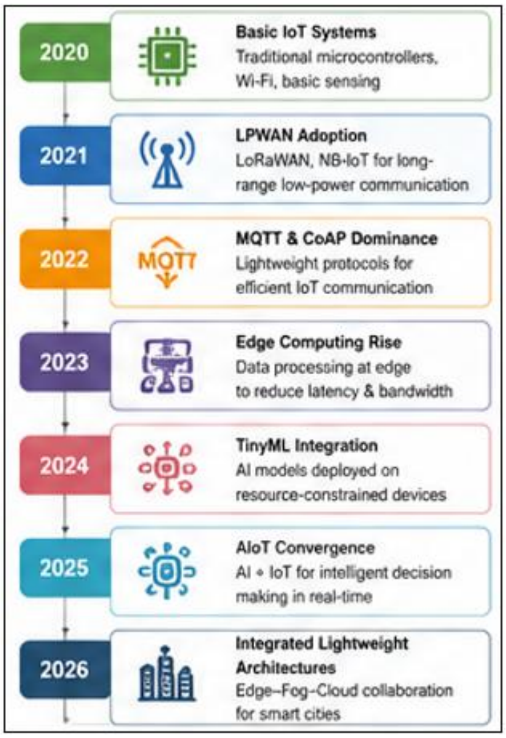

Figure 3: Conceptual timeline of lightweight IoT technology trends (2020–2026), synthesized from the reviewed literature.

4. Comparative Analysis of Existing Lightweight IoT Architectures

The systematic review presented in the previous section highlights considerable progress in the development of lightweight Internet of Things (IoT) architectures for smart waste management and smart sewage monitoring. However, the reviewed studies exhibit significant differences in hardware selection, communication technologies, computing paradigms, intelligent analytics, deployment strategies, and performance objectives. These variations make direct comparison difficult and underscore the necessity for a structured comparative analysis. This section critically evaluates the major architectural components adopted in recent studies and identifies their respective strengths, limitations, and applicability to large-scale smart city deployments.

a) *Comparative Analysis of Embedded Hardware Platforms*

Embedded hardware forms the computational foundation of lightweight IoT architectures. The reviewed literature demonstrates that the choice of microcontroller significantly influences system performance, power consumption, communication capability, deployment cost, and scalability.

ESP32 has become the most widely adopted embedded platform because it integrates Wi-Fi and Bluetooth connectivity with sufficient computational capability while maintaining low energy consumption. Its compatibility with numerous sensors and software development frameworks makes it suitable for both smart waste management and sewage monitoring applications.

STM32 microcontrollers provide improved computational efficiency and lower power consumption for industrial applications requiring high reliability and real-time processing. However, their development complexity is generally higher than that of ESP32-based platforms.

Arduino Uno remains a popular educational and prototyping platform because of its simplicity and extensive community support. Nevertheless, limited processing capability, restricted memory resources, and the absence of integrated wireless communication reduce its suitability for large-scale smart city deployments.

Raspberry Pi provides significantly higher computational capability than conventional microcontrollers and is particularly appropriate for gateway applications involving multimedia processing, local databases, and artificial intelligence. However, its comparatively higher power consumption and operational cost make it less suitable for battery-powered distributed sensing nodes.

Overall, the reviewed literature indicates that lightweight environmental monitoring systems increasingly favor ESP32-based architectures due to their balanced performance, affordability, integrated connectivity, and support for edge intelligence.

Table V: Embedded Hardware Platform Comparison

Platform	Processor	Clock Speed	Connectivity	Advantages	Limitations
Arduino Uno	ATmega328P	16 MHz	No integrated wireless	Low cost, very easy to use, large community	Limited processing power and memory (2 KB SRAM)
ESP32	Dual-core Xtensa LX6	Up to 240 MHz	Integrated Wi-Fi + Bluetooth	Low cost, integrated wireless, good performance/price ratio	Power draw rises during active Wi-Fi transmission
Raspberry Pi Pico W	Dual-core RP2040 (Cortex-M0+)	133 MHz	Integrated Wi-Fi	Low cost, Wi-Fi enabled, good for lightweight edge tasks	Limited RAM (264 KB); no Bluetooth on base module
STM32 Nucleo (F4 series)	ARM Cortex-M4	Up to 168 MHz	No integrated wireless (external module needed)	Low power, high reliability, real-time performance	Steeper development/tooling learning curve

b) Comparative Analysis of Communication Technologies

Reliable communication is essential for continuous environmental monitoring. The reviewed studies employ several communication technologies, each optimized for different deployment scenarios.

Wi-Fi provides high data throughput and straightforward integration with existing infrastructure but suffers from limited communication range and relatively high energy consumption.

Bluetooth Low Energy (BLE) offers excellent power efficiency for short-range communication but is unsuitable for geographically distributed monitoring applications.

MQTT has become the dominant lightweight messaging protocol because its publish-subscribe architecture minimizes communication overhead and supports scalable communication among heterogeneous IoT devices. Its reliability and simplicity make it particularly suitable for municipal monitoring applications. CoAP represents another lightweight communication protocol specifically designed for constrained embedded systems. Compared with MQTT, CoAP offers lower protocol overhead in request-response communication scenarios but provides fewer built-in mechanisms for large-scale asynchronous communication.

For city-wide deployments, LPWAN technologies such as LoRaWAN and NB-IoT have emerged as practical communication solutions. LoRaWAN offers long-range communication with extremely low power consumption and minimal infrastructure cost, whereas NB-IoT provides enhanced reliability and security by utilizing existing cellular infrastructure. The choice between these technologies depends on deployment scale, network availability, communication latency, operational cost, and application-specific requirements.

Table VI: Communication Protocol Comparison

Protocol	Range	Data Rate	Latency	Power Use	Best Use Case
Wi-Fi	30–50 m	High (up to 54 Mbps)	Low	High	High-data-rate local applications
Bluetooth Low Energy	10–30 m	Low (~1 Mbps)	Low	Very low	Wearables, short-range sensors
LoRaWAN	2–15 km	Very low (0.3–50 kbps)	High	Very low	Long-range, low-power municipal sensing
NB-IoT	1–10 km	Low (20–250 kbps)	Medium	Low	Cellular-network IoT applications
MQTT (application layer)	Depends on underlying network	Depends on network	Low	Very low (protocol overhead)	Scalable publish/subscribe messaging
CoAP (application layer)	Depends on underlying network	Low overhead (UDP-based)	Low	Very low (protocol overhead)	Constrained request/response messaging

c) Comparative Analysis of Computing Paradigms

The evolution of computing paradigms has significantly influenced the design of modern lightweight IoT architectures.

Traditional cloud-centric architectures provide virtually unlimited computational resources and centralized management capabilities but frequently introduce higher communication latency and increased bandwidth utilization.

Edge computing addresses these limitations by relocating computational tasks closer to sensing devices. Local processing reduces response time, minimizes unnecessary data transmission, and supports real-time environmental monitoring. Fog computing extends distributed processing by introducing intermediate computational nodes between edge devices and cloud infrastructure. Fog nodes aggregate data from multiple sensing devices, coordinate local analytics, and improve scalability within geographically distributed smart city deployments.

The reviewed studies consistently indicate that hybrid architectures combining edge, fog, and cloud computing achieve superior performance compared with purely cloud-based systems by balancing computational efficiency, communication cost, and scalability.

d) Comparative Analysis of Artificial Intelligence Techniques

Artificial intelligence has become an increasingly important component of lightweight IoT architectures.

Conventional machine learning techniques are widely applied for predictive maintenance, waste generation forecasting, anomaly detection, water quality prediction, and intelligent scheduling. These approaches improve operational efficiency by transforming raw sensor data into actionable information.

Deep learning techniques provide higher predictive capability for complex environmental datasets but typically require substantial computational resources, making cloud-based deployment more practical.

Recent advances in TinyML have enabled optimized machine learning models to execute directly on embedded microcontrollers. This significantly reduces communication latency while improving privacy, energy efficiency, and system autonomy.

The reviewed literature indicates that future lightweight IoT architectures will increasingly integrate distributed artificial intelligence, enabling intelligent decision-making across sensing devices, edge gateways, and cloud platforms.

e) Comparative Analysis of Architectural Characteristics

Although individual implementations differ considerably, several architectural characteristics consistently appear across recent lightweight IoT systems.

Most architectures employ modular layered designs separating sensing, communication, processing, storage, and application services. Such modularity improves maintainability, scalability, and interoperability while simplifying future system expansion. Energy-efficient communication protocols and low-power embedded hardware are preferred to maximize battery lifetime and reduce maintenance costs.

Distributed computing strategies combining edge and cloud computing are increasingly replacing centralized architectures to improve response time and reduce communication overhead.
Artificial intelligence is gradually evolving from cloud-exclusive deployment toward distributed edge intelligence using optimized machine learning models.
Despite these positive developments, relatively few studies propose unified architectures capable of simultaneously supporting multiple environmental monitoring applications within a common infrastructure.

f) Comparative Discussion

The comparative analysis demonstrates that no single hardware platform, communication protocol, or computing paradigm can satisfy every requirement of environmental monitoring applications. Instead, successful lightweight IoT architectures result from careful integration of complementary technologies selected according to deployment objectives, environmental conditions, communication infrastructure, and energy constraints.

The literature consistently suggests that future smart city systems should prioritize modular architectures based on low-power embedded hardware, lightweight communication protocols, distributed computing, and intelligent analytics. Such architectures improve scalability, interoperability, operational efficiency, and long-term sustainability while reducing deployment and maintenance costs.

These observations also reveal several unresolved technical challenges, including heterogeneous device interoperability, cybersecurity, long-term energy management, standardized architectural frameworks, and integrated monitoring of multiple municipal services. Addressing these challenges provides the motivation for the research gap analysis presented in the following section.

5. Research Gap Analysis

The systematic review and comparative analysis presented in the previous sections reveal that significant progress has been achieved in the development of lightweight Internet of Things (IoT) architectures for smart waste management and smart sewage monitoring. Numerous studies have proposed efficient sensing platforms, low-power communication protocols, cloud-based monitoring systems, and intelligent analytics to improve environmental monitoring within smart city ecosystems. However, despite these advancements, several technical and architectural challenges remain unresolved. These research gaps limit the scalability, interoperability, long-term reliability, and practical deployment of existing solutions, thereby highlighting the need for more comprehensive and integrated lightweight IoT architectures.

One of the most evident research gaps is the **fragmented nature of existing monitoring systems**. The majority of published studies focus on a single application domain, such as smart waste management or smart sewage monitoring, without considering the integration of multiple municipal services within a unified IoT framework. Since both applications share common architectural components, including sensing devices, embedded controllers, communication networks, edge gateways, cloud infrastructure, and visualization platforms, the development of separate infrastructures results in increased deployment cost, redundant hardware resources, and higher maintenance complexity. An integrated architecture capable of supporting multiple environmental monitoring services through shared infrastructure remains insufficiently explored.

Another major limitation identified across the reviewed literature is the **absence of standardized lightweight architectural frameworks**. Although numerous prototype implementations demonstrate the feasibility of IoT-based monitoring systems, their architectural designs often vary considerably with respect to hardware platforms, communication protocols, software frameworks, and data management strategies. This lack of architectural standardization complicates interoperability among heterogeneous devices and restricts the large-scale adoption of IoT solutions across different municipalities and smart city initiatives.

Energy efficiency continues to represent a significant challenge, particularly for battery-powered sensing devices deployed in remote or difficult-to-access environments. While many studies employ low-power communication technologies such as LoRaWAN and NB-IoT, relatively few investigate comprehensive energy management strategies involving adaptive sensing, intelligent duty cycling, dynamic transmission scheduling, or renewable energy harvesting. Consequently, extending the operational lifetime of distributed sensor networks remains an important research priority.

The review also indicates that **interoperability** remains insufficiently addressed in many existing implementations. Most proposed systems are optimized for specific hardware platforms or proprietary software environments, limiting their compatibility with heterogeneous sensing devices and third-party municipal information systems. The absence of common data models, standardized communication interfaces, and platform-independent software architectures restricts the scalability of current IoT deployments and complicates future system expansion.

Although artificial intelligence has become increasingly integrated into environmental monitoring applications, most implementations continue to rely on centralized cloud-based analytics. Comparatively fewer studies investigate lightweight artificial intelligence techniques capable of executing directly on embedded devices. The practical deployment of TinyML, Edge AI, and distributed intelligence remains at an early stage despite their significant potential for reducing communication overhead, improving privacy, and enabling autonomous decision-making within resource-constrained environments. Further investigation is therefore required to optimize AI model deployment while balancing computational complexity, energy consumption, and prediction accuracy.

Cybersecurity and data privacy constitute another important research gap. Environmental monitoring systems exchange operational information through wireless communication networks that may be vulnerable to unauthorized access, data manipulation, replay attacks, and denial-of-service attacks. While conventional security mechanisms provide adequate protection for resource-rich systems, they are often unsuitable for lightweight embedded devices because of their computational and memory requirements. Existing literature contains relatively limited investigation into lightweight encryption algorithms, secure authentication mechanisms, blockchain-assisted trust management, and privacy-preserving communication specifically designed for constrained IoT environments.

Another limitation concerns the **lack of comprehensive real-world validation**. A substantial proportion of published studies evaluate proposed architectures using laboratory prototypes, simulation environments, or small-scale pilot deployments. Long-term operational studies conducted under realistic municipal conditions remain comparatively scarce. Consequently, limited evidence is available regarding system reliability, maintenance requirements, component degradation, communication stability, scalability, and lifecycle cost over extended deployment periods.

The review further reveals limited attention to **economic sustainability and environmental impact assessment**. Most existing studies emphasize technical performance indicators such as communication latency, sensor accuracy, and prediction accuracy while providing comparatively little discussion regarding deployment cost, return on investment, operational expenditure, lifecycle maintenance, carbon footprint, and environmental sustainability. These practical considerations are essential for municipal authorities responsible for adopting and maintaining smart city infrastructure.

Emerging technologies such as Digital Twins, Federated Learning, Green IoT, blockchain-enabled security, and future 6G communication networks have attracted increasing research attention in recent years. However, their integration into lightweight environmental monitoring architectures remains fragmented and largely conceptual. Comprehensive frameworks demonstrating the coordinated utilization of these technologies for integrated municipal monitoring are still limited in the current literature.

Based on these observations, it can be concluded that future research should focus on the development of **unified, modular, interoperable, energy-efficient, secure, and intelligent lightweight IoT architectures** capable of simultaneously supporting multiple environmental monitoring applications within smart city ecosystems. Such architectures should integrate distributed intelligence, standardized communication protocols, scalable edge-cloud collaboration, lightweight cybersecurity mechanisms, and sustainable energy management while remaining sufficiently flexible to accommodate future technological advancements.

The research gaps identified in this section provide the primary motivation for the unified lightweight IoT architecture proposed in the next section. The proposed conceptual framework aims to address several of these limitations by integrating smart waste management and smart sewage monitoring into a common modular architecture designed to improve scalability, interoperability, operational efficiency, and long-term sustainability.

Table VII: Summary of Research Gaps Identified in this Review

ID	Existing Limitation	Impact	Proposed Direction (this review)
G1	Fragmented, application-specific monitoring systems	Increases deployment cost and infrastructure redundancy	Unified architecture sharing sensing, communication, and cloud infrastructure
G2	Absence of standardized lightweight architectural frameworks	Limits interoperability across vendors and municipalities	Modular, standards-oriented layered architecture
G3	Limited long-term energy-management strategies	Shortens sensor-node operational lifetime	Adaptive duty cycling, event-driven transmission, energy harvesting
G4	Restricted interoperability among heterogeneous devices	Complicates large-scale, multi-vendor deployment	Common data models and platform-independent interfaces
G5	Early-stage adoption of on-device AI (Edge AI / TinyML)	Keeps most analytics cloud-dependent, raising latency	Distributed intelligence across sensing, edge, and cloud layers
G6	Limited attention to lightweight cybersecurity and privacy	Leaves constrained devices vulnerable to attack	Lightweight authentication, encryption, and blockchain-assisted trust
G7	Reliance on lab-scale or small pilot validation	Little evidence on long-term real-world reliability	Extended municipal-scale field deployment and evaluation

6. Proposed Unified Lightweight IoT Architecture

Based on the research gaps identified in the previous section, this paper proposes a **conceptual unified lightweight Internet of Things (IoT) architecture** for integrated smart waste and smart sewage monitoring in smart cities. The proposed architecture is **not intended as a validated implementation**; rather, it is a reference framework that consolidates widely adopted architectural components reported in recent literature while addressing key limitations such as fragmented deployments, limited interoperability, excessive cloud dependency, and insufficient support for distributed intelligence.

The proposed framework adopts a modular layered architecture that facilitates interoperability, scalability, energy efficiency, and maintainability. Instead of deploying separate infrastructures for waste management and sewage monitoring, the framework enables both applications to share sensing, communication, processing, and visualization resources while allowing application-specific sensing modules where required. Such an approach has the potential to reduce deployment cost, simplify maintenance, and improve resource utilization across municipal infrastructure.

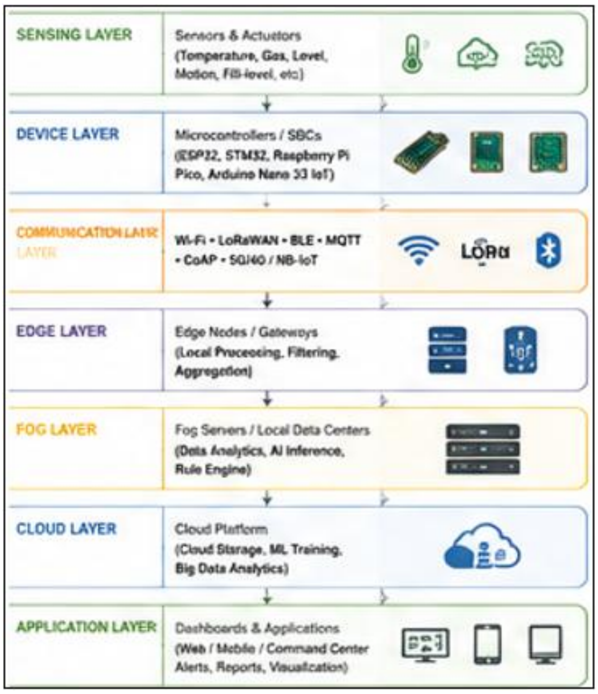

Figure 4: Proposed unified lightweight IoT architecture

a) *Sensing Layer*

The sensing layer represents the physical interface between environmental infrastructure and the digital monitoring system. It consists of distributed sensor nodes deployed across waste collection bins, sewage pipelines, pumping stations, drainage channels, and wastewater treatment facilities.

For smart waste management, the sensing layer may include ultrasonic sensors for fill-level estimation, load cells for weight measurement, temperature and humidity sensors for environmental monitoring, and gas sensors capable of detecting methane, ammonia, or smoke associated with decomposing waste.

For smart sewage monitoring, sensing devices may include pH sensors, turbidity sensors, dissolved oxygen sensors, electrical conductivity sensors, water-level sensors, flow sensors, and hazardous gas sensors such as methane and hydrogen sulfide detectors.

The proposed framework supports heterogeneous sensing devices through standardized sensor interfaces, allowing future expansion without major architectural modifications.

b) Embedded Edge Processing Layer

Each sensing node is connected to a lightweight embedded controller responsible for sensor interfacing, local preprocessing, device management, and communication control. Resource-efficient microcontrollers such as ESP32 or STM32 are suitable candidates because they provide integrated wireless communication, adequate computational capability, and low power consumption.

Rather than transmitting raw sensor readings continuously, embedded devices perform preliminary processing including sensor validation, noise filtering, timestamp generation, threshold evaluation, and event detection. This localized processing reduces unnecessary network traffic and conserves energy.

Where computational resources permit, lightweight machine learning models can also be deployed to perform simple anomaly detection or event classification directly at the sensing node.

c) Communication Layer

The communication layer provides reliable data exchange between distributed sensing devices, edge gateways, and cloud infrastructure.

The proposed architecture is communication-independent and supports multiple technologies depending on deployment requirements. Short-range deployments may utilize Wi-Fi or Bluetooth Low Energy, whereas large-scale municipal deployments may benefit from LoRaWAN or NB-IoT for long-range, energy-efficient communication.

Application-layer communication is expected to employ lightweight messaging protocols such as MQTT or CoAP to minimize communication overhead while supporting scalable data exchange among heterogeneous devices.
The architecture is intentionally modular so that communication technologies can be replaced or upgraded without affecting higher architectural layers.

d) Edge-Fog Computing Layer

A distinguishing characteristic of the proposed framework is the incorporation of edge and fog computing to reduce dependence on centralized cloud infrastructure.
Edge gateways receive data from nearby sensing devices and perform preliminary analytics, including data aggregation, anomaly detection, event prioritization, and temporary storage. Fog nodes coordinate information received from multiple edge gateways and perform regional processing before forwarding summarized information to cloud services.

This hierarchical processing strategy reduces bandwidth consumption, improves response time, and enhances operational reliability, particularly during temporary communication interruptions or network congestion.

e) Cloud and Data Management Layer

The cloud layer provides centralized services that require substantial computational or storage resources. These services include long-term database management, historical data analysis, visualization dashboards, device management, user authentication, and software updates.

The cloud infrastructure also supports large-scale analytics and facilitates integration with municipal information systems. By receiving processed information rather than continuous raw sensor streams, cloud services can operate more efficiently while reducing communication costs.

f) Artificial Intelligence and Decision Support Layer

The proposed architecture incorporates artificial intelligence as a decision-support mechanism rather than merely a data analysis tool.

Historical sensor data collected through the cloud infrastructure may be utilized for predictive analytics such as waste generation forecasting, sewage overflow prediction, water quality trend analysis, predictive maintenance, and operational optimization.

Where computationally feasible, TinyML-based models deployed on embedded devices or edge gateways can perform localized anomaly detection and classification, thereby improving responsiveness while minimizing cloud dependency.

The separation of AI functionality from hardware-specific implementation ensures flexibility and allows future integration of more advanced machine learning techniques without significant architectural redesign.

g) Application Layer

The application layer provides interfaces through which municipal authorities, environmental agencies, maintenance personnel, and decision makers interact with the monitoring system.

Typical application services include:

- Real-time environmental monitoring dashboards.
- Smart waste collection scheduling.
- Sewage network status visualization.
- Water quality monitoring.
- Predictive maintenance alerts.
- Hazardous gas notifications.
- Historical trend analysis.
- Asset management and reporting.

Role-based access control should be employed to ensure that different categories of users receive only information relevant to their operational responsibilities.

h) Architectural Advantages

Compared with many existing application-specific solutions reported in the literature, the proposed conceptual architecture offers several potential advantages:

- Unified support for both smart waste and smart sewage monitoring within a common framework.
- Modular layered design that simplifies maintenance and future expansion.

- Support for heterogeneous sensors and multiple communication technologies.
- Reduced cloud dependency through edge-fog collaboration.
- Improved scalability for municipal-scale deployments.
- Better energy efficiency through localized processing and lightweight communication protocols.
- Flexibility to integrate TinyML, Digital Twins, Federated Learning, blockchain-assisted security, and future communication technologies.
- Potential interoperability with other smart city services, including water distribution, air quality monitoring, and traffic management.

Although these advantages are conceptual, they directly address several research gaps identified in the preceding section and provide a roadmap for future implementation-oriented research.

7. Discussion

The proposed architecture should be considered a **reference conceptual framework** synthesized from the trends and limitations identified across the reviewed literature. Its objective is not to replace existing architectures but to demonstrate how modular design principles, distributed intelligence, lightweight communication, and interoperable system components can be integrated into a unified monitoring platform. Future work should focus on prototype development, performance evaluation, security assessment, interoperability testing, and large-scale municipal validation to assess the practical feasibility of this architecture.

8. Qualitative Performance Evaluation of the Proposed Architecture

The proposed unified lightweight IoT architecture presented in the previous section is intended as a conceptual framework synthesized from the strengths and limitations identified in the reviewed literature. Since the proposed architecture has not yet been implemented or experimentally validated, its evaluation is performed qualitatively by comparing its architectural characteristics with the commonly reported features of existing lightweight IoT solutions. The assessment focuses on key performance attributes that are consistently considered important for smart waste management and smart sewage monitoring systems, including scalability, energy efficiency, communication efficiency, interoperability, intelligence, security readiness, and maintainability.

a) *Scalability*

Scalability is a fundamental requirement for smart city applications because environmental monitoring systems often involve hundreds or thousands of geographically distributed sensing devices. Many existing implementations are designed for small-scale deployments and provide limited discussion regarding large-scale expansion. The proposed architecture adopts a modular layered design combined with distributed edge-fog-cloud processing, enabling additional sensing nodes and monitoring services to be incorporated with minimal architectural modifications. This modular approach is expected to improve scalability while reducing the complexity associated with system expansion.

b) Energy Efficiency

Energy consumption directly influences the operational lifetime and maintenance cost of IoT sensor networks. Existing studies primarily improve energy efficiency through low-power embedded controllers and communication technologies such as LoRaWAN and NB-IoT. The proposed architecture further emphasizes localized data processing at embedded devices and edge gateways, thereby reducing unnecessary communication with cloud servers. Event-driven transmission, lightweight communication protocols, and compatibility with future energy-harvesting techniques provide additional opportunities for extending battery life and improving long-term sustainability.

c) Communication Efficiency

Continuous transmission of raw sensor data can significantly increase bandwidth utilization and communication latency. The proposed framework addresses this limitation by supporting lightweight messaging protocols, including MQTT and CoAP, together with adaptive communication technologies selected according to deployment requirements. Preliminary filtering and aggregation at the edge reduce redundant transmissions, allowing cloud services to receive only relevant or summarized information. Such an approach is expected to improve communication efficiency while minimizing network congestion.

d) Interoperability and Flexibility

One of the recurring limitations identified in the reviewed literature is the dependence on application-specific hardware and proprietary software frameworks. The proposed architecture adopts standardized layered abstraction in which sensing, communication, processing, and application services are logically separated. This design facilitates integration of heterogeneous sensors, multiple communication technologies, and different cloud platforms without requiring significant architectural redesign. Consequently, the framework provides greater flexibility for future technological upgrades and multi-vendor deployments.

e) Intelligent Decision Support

Unlike conventional monitoring systems that primarily collect and visualize sensor data, the proposed framework incorporates artificial intelligence as an integral architectural component. Support for edge intelligence and TinyML enables preliminary anomaly detection, event classification, and predictive analytics to be performed closer to the sensing devices. Cloud services complement these capabilities by providing historical trend analysis, predictive maintenance, and municipal decision support. This distributed intelligence is expected to improve responsiveness while reducing dependence on centralized processing.

f) Security Readiness

Although cybersecurity mechanisms are not explicitly implemented within the proposed framework, the architecture has been designed to accommodate lightweight security services without major structural modification. Secure communication protocols, lightweight authentication, encrypted data transmission, secure firmware updates, and future integration of blockchain-assisted trust management can be incorporated at appropriate architectural layers. This extensible design provides a foundation for future security enhancement while maintaining compatibility with resource-constrained embedded devices.

g) Maintainability and Practical Deployment

Maintainability represents an important consideration for long-term municipal deployments. The modular organization of the proposed architecture allows sensing devices, communication modules, and software services to be upgraded independently without requiring complete system redesign. This separation of functional layers simplifies troubleshooting, maintenance scheduling, and technology replacement while reducing operational downtime. The architecture is therefore expected to support gradual infrastructure evolution as newer sensing devices, communication protocols, and artificial intelligence techniques become available.

h) Overall Qualitative Assessment

Based on the comparative analysis of recent literature, the proposed unified architecture demonstrates several conceptual advantages over many application-specific IoT solutions. These include improved modularity, support for heterogeneous sensing platforms, reduced cloud dependency through edge-fog collaboration, readiness for lightweight artificial intelligence, and flexibility for integrating future technologies such as Digital Twins, Federated Learning, and Green IoT. While these observations indicate the potential suitability of the proposed framework for smart city environmental monitoring, comprehensive experimental validation remains necessary to quantify improvements in latency, energy consumption, communication efficiency, scalability, and operational reliability.

Future work should therefore focus on implementing a prototype of the proposed architecture, conducting real-world deployments, and performing quantitative performance analysis under representative municipal operating conditions. Such experimental validation will provide objective evidence regarding the effectiveness of the proposed framework and support its adoption within practical smart city infrastructures.

Table VIII: Qualitative Performance Evaluation of the Proposed Architecture

Performance Parameter	Existing Lightweight IoT Systems	Proposed Unified Architecture
Scalability	Moderate; often application-specific (★★☆☆☆)	High; modular layered architecture (★★★★☆)
Energy Efficiency	Improved through low-power hardware (★★☆☆☆)	Enhanced with edge processing and lightweight communication (★★★★☆)
Communication Efficiency	Protocol-dependent (★★☆☆☆)	Optimized through MQTT/CoAP with edge filtering (★★★★☆)
Interoperability	Limited support for heterogeneous systems (★★☆☆☆)	Designed for heterogeneous devices and protocols (★★★★☆)
Intelligence	Mostly cloud-based analytics (★★☆☆☆)	Distributed intelligence with Edge AI/TinyML readiness (★★★★☆)
Security Readiness	Basic security mechanisms in many studies (★★☆☆☆)	Extensible framework supporting lightweight security integration (★★★★☆)
Maintainability	Component replacement may require redesign (★★☆☆☆)	Modular architecture simplifies upgrades and maintenance (★★★★☆)
Multi-Service Support	Typically single-application focused (★☆☆☆☆)	Unified support for waste and sewage monitoring (★★★★★)

9. Future Research Directions

The rapid evolution of lightweight Internet of Things (IoT) technologies has significantly improved the capabilities of smart waste management and smart sewage monitoring systems. Nevertheless, the literature review and comparative analysis indicate that several research challenges remain unresolved. Future research should therefore focus not only on improving individual system components but also on developing integrated, scalable, intelligent, and sustainable architectures capable of supporting next-generation smart city infrastructures. This section highlights key research directions that are expected to shape the future development of lightweight IoT-based environmental monitoring systems.

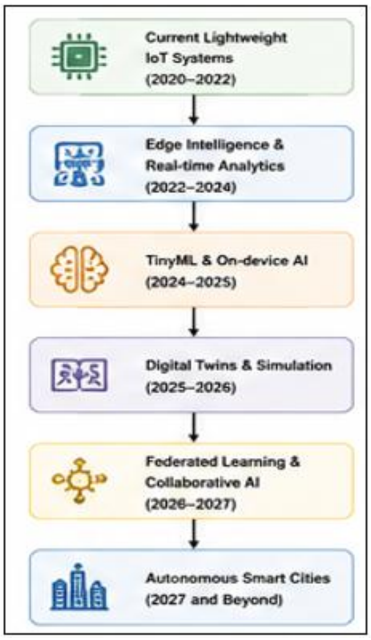

Figure 5: Conceptual future research roadmap synthesized from this review

a) Edge Intelligence and TinyML

One of the most promising research directions is the wider adoption of **Edge Intelligence** through lightweight machine learning models deployed directly on embedded devices. While many current systems continue to rely on cloud-based analytics, executing inference at the network edge can substantially reduce communication latency, bandwidth consumption, and energy usage. Future studies should investigate efficient model compression techniques, adaptive inference mechanisms, and hardware-aware optimization methods that enable accurate machine learning on resource-constrained microcontrollers without compromising system reliability.

b) Unified Multi-Service Smart City Platforms

Most existing environmental monitoring solutions are developed for individual applications such as waste management or sewage monitoring. Future research should investigate unified IoT platforms capable of integrating multiple municipal services, including water distribution, air quality monitoring, traffic management, and energy management, within a common architectural framework. Shared communication infrastructure, interoperable sensing platforms, and standardized data models can improve scalability while reducing deployment and maintenance costs.

c) Energy-Aware and Green IoT Architectures

Energy efficiency will remain a fundamental requirement for long-term IoT deployments. Although low-power communication technologies have significantly reduced energy consumption, future architectures should incorporate intelligent power management strategies, adaptive duty cycling, energy harvesting, and resource-aware scheduling. Solar-powered sensing nodes, vibration-based harvesting, and hybrid renewable energy solutions represent promising directions for extending the operational lifetime of distributed environmental monitoring systems while supporting Green IoT initiatives.

d) Interoperability and Standardization

The increasing diversity of hardware platforms, communication protocols, and software ecosystems continues to create interoperability challenges. Future research should emphasize standardized communication interfaces, common semantic data models, and platform-independent software architectures that enable seamless interaction among heterogeneous IoT devices. The adoption of open standards and modular design principles will facilitate technology integration and reduce vendor dependence in large-scale smart city deployments.

e) Secure and Privacy-Preserving IoT Systems

As environmental monitoring systems become increasingly interconnected, cybersecurity and data privacy will become even more critical. Future lightweight IoT architectures should integrate efficient authentication mechanisms, lightweight cryptographic algorithms, secure firmware update frameworks, and robust access control policies that are specifically designed for resource-constrained devices. In addition, privacy-preserving techniques should be explored to ensure secure handling of operational and infrastructure-related data while maintaining computational efficiency.

f) Federated Learning and Distributed Artificial Intelligence

Federated Learning has emerged as a promising paradigm for collaborative model training without centralized collection of raw sensor data. By allowing distributed devices to participate in model optimization while retaining local datasets, Federated Learning can improve privacy, reduce communication overhead, and enhance system resilience. Future research should investigate lightweight federated learning frameworks that are suitable for embedded IoT environments with limited processing capability and intermittent network connectivity.

g) Digital Twins for Environmental Infrastructure

Digital Twin technology offers significant potential for improving environmental monitoring and municipal asset management. Virtual representations of waste collection systems and sewage networks can support real-time visualization, predictive maintenance, infrastructure simulation, and operational optimization. Future research should explore efficient synchronization mechanisms between physical infrastructure and digital models while addressing challenges related to scalability, computational complexity, and real-time data integration.

h) Intelligent Communication Networks

Emerging wireless communication technologies, including advanced LPWAN solutions and future sixth-generation (6G) communication networks, are expected to further enhance IoT performance through ultra-low latency, higher reliability, improved spectrum efficiency, and massive device connectivity. Future lightweight architectures should investigate adaptive communication strategies capable of dynamically selecting the most appropriate protocol based on application requirements, energy availability, network quality, and environmental conditions.

i) Sustainable and Resilient Smart City Ecosystems

Future environmental monitoring systems should be designed with sustainability and resilience as primary architectural objectives. Beyond technical performance, researchers should evaluate lifecycle energy consumption, maintenance requirements, environmental impact, cost-effectiveness, and resilience against communication failures or extreme environmental conditions. Integrating sustainability metrics into system design and evaluation will enable municipalities to adopt IoT solutions that are both technologically effective and environmentally responsible.

j) Towards Intelligent Integrated Environmental Monitoring

The long-term vision for lightweight IoT architectures is the development of intelligent, adaptive, and self-managing environmental monitoring ecosystems capable of coordinating multiple municipal services through distributed sensing, edge intelligence, cloud analytics, and standardized communication frameworks. Such systems should support autonomous decision-making, predictive maintenance, efficient resource utilization, and seamless interoperability while remaining flexible enough to incorporate future technological innovations. Achieving this vision will require interdisciplinary collaboration among researchers in embedded systems, communication networks, artificial intelligence, environmental engineering, cybersecurity, and urban planning.

Overall, the future evolution of lightweight IoT architectures is expected to move beyond isolated monitoring applications toward unified smart city ecosystems characterized by distributed intelligence, sustainable operation, secure communication, and adaptive resource management. Addressing these research directions will not only improve the performance of smart waste and smart sewage monitoring systems but will also contribute to the realization of resilient, data-driven, and environmentally sustainable urban infrastructure.

Table IX: Summary of Future Research Directions

Research Area	Current Status (per this review)	Future Direction
Edge Intelligence / TinyML	Model compression enabling early on-device inference	Wider adoption of accurate, hardware-aware inference on microcontrollers
Interoperability & Standardization	Heterogeneous, largely proprietary implementations	Open standards and common semantic data models
Energy-Aware / Green IoT	Mostly low-power hardware and LPWAN selection	Adaptive duty cycling and renewable energy harvesting
Security & Privacy	Basic mechanisms in many implementations	Lightweight cryptography, secure updates, blockchain-assisted trust
Federated Learning	Early-stage exploration in IoT contexts	Privacy-preserving distributed model training on constrained devices
Digital Twins	Conceptual / early prototypes	Real-time virtual replicas for predictive maintenance
Intelligent Communication (incl. future 6G)	LPWAN (LoRaWAN, NB-IoT) dominant	Adaptive, context-aware protocol selection at scale

10. Conclusion

The rapid expansion of smart city initiatives has significantly increased the demand for intelligent, scalable, and energy-efficient environmental monitoring systems capable of supporting sustainable urban development. Among the various application domains, smart waste management and smart sewage monitoring have emerged as critical components of municipal infrastructure due to their direct influence on public health, environmental protection, operational efficiency, and resource utilization. The integration of lightweight Internet of Things (IoT) technologies has provided new opportunities to transform conventional monitoring approaches into intelligent, data-driven systems capable of real-time sensing, remote supervision, and predictive decision-making.

This paper presented a systematic review of lightweight IoT architectures for smart waste and smart sewage monitoring systems by synthesizing recent developments in embedded hardware platforms, communication technologies, distributed computing paradigms, and artificial intelligence. The review demonstrated that the evolution of lightweight IoT systems has progressed from cloud-centric monitoring architectures toward distributed edge-cloud frameworks that improve communication efficiency, reduce latency, optimize energy consumption, and enhance scalability. The analysis further highlighted the increasing adoption of resource-efficient embedded controllers, lightweight communication protocols, LPWAN technologies, edge computing, and TinyML as key enablers of next-generation environmental monitoring systems.

A comparative analysis of existing lightweight IoT architectures revealed that although significant technological progress has been achieved, many reported solutions remain application-specific and exhibit limitations related to interoperability, architectural standardization, long-term energy management, cybersecurity, and practical large-scale deployment. The literature also indicates that the majority of existing systems focus on individual municipal applications, while comparatively limited attention has been devoted to developing unified frameworks capable of integrating multiple environmental monitoring services within a common infrastructure.

Based on the identified research gaps, this paper proposed a **conceptual unified lightweight IoT architecture** that integrates smart waste management and smart sewage monitoring through a modular layered framework comprising sensing, embedded processing, communication, edge-fog computing, cloud services, artificial intelligence, and application layers. The proposed architecture emphasizes interoperability, scalability, modularity, distributed intelligence, and flexibility while providing a foundation for the future integration of emerging technologies such as TinyML, Federated Learning, Digital Twins, blockchain-assisted security, and Green IoT. A qualitative performance evaluation further demonstrated how the proposed framework conceptually addresses several limitations observed in existing architectures.

The findings of this review suggest that future environmental monitoring systems should move beyond isolated application-specific implementations toward integrated, standards-oriented IoT ecosystems capable of supporting multiple municipal services through shared infrastructure and intelligent resource management. Such an evolution is expected to improve operational efficiency, reduce deployment and maintenance costs, enhance sustainability, and strengthen the resilience of smart city infrastructure.

It is important to acknowledge that the proposed architecture presented in this review is conceptual and has not been experimentally validated. Consequently, the qualitative assessment presented in this paper should be interpreted as an architectural evaluation synthesized from the reviewed literature rather than as experimental performance evidence. Future work should therefore focus on prototype implementation, quantitative performance evaluation, interoperability testing, cybersecurity assessment, and long-term field deployment to validate the practical effectiveness of the proposed framework under real-world operating conditions.

In summary, this review consolidates recent advances in lightweight IoT architectures for environmental monitoring, identifies key technological trends and research gaps, and presents a unified conceptual framework to support future research in smart waste and smart sewage monitoring. It is anticipated that the insights presented in this work will assist researchers, engineers, and municipal authorities in designing more intelligent, interoperable, and sustainable IoT-enabled environmental monitoring systems for next-generation smart cities.

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