Proceedings of International Conference on "Recent Innovations in Engineering, Technology & Science for Sustainable Development (RIETSSD-2026)"
Career Point International Journal of Research (CPIJR)
©2022 CPIJR | Special Issue | ISSN : 2583-1895
Conference Paper | DOI: https://doi.org/10.5281/zenodo.20576679

A Systematic Review of Secure and Scalable IoT Frameworks for Smart Environmental Monitoring

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Abstract

The rapid advancement of the Internet of Things (IoT) has significantly enhanced smart environmental monitoring by enabling real-time, large-scale data collection and analysis. IoT-based monitoring systems are widely applied in areas such as air and water quality monitoring, climate observation, and disaster management. However, the large-scale deployment of heterogeneous IoT devices introduces critical challenges related to security, scalability, data integrity, and efficient resource management. Addressing these challenges is essential to ensure reliable and trustworthy environmental monitoring systems. This paper presents a systematic review of secure and scalable IoT frameworks for smart environmental monitoring. A comprehensive analysis of existing literature from major scientific databases is conducted to examine prevailing IoT architectures, communication technologies, security mechanisms, and scalability strategies. Key security approaches, including authentication, encryption, access control, and blockchain-based solutions, are reviewed alongside scalability techniques such as edge computing, cloud-based architectures, and lightweight communication protocols. The review synthesizes current research trends, provides a comparative analysis of existing frameworks, and identifies limitations and open research challenges. Furthermore, potential future research directions are discussed, emphasizing the need for energy-efficient security solutions, interoperability, privacy preservation, and intelligent data analytics. This study aims to support researchers and practitioners in designing robust, secure, and scalable IoT-based environmental monitoring systems.

Keywords: Internet of Things (IoT), Smart Environmental Monitoring, Security, Scalability, Edge Computing, Cloud Computing

Career Point International Journal of Research (CPIJR)
©2022 CPIJR | Volume 4 | Issue 4 | ISSN : 2583-1895
Conference Paper | DOI: https://doi.org/10.5281/zenodo.19270361

1. Introduction

Environmental monitoring is essential for understanding and managing the impact of human activities and natural processes on ecosystems and public health. Continuous monitoring of environmental parameters such as air and water quality, temperature, humidity, soil conditions, and noise levels supports informed decision-making in areas including urban planning, agriculture, climate change mitigation, and disaster management. However, traditional environmental monitoring systems often rely on manual data collection or isolated sensing infrastructures, which are limited in spatial coverage, costly to maintain, and incapable of providing real-time insights. These limitations hinder timely responses to environmental hazards and reduce the effectiveness of long-term environmental management strategies [1] [3] [5].

The Internet of Things (IoT) has emerged as a transformative technology for smart environmental monitoring. IoT-based systems integrate heterogeneous sensors, communication networks, and data processing platforms to enable continuous, real-time, and large-scale environmental data acquisition. By leveraging wireless sensor networks, cloud computing, and edge computing, IoT frameworks facilitate automated data collection, remote monitoring, and intelligent analysis. As a result, IoT has significantly improved the accuracy, scalability, and responsiveness of environmental monitoring applications across diverse domains.

Despite these advantages, the widespread deployment of IoT systems introduces critical challenges related to security and scalability. Environmental monitoring systems often operate in open and unattended environments, making IoT devices vulnerable to security threats such as unauthorized access, data manipulation, eavesdropping, and denial-of-service attacks. Compromised sensor data can lead to incorrect environmental assessments and flawed decision-making. At the same time, scalability remains a major concern as IoT-based monitoring systems may involve thousands of geographically distributed devices generating continuous data streams. Efficient data management, low-latency communication, interoperability among heterogeneous devices, and resource-constrained sensor operation are essential to support large-scale deployments [10][18][19]. Without robust security mechanisms and scalable architectures, IoT-based environmental monitoring systems cannot achieve long-term reliability or trustworthiness.

Although numerous IoT frameworks and solutions have been proposed to address environmental monitoring challenges, existing studies often focus on specific applications or

technologies, with limited emphasis on comprehensive security and scalability analysis[13][14]. Moreover, there is a lack of consolidated reviews that systematically examine and compare existing IoT frameworks from both security and scalability perspectives. This gap motivates the need for a structured and critical review of current research efforts in this domain.

Contributions of This Review

This systematic review aims to provide a comprehensive understanding of secure and scalable IoT frameworks for smart environmental monitoring. The key contributions of this review are as follows:

- A structured overview of IoT architectures used in smart environmental monitoring applications.
- A comprehensive analysis of security mechanisms, including authentication, encryption, access control, and emerging blockchain-based solutions.
- An in-depth review of scalability strategies, such as edge computing, cloud-based architectures, and lightweight communication protocols.
- A comparative analysis of existing IoT frameworks, highlighting strengths, limitations, and design trade-offs.
- Identification of open research challenges and future directions to guide the development of robust, secure, and scalable environmental monitoring systems.

2. Review Methodology

This systematic review follows a structured methodology to identify, select, and analyze relevant studies on secure and scalable IoT frameworks for smart environmental monitoring. The review process was designed to ensure comprehensive coverage, transparency, and reproducibility.

2.1 Data Sources: Relevant studies were collected from well-established scientific databases, including IEEE Xplore, SpringerLink, Elsevier (ScienceDirect), and Google Scholar. These databases were selected due to their extensive coverage of high-quality, peer-reviewed research in the fields of IoT, environmental monitoring, and information security.

2.2 Search Strategy: A keyword-based search strategy was employed to retrieve relevant literature. The primary search terms included combinations of the following keywords:

- Internet of Things (IoT)
- Environmental monitoring
- Smart environment

- IoT frameworks
- Security
- Scalability
- Edge computing
- Cloud computing

A keyword-based search strategy was adopted to retrieve relevant literature from the selected databases. Search queries were formulated using combinations of terms related to IoT, environmental monitoring, security, and scalability. Boolean operators such as **AND** and **OR** were used to refine the search results and ensure the inclusion of studies addressing both architectural and security-related aspects of IoT-based environmental monitoring systems [12] [25].

2.3 Study Selection Criteria

To ensure the relevance and quality of the selected studies, explicit inclusion and exclusion criteria were applied.

Inclusion Criteria

- Peer-reviewed journal articles and conference papers
- Studies focusing on IoT-based environmental monitoring systems
- Research addressing security, scalability, or both
- Articles presenting frameworks, architectures, or systematic analyses
- Papers written in English

Exclusion Criteria

- Non-peer-reviewed articles, theses, and technical reports
- Studies unrelated to environmental monitoring applications
- Papers focusing solely on hardware design without system-level analysis
- Duplicate studies or extended versions of previously published work
- Articles lacking sufficient technical or analytical details

2.4 Study Screening and Selection

The initial database search yielded a large set of publications. Titles and abstracts were first screened to remove irrelevant and duplicate studies. The remaining articles were then assessed through full-text review to ensure compliance with the defined inclusion criteria.

Following the screening process, approximately fifty plus relevant studies were selected for detailed analysis and synthesis in this review. These studies were categorized and analyzed

based on IoT architecture, security mechanisms, scalability strategies, communication technologies, and application domains.

3. IoT Frameworks for Environmental Monitoring

IoT frameworks provide the architectural foundation for smart environmental monitoring systems by enabling efficient data acquisition, communication, processing, and visualization. These frameworks integrate heterogeneous sensing devices, networking technologies, and computing platforms to support continuous and large-scale environmental monitoring [3] [6]. Existing research broadly categorizes IoT frameworks for environmental monitoring into layered architectures, cloud-based frameworks, and edge/fog-based frameworks, each offering distinct advantages and limitations in terms of performance, scalability, and security.

3.1 Layered IoT Architectures

Layered architectures are the most widely adopted design model for IoT-based environmental monitoring systems due to their modularity and ease of implementation. These architectures typically organize system components into logical layers, each responsible for specific functionalities.

The most common layered model includes:

- Perception Layer, which consists of environmental sensors and data acquisition devices responsible for collecting physical parameters such as temperature, humidity, air quality, and water quality.
- Network Layer, which enables data transmission using wired or wireless communication technologies, including Wi-Fi, cellular networks, LoRaWAN, and NB-IoT.
- Processing Layer, which handles data storage, analytics, and decision-making using cloud or edge computing resources.
- Application Layer, which provides user interfaces, visualization dashboards, and alert systems for stakeholders.

Layered architectures enhance scalability by allowing individual layers to be independently upgraded or expanded. From a security perspective, they support the integration of security mechanisms at multiple levels, such as secure device authentication at the perception layer and encrypted communication at the network layer. However, these architectures may suffer from increased latency and centralized dependency when large volumes of data are transmitted directly to the cloud.

3.2 Cloud-Based IoT Frameworks

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©2022 CPIJR | Volume 4 | Issue 4 | ISSN : 2583-1895
Conference Paper | DOI: https://doi.org/10.5281/zenodo.19270361

Cloud-based IoT frameworks leverage centralized cloud infrastructures to manage data ingestion, storage, processing, and visualization. In environmental monitoring applications, cloud platforms provide elastic computing resources capable of handling large-scale sensor deployments and high data volumes.

These frameworks typically rely on:

- Centralized data storage systems, such as distributed databases
- Scalable analytics platforms for real-time and batch processing
- Cloud-native services for device management and monitoring

Cloud-based frameworks offer strong scalability, as computational and storage resources can be dynamically allocated based on system demands. They also simplify system maintenance and integration with advanced analytics, such as machine learning-based environmental prediction models. Security mechanisms, including access control, encryption, and identity management, are often integrated at the platform level [2]. Despite these advantages, cloud-based frameworks face challenges related to latency, network bandwidth consumption, and single-point-of-failure risks. Additionally, transmitting raw environmental data to centralized cloud servers may raise concerns regarding data privacy and security, particularly in large-scale or geographically distributed monitoring scenarios[6][10].

3.3 Edge and Fog-Based IoT Frameworks

Edge and fog-based IoT frameworks have emerged as an effective solution to address the limitations of cloud-centric architectures. These frameworks introduce intermediate computing layers closer to the data sources, enabling local data processing, aggregation, and analysis.

In environmental monitoring systems, edge or fog nodes—such as gateways or local servers—perform tasks including:

- Data filtering and aggregation
- Real-time anomaly detection
- Local decision-making and alert generation

By processing data closer to the sensors, edge and fog-based frameworks significantly reduce latency and network traffic, making them suitable for time-sensitive environmental applications. From a security standpoint, localized processing limits the exposure of raw data and supports faster detection of malicious activities or abnormal sensor behavior [18] [19]. However, edge and fog-based frameworks introduce new challenges, including increased system complexity, resource management at distributed nodes, and the need for secure

coordination between edge, fog, and cloud components. Ensuring consistent security policies and interoperability across heterogeneous edge devices remains an open research issue. Layered architectures provide structural clarity and modularity, cloud-based frameworks offer high scalability and powerful analytics, while edge and fog-based frameworks enhance responsiveness and efficiency. Most modern IoT-based environmental monitoring systems adopt hybrid architectures that combine cloud and edge/fog computing to balance scalability, performance, and security. Understanding the strengths and limitations of these frameworks is essential for designing robust and secure environmental monitoring solutions.

4. Security Mechanisms in IoT-Based Environmental Monitoring

Security is a fundamental requirement for IoT-based environmental monitoring systems, as these systems often operate in open, unattended, and resource-constrained environments. The integrity, confidentiality, and availability of environmental data are critical for reliable monitoring and decision-making [11]. Existing research proposes a variety of security mechanisms to address these concerns, including authentication and access control, encryption techniques, blockchain-based security, and threat modeling.

4.1 Authentication and Access Control: Authentication ensures that only legitimate devices and users can access the IoT system, while access control defines the permissions granted to authenticated entities. Common approaches include device identity management using digital certificates, key-based authentication, and role-based access control (RBAC). In large-scale environmental monitoring deployments, lightweight authentication mechanisms are preferred due to the limited computational and energy resources of sensor nodes[13] [25]. However, managing identities and access rights across heterogeneous and geographically distributed devices remains a significant challenge.

4.2 Encryption Techniques: Encryption is widely used to protect sensitive environmental data during transmission and storage. Symmetric encryption algorithms, such as Advanced Encryption Standard (AES), are commonly adopted due to their efficiency, while asymmetric techniques, including Elliptic Curve Cryptography (ECC), are used for secure key exchange and authentication [12] [14]. End-to-end encryption ensures data confidentiality across the entire communication path. Despite their effectiveness, encryption mechanisms must be carefully designed to balance security strength with energy consumption and processing overhead.

4.3 Blockchain-Based Security: Blockchain technology has gained attention as a promising solution for enhancing trust, transparency, and data integrity in IoT-based environmental

monitoring systems. By maintaining an immutable distributed ledger, blockchain enables secure data sharing, decentralized access control, and tamper-resistant data storage. Smart contracts can further automate authentication and authorization processes. However, blockchain-based solutions often introduce additional latency, computational complexity, and storage overhead, which may limit their suitability for resource-constrained IoT devices.

4.4 Threat Models: Threat modeling is essential for understanding potential vulnerabilities in IoT-based environmental monitoring systems. Common threats include unauthorized access, data tampering, replay attacks, denial-of-service attacks, and physical device compromise. Several studies emphasize the need for security-aware system design that incorporates threat models at different architectural layers. Nonetheless, many existing frameworks address security in isolation, without providing a comprehensive and integrated threat mitigation strategy.

5. Scalability Approaches

Scalability is a critical requirement for environmental monitoring systems that involve large numbers of sensors generating continuous data streams. To handle increasing system size and data volume, various scalability approaches have been proposed in the literature.

5.1 Edge Computing

Edge computing shifts data processing closer to the data source, reducing the need to transmit raw sensor data to centralized cloud servers. In environmental monitoring, edge nodes perform tasks such as data aggregation, filtering, and anomaly detection. This approach reduces network congestion, improves response time, and enhances system scalability. However, managing distributed edge resources and ensuring consistent security policies across edge nodes remains challenging.

5.2 Lightweight Communication Protocols

Lightweight communication protocols play a key role in scalable IoT deployments. Protocols such as MQTT, CoAP, and LoRaWAN are designed to minimize communication overhead and support efficient data transmission in constrained environments. These protocols enable scalable message exchange between sensors, gateways, and cloud platforms[11]. Nevertheless, ensuring secure and reliable communication over lightweight protocols requires additional security mechanisms.

5.3 Microservices and Containerization

Microservices-based architectures decompose IoT system functionalities into independent services that can be deployed and scaled individually. Containerization technologies further

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©2022 CPIJR | Volume 4 | Issue 4 | ISSN : 2583-1895
Conference Paper | DOI: https://doi.org/10.5281/zenodo.19270361

enhance portability and resource efficiency[16]. In environmental monitoring systems, this approach supports flexible scaling of data ingestion, processing, and visualization components. However, increased architectural complexity and service orchestration overhead must be carefully managed.

5.4 Big Data Management

Large-scale environmental monitoring generates massive volumes of heterogeneous data. Big data technologies, including distributed storage systems and stream processing frameworks, are commonly employed to manage, analyze, and visualize this data. Effective data management strategies improve system scalability and support advanced analytics, but they also raise concerns related to data security, privacy, and long-term storage costs [18].

6. Comparative Analysis of IoT Frameworks for Environmental Monitoring

To better understand how existing frameworks address security and scalability challenges, a comparative analysis of representative IoT-based environmental monitoring frameworks is presented below.

Framework Type	Key Characteristics	Security Support	Scalability Support	Limitations
Layered IoT Architecture	Modular multi-layer design (sensing, network, processing, application)	Layer-wise security integration	Moderate scalability	Increased latency, centralized dependency
Cloud-Based Framework	Centralized cloud processing and storage	Built-in encryption and access control	High scalability	High latency, bandwidth usage
Edge/Fog-Based Framework	Local processing near data sources	Reduced data exposure	High scalability with low latency	Complex management, heterogeneous devices
Hybrid Cloud-Edge Framework	Combines cloud analytics with edge processing	Distributed security enforcement	Very high scalability	Increased architectural complexity

Table 1. Comparison of IoT Framework Architectures

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Conference Paper | DOI: https://doi.org/10.5281/zenodo.19270361

Author	Monitoring Domain	Security Approach	Scalability Technique	Limitations
Zanella et al. [6]	Smart Environmental Monitoring	Secure communication, authentication	Cloud-based architecture	High latency
Al-Fuqaha et al. [2]	Environmental IoT Systems	Encryption, access control	Scalable cloud services	Centralized dependency
Singh et al. [10]	Air Quality Monitoring	Lightweight encryption	Edge computing	Limited edge security
Dorri et al. [16]	Smart Environment	Blockchain-based security	Distributed IoT architecture	Computational overhead
Rahman et al. [26]	Water Quality Monitoring	Secure data aggregation	Fog computing	Interoperability issues
Gubbi et al. [3]	Smart Sensing Environments	Secure data transmission	Hybrid cloud–edge	Scalability complexity
Li et al. [24]	Smart City Monitoring	Authentication, privacy protection	Big data platforms	Privacy risks
Perera et al. [9]	Context-Aware Monitoring	Access control	Middleware-based scaling	Limited real-world validation

Table 2. Security and Scalability Comparison of Representative Studies

Security Mechanism	Advantages	Challenges
Authentication & Access Control	Prevents unauthorized access	Identity management at scale
Encryption Techniques	Ensures data confidentiality	Energy and computation overhead
Blockchain-Based Security	Tamper-proof data, transparency	Latency and resource consumption
Threat Modeling	Proactive security planning	Limited real-world adoption

Table 3. Comparison of Security Mechanisms Used in IoT Monitoring Systems

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Conference Paper | DOI: https://doi.org/10.5281/zenodo.19270361

7. Research Gaps and Open Challenges

Despite significant progress, several research gaps remain in the design of secure and scalable IoT frameworks for environmental monitoring:

- Many existing security mechanisms are computationally intensive and unsuitable for low-power IoT devices.
- The lack of standardized frameworks hinders seamless integration across heterogeneous devices and platforms.
- Protecting sensitive location and environmental data while enabling large-scale analytics remains a challenge.
- Many proposed frameworks are evaluated through simulations or small-scale prototypes, with limited validation in real-world environments.

8. Future Research Directions

Future research should focus on addressing the identified challenges and enhancing the robustness of IoT-based environmental monitoring systems:

- Machine learning techniques can be employed for adaptive threat detection and intrusion prevention.
- Virtual representations of physical environments can improve monitoring accuracy and predictive analysis.
- Energy harvesting and energy-aware system design can reduce the environmental impact of large-scale IoT deployments.
- Adopting zero-trust principles can strengthen security by continuously verifying device and user identities.

9. Conclusion

This systematic review examined secure and scalable IoT frameworks for smart environmental monitoring by analyzing existing architectures, security mechanisms, and scalability approaches. The review highlights that while layered, cloud-based, and edge/fog-based frameworks offer distinct advantages, no single solution fully addresses the combined challenges of security, scalability, and resource constraints. Existing studies demonstrate promising techniques such as lightweight encryption, edge computing, and blockchain-based security; however, significant research gaps remain, particularly in energy-efficient security, interoperability, and real-world deployment validation. By identifying key challenges and

future research directions, this review aims to guide researchers and practitioners toward the development of robust, secure, and scalable IoT-based environmental monitoring systems.

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