

# Smart Environmental Monitoring Using IoT Sensor Networks

**Prof. Antonio J. Jara**

Professor, University of Murcia, Spain

## Abstract

Smart environmental monitoring has become an important application of Internet of Things technologies because environmental conditions require continuous observation, reliable data collection, and timely analysis. IoT sensor networks integrate distributed sensing devices, wireless communication, edge computing, cloud platforms, and analytical tools to monitor environmental parameters across urban, industrial, agricultural, and natural environments. This study examines smart environmental monitoring using IoT sensor networks, with particular emphasis on sensor deployment, real-time data collection, communication, data processing, environmental analytics, and intelligent decision support.

A qualitative descriptive and conceptual research design was adopted using secondary academic literature. The analysis indicates that IoT sensor networks can improve environmental visibility by enabling continuous monitoring of air quality, water quality, temperature, humidity, soil conditions, noise, and other environmental parameters. Distributed sensors provide localized information, while communication networks enable information transfer to edge or cloud platforms for processing. Intelligent analytics can support anomaly detection, environmental assessment, trend identification, and early warning.

However, practical implementation is influenced by sensor accuracy, energy limitations, network reliability, data security, interoperability, deployment costs, and environmental exposure. The study concludes that IoT sensor networks can provide an effective technological foundation for responsive and data-driven environmental monitoring when sensing, communication, processing, and analytical capabilities are properly integrated. Future research should focus on energy-efficient sensor networks, edge-based environmental analytics, autonomous sensing, robust sensors, interoperable architectures, and privacy- and security-aware environmental data management.

**Keywords:** Environmental Monitoring, Internet of Things, IoT Sensor Networks, Smart Sensors, Environmental Sensing, Real-Time Monitoring, Edge Computing, Environmental Data, Wireless Sensor Networks, Smart Environment.

## 1. Introduction

Environmental monitoring plays an important role in understanding changes in natural and built environments and supporting appropriate environmental management. Conventional monitoring approaches often rely on fixed stations, manual sampling, periodic measurements, and centralized analysis. Although these approaches provide valuable information, they may have limitations related to

monitoring frequency, geographic coverage, response time, and operational cost. The Internet of Things has created new possibilities by connecting distributed sensors and communication technologies to provide continuous and geographically distributed environmental information.

IoT sensor networks combine sensing devices, wireless communication, data-processing platforms, and application services. Environmental sensors can measure parameters such as temperature, humidity, air pollutants, water-quality indicators, soil conditions, noise, and other environmental variables. These measurements can be transmitted through wireless networks to gateways, edge nodes, or cloud platforms. Gubbi et al. (2013) described IoT environments as interconnected systems in which sensing, communication, computation, and intelligent services operate together, providing a suitable technological foundation for smart environmental monitoring.

Real-time environmental information can support faster identification of environmental changes and abnormal conditions. Distributed sensor networks can provide information from multiple locations rather than relying on a limited number of monitoring stations. This spatial distribution can improve environmental visibility and support localized assessment. IoT connectivity also enables monitoring platforms to collect information continuously, allowing trends and variations to be identified over time. Such capabilities can support environmental management, infrastructure planning, agricultural monitoring, and urban environmental services.

Wireless sensor networks are particularly important because many environmental monitoring applications require sensors to operate in remote, distributed, or difficult-to-access locations. Low-power communication technologies can allow sensor nodes to transmit information while conserving energy. However, environmental monitoring systems often require long-term operation, making battery consumption and maintenance important considerations. Intelligent sampling, low-power communication, local processing, and energy-efficient network protocols can contribute to longer operational periods and reduce maintenance requirements.

The integration of edge computing and intelligent analytics can further improve environmental monitoring. Edge computing allows sensor information to be processed closer to its source, reducing communication requirements and supporting rapid responses. Machine-learning methods can identify environmental patterns, detect anomalies, classify conditions, and support predictive analysis. Cloud platforms can provide large-scale storage and computational capabilities, while edge systems can handle time-sensitive processing. Combining these capabilities can create flexible environmental monitoring architectures.

IoT-based environmental monitoring has applications across multiple domains. Urban environments can use connected sensors to monitor air quality, noise, temperature, and other conditions. Agricultural environments can monitor soil moisture and environmental parameters, while water-monitoring systems can assess selected water-quality conditions. Industrial environments can use connected sensors to identify environmental changes around facilities. Natural ecosystems can also benefit from distributed sensing where appropriate. These applications demonstrate the broad potential of IoT sensor networks.

Despite these benefits, smart environmental monitoring systems face several challenges. Sensors may experience measurement errors, calibration problems, physical degradation, or environmental interference. Distributed networks can encounter communication failures, limited connectivity, and

energy constraints. Large-scale deployments can also produce substantial quantities of data requiring efficient processing and storage. Cybersecurity and data integrity are additional concerns when monitoring systems are connected to networks. Interoperability between sensors and platforms can further influence system scalability.

This study examines smart environmental monitoring using IoT sensor networks by analyzing sensing technologies, communication mechanisms, real-time data collection, edge and cloud processing, intelligent analytics, and environmental applications. It also evaluates major implementation challenges and identifies future research opportunities. The study seeks to provide a structured understanding of how IoT sensor networks can support continuous, distributed, intelligent, and responsive environmental monitoring across different environmental contexts.

## 2. Objectives of the Study

### Primary Objective

The primary objective of this study is to examine smart environmental monitoring using IoT sensor networks by analyzing distributed sensing, wireless communication, real-time data collection, edge and cloud processing, intelligent analytics, and environmental applications.

The study seeks to understand how IoT technologies can improve environmental visibility, monitoring efficiency, data availability, anomaly identification, and decision support across diverse environmental settings.

### 2.1 Examination of IoT Sensor Network Technologies

The first objective is to examine the principal technologies supporting IoT-based environmental monitoring, including environmental sensors, wireless sensor networks, communication gateways, edge computing, cloud platforms, and analytical systems. The study evaluates how these components interact to collect, transmit, process, and interpret environmental information.

Particular attention is given to sensor deployment, communication efficiency, energy management, real-time processing, and system integration.

### 2.2 Assessment of Environmental Monitoring Applications

The second objective is to assess applications of IoT sensor networks across urban, agricultural, industrial, water, and natural environmental contexts. The study examines how distributed sensing can support air-quality monitoring, water-quality assessment, soil observation, weather-related measurement, noise monitoring, and environmental anomaly detection.

The objective also considers how continuous environmental information can support timely assessment, planning, and intelligent environmental management.

### 2.3 Identification of Implementation Challenges

The third objective is to identify major challenges associated with IoT-based environmental monitoring, including sensor accuracy, energy limitations, communication reliability, environmental exposure, data management, cybersecurity, interoperability, scalability, and maintenance requirements. The study evaluates how these limitations influence monitoring performance. Identifying such challenges can

support the development of reliable, energy-efficient, secure, scalable, and environmentally robust IoT sensor networks.

### 3. Review of Literature

#### 3.1 IoT Sensor Networks for Environmental Monitoring

Gubbi et al. (2013) identified sensing, communication, computation, and intelligent services as fundamental elements of IoT architectures. These components are particularly relevant to environmental monitoring because environmental information must be collected from distributed locations and transferred to processing systems. IoT-enabled sensors can continuously observe environmental parameters and provide information to centralized or distributed platforms. This capability supports more frequent monitoring and improves the availability of environmental information for analysis and decision-making.

Akyildiz et al. (2002) examined wireless sensor networks as distributed systems consisting of sensor nodes capable of sensing and communicating information. Such networks provide a foundation for environmental monitoring because sensors can be deployed across geographically distributed areas. Wireless communication enables information exchange among sensor nodes and collection points without extensive physical infrastructure. However, energy consumption, network organization, reliability, and communication range remain important considerations for long-term environmental monitoring deployments.

#### 3.2 Environmental Sensing and Real-Time Data Collection

Environmental monitoring requires accurate measurement of physical and chemical parameters. IoT sensors can provide continuous measurements of temperature, humidity, air quality, water conditions, soil characteristics, and other environmental variables. Real-time data collection can improve awareness of changing environmental conditions and provide information for identifying unusual events. Distributed sensing also enables environmental measurements to be collected from multiple locations, supporting more detailed spatial analysis.

Hart and Martinez (2006) discussed the role of environmental sensor networks in ecological monitoring and highlighted their potential to collect information from remote environments. Sensor networks can support long-term observation while reducing dependence on manual measurement. However, environmental sensor deployments must account for calibration, physical exposure, maintenance, and communication limitations. These considerations remain important for contemporary IoT-based environmental monitoring systems where sensors are expected to operate continuously.

#### 3.3 Intelligent Environmental Data Processing

Large-scale environmental sensor networks can generate significant quantities of information that require efficient processing and interpretation. Cloud computing provides extensive storage and computational resources for environmental datasets, while edge computing can process information closer to sensor locations. Shi et al. (2016) highlighted the potential of edge computing to reduce latency and support processing near data sources. This approach can be valuable when environmental monitoring applications require rapid detection or response.

Artificial intelligence can further enhance environmental monitoring by identifying patterns and anomalies within sensor data. Machine-learning techniques can support environmental classification, forecasting, anomaly detection, and predictive analysis.

Intelligent processing can help distinguish normal environmental variation from potentially important changes. However, the quality of analytical outputs depends on sensor reliability, data completeness, appropriate model selection, and sufficient training information. Combining reliable sensing with appropriate analytics is therefore essential.

## 4. Research Methodology

### 4.1 Research Design

This study adopted a qualitative descriptive and conceptual research design to examine smart environmental monitoring using IoT sensor networks. The study relied on secondary academic literature addressing IoT, wireless sensor networks, environmental sensing, edge computing, cloud computing, data analytics, and intelligent environmental monitoring. This design was selected to synthesize existing knowledge and identify important relationships among sensing, communication, processing, and environmental applications.

The conceptual framework considered environmental sensors, sensor networks, communication gateways, edge computing, cloud platforms, analytical models, and monitoring applications as interconnected components. These components were examined according to monitoring continuity, sensor accuracy, communication performance, energy efficiency, data processing, scalability, security, and reliability. The framework provided a structured basis for understanding how IoT sensor networks can support smart environmental monitoring.

### 4.2 Data Collection

Secondary information was collected from peer-reviewed journal articles, academic conference publications, scholarly books, and established research addressing IoT sensor networks and environmental monitoring. Literature concerning environmental sensing, wireless sensor networks, smart cities, ecological monitoring, air-quality monitoring, water monitoring, agricultural sensing, edge computing, and environmental data analytics was reviewed. Sources were selected based on relevance to the research objectives.

The reviewed literature was organized into technological and application-oriented categories. Technological studies addressed sensors, communication networks, energy management, edge computing, cloud platforms, and analytics. Application studies examined environmental monitoring in urban, agricultural, industrial, water, and natural settings. Research concerning sensor accuracy, network reliability, security, interoperability, scalability, and maintenance was also examined to identify barriers affecting IoT-based environmental monitoring.

### 4.3 Data Analysis

The collected literature was analyzed through thematic analysis. Major themes included environmental sensing, real-time monitoring, wireless communication, energy efficiency, data processing, edge computing, intelligent analytics, security, interoperability, reliability, and scalability. Each theme was

evaluated according to its contribution to environmental monitoring and its relationship with IoT sensor network architecture.

A comparative synthesis was then conducted to identify interactions among sensing, communication, processing, and application layers. Sensors were treated as primary data-generation mechanisms, communication networks enabled information transfer, and edge or cloud platforms supported data processing. Analytical models transformed collected information into environmental insights, while monitoring applications used these insights for assessment and decision support. This approach provided a structured analysis of IoT-enabled environmental monitoring systems.

**5. Analysis**  
**5.1 Core Components of IoT Environmental Monitoring Systems**

Smart environmental monitoring systems depend on coordinated sensing, communication, processing, and analytical components.

**Table 1: Core Components of IoT-Based Environmental Monitoring**

| Component             | Primary Function                | Contribution                  |
|-----------------------|---------------------------------|-------------------------------|
| Environmental Sensors | Parameter measurement           | Environmental data collection |
| Sensor Nodes          | Local sensing and processing    | Distributed monitoring        |
| Wireless Network      | Information transmission        | Connectivity                  |
| Gateway               | Data aggregation                | Network coordination          |
| Edge Computing        | Local processing                | Rapid analysis                |
| Cloud Platform        | Storage and advanced processing | Large-scale analysis          |
| AI Analytics          | Pattern and anomaly analysis    | Intelligent interpretation    |
| Monitoring Dashboard  | Information presentation        | Decision support              |

The analysis demonstrates that IoT-based environmental monitoring is based on multiple interconnected layers. Sensors provide environmental measurements, while sensor nodes and wireless networks facilitate distributed information collection and transmission. Gateways aggregate information before processing, while edge computing can provide rapid local analysis.

Cloud platforms support extensive storage and computation. AI-based analytics can identify environmental patterns and anomalies, while monitoring dashboards present processed information for assessment and decision support.

**5.2 Environmental Monitoring Applications**

IoT sensor networks can support environmental monitoring across different application environments.

**Table 2: Applications of IoT-Based Environmental Monitoring**

| Application Area     | Monitoring Function                | Potential Contribution    |
|----------------------|------------------------------------|---------------------------|
| Urban Environment    | Air and noise monitoring           | Environmental assessment  |
| Agriculture          | Soil and microclimate monitoring   | Resource management       |
| Water Systems        | Water-condition monitoring         | Quality assessment        |
| Industrial Areas     | Environmental parameter monitoring | Operational oversight     |
| Natural Ecosystems   | Ecological sensing                 | Environmental observation |
| Smart Buildings      | Indoor environmental monitoring    | Environmental control     |
| Weather Monitoring   | Temperature and humidity sensing   | Condition assessment      |
| Pollution Monitoring | Pollutant detection                | Early identification      |

The analysis indicates that IoT sensor networks can support environmental monitoring in both natural and human-developed environments. Urban systems can provide information about air quality and noise, while agricultural networks can monitor soil and environmental conditions.

Water-monitoring systems can collect relevant water information, and industrial deployments can observe environmental parameters around facilities. The distributed nature of IoT sensing allows monitoring systems to provide localized information and continuous observation.

## 6. Discussion

IoT sensor networks provide an important foundation for continuous and distributed environmental monitoring. Unlike monitoring approaches based primarily on periodic manual measurement, connected sensors can generate information at regular intervals and transmit it to processing platforms. This can improve temporal and spatial visibility of environmental conditions. Distributed sensing is particularly useful where environmental conditions vary significantly across locations, because multiple sensor nodes can provide more localized observations.

The integration of edge computing and intelligent analytics can improve the responsiveness of environmental monitoring systems. Edge nodes can process selected information close to sensor locations, allowing abnormal conditions to be identified without requiring all raw information to be transmitted to centralized cloud platforms. Machine-learning models can support pattern recognition, anomaly detection, and environmental forecasting. However, analytical reliability depends strongly on sensor accuracy, data quality, model suitability, and appropriate environmental context.

IoT-based environmental monitoring also provides opportunities for smart-city management, agricultural observation, industrial environmental assessment, water monitoring, and ecosystem research. Nevertheless, long-term deployments must address sensor degradation, energy limitations, network reliability, security, and interoperability.

Environmental sensors may operate under demanding physical conditions, requiring robust hardware and appropriate maintenance. Future systems should therefore integrate energy-efficient sensing, resilient communication, secure data management, intelligent processing, and standardized interfaces to improve reliability and scalability.

## 7. Challenges

### 7.1 Sensor Accuracy and Environmental Exposure

Sensor accuracy is a major challenge in smart environmental monitoring because environmental sensors may be exposed to temperature changes, humidity, dust, moisture, chemical substances, vibration, and other physical conditions. These factors can influence sensor performance and measurement consistency. Calibration, sensor validation, signal filtering, and appropriate placement are therefore essential for producing reliable environmental information. Poor-quality sensor measurements can directly affect subsequent analysis and reduce confidence in monitoring results.

Long-term environmental deployments can also cause physical deterioration of sensing equipment. Sensors positioned in outdoor or remote environments may require protective enclosures and periodic maintenance. Environmental exposure can gradually influence measurement sensitivity and operational reliability. Robust sensor design, calibration procedures, fault detection, and sensor redundancy can reduce these risks. Combining information from multiple sensors can also help identify inconsistent measurements and improve the reliability of environmental observations.

### 7.2 Energy and Network Limitations

Many IoT environmental monitoring networks contain battery-powered sensor nodes that must operate for extended periods. Continuous sensing and wireless transmission can consume significant energy, particularly when sensors are deployed in remote locations where battery replacement is difficult. Energy-efficient communication protocols, adaptive sampling, local processing, and intelligent transmission schedules can reduce energy consumption. Solar or other energy-harvesting approaches may also support longer operational periods where environmental conditions permit.

Network reliability is another concern because environmental sensors may be distributed over large or geographically difficult areas. Wireless communication can be affected by distance, physical obstacles, interference, weather conditions, or limited infrastructure. Network interruptions can result in missing environmental information. Multi-hop communication, redundant connectivity, local storage, and fault-tolerant network architectures can improve reliability. Effective network planning is therefore necessary to maintain continuous environmental information collection.

### 7.3 Data Security and Privacy

Connected environmental monitoring systems exchange information across sensor nodes, gateways, communication networks, edge devices, and cloud platforms. Vulnerabilities in these components can

allow unauthorized access, data manipulation, or disruption of monitoring services. Secure authentication, encryption, access control, device management, and network monitoring are therefore important for protecting environmental information and maintaining system integrity.

Although environmental datasets may not always contain personal information, some smart-city and building-monitoring applications can generate information associated with locations, facilities, or user activities. Improper data handling may therefore create confidentiality concerns. Secure storage, controlled access, data minimization, and privacy-aware analytics can help reduce these risks. Security mechanisms should be integrated throughout the monitoring architecture rather than implemented only at the application layer.

## 7.4 Interoperability and Scalability

Environmental monitoring systems may combine sensors from different manufacturers, communication technologies, data formats, gateways, analytical platforms, and application interfaces. Differences among these components can create interoperability problems and make system expansion difficult. Standardized communication protocols, common data formats, open interfaces, and middleware can facilitate integration. Interoperability is particularly important when environmental information from multiple monitoring networks must be combined.

Scalability becomes increasingly important as sensor deployments expand geographically and generate larger data volumes. Centralized platforms may face increasing storage, processing, and communication demands. Edge computing can reduce these pressures by filtering and processing selected information locally. Hierarchical architectures can also organize sensors, gateways, edge nodes, and cloud platforms efficiently. Scalable system design should therefore account for future growth in sensors, geographic coverage, data volume, and analytical requirements.

## 8. Future Research

Future research should focus on developing energy-efficient and environmentally robust IoT sensor networks capable of long-term operation. Adaptive sensing, low-power communication, energy harvesting, intelligent duty cycling, and edge-based data processing should be investigated to reduce maintenance requirements. Research should also examine more robust sensing technologies capable of maintaining measurement accuracy under variable environmental conditions. Autonomous calibration and sensor-fault detection could further improve monitoring reliability.

Further research should investigate AI-enabled and interoperable environmental monitoring platforms capable of integrating information from heterogeneous sensor networks. Privacy-aware data management, secure communication, standardized interfaces, distributed analytics, and edge-cloud collaboration should receive greater attention.

## 9. Conclusion

Smart environmental monitoring using IoT sensor networks provides an effective approach for collecting continuous and distributed environmental information. Connected sensors can monitor environmental parameters across multiple locations and transmit information to processing platforms. This capability can improve temporal monitoring, spatial visibility, and environmental data availability.

IoT technologies therefore provide a foundation for moving environmental monitoring toward more connected and data-driven approaches.

The analysis demonstrates that effective monitoring depends on the integration of sensing, communication, processing, and analytical technologies. Environmental sensors collect measurements, wireless networks provide connectivity, gateways aggregate information, and edge or cloud platforms process collected data. Intelligent analytics can identify patterns and anomalies, while monitoring interfaces support environmental assessment. Coordinated operation of these components is necessary for reliable monitoring performance.

IoT sensor networks can support diverse applications, including urban environmental monitoring, agricultural sensing, water monitoring, industrial observation, natural ecosystem assessment, and smart-building applications. Distributed sensing provides localized information that can support environmental assessment and management. However, the effectiveness of these applications depends on sensor accuracy, communication reliability, energy availability, data quality, and system scalability.

Overall, IoT-based environmental monitoring has significant potential to improve environmental observation through continuous sensing and intelligent information processing. Nevertheless, sensor degradation, energy limitations, network failures, cybersecurity, interoperability, and maintenance requirements must be addressed systematically. Future systems should combine robust sensors, energy-efficient communication, secure data management, edge intelligence, and interoperable architectures. Such integration can contribute to reliable, scalable, responsive, and sustainable environmental monitoring systems.

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