Trends and Technologies in Environmental Monitoring: A Review of Sensors, Communication, and AI-Enabled Systems*

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Abstract

Wireless Sensor Networks (WSNs) are foundational for addressing modern environmental monitoring challenges driven by climate change. This review provides an integrated analysis of the trends and challenges, examining sensing technologies for water, soil, and air, alongside communication protocols and best practices. We consolidate advances across sensors, networking, and system-level challenges, including energy efficiency, security, and the integration of the Artificial Intelligence of Things (AIoT). By bridging these multidisciplinary domains, this work serves as a foundational guide for future research and the development of next-generation monitoring systems.

Index Terms

Environmental monitoring, Wireless Sensor Networks, Internet of Things (IoT), LoRaWAN, Artificial Intelligence of Things (AIoT).

I. INTRODUCTION

The increasing urbanization and climate change have diverse impacts on different layers of society, threatening individuals in vulnerable situations during disasters such as floods, or affecting agricultural production due to climatic variations [1]. These phenomena highlight the need for monitoring systems that can provide more data on environmental conditions and help us monitor, analyze, and predict such events [2].

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When we talk about environmental monitoring, we refer to a wide range of applications and devices. Particularly in remote and hard-to-reach areas, this represents a significant technical challenge. The vastness of these territories, combined with adverse environmental conditions and the growing demand for real-time data, requires technological solutions that are robust, cost-effective, and scalable [3], [4].

While many reviews focus on specific aspects such as soil sensors or water level measurement, few provide an integrated perspective combining sensing technologies, communication infrastructures, energy efficiency, artificial intelligence, and security. This review addresses that gap by consolidating advances across soil, water, and air monitoring domains to highlight overlooked technologies and guide future research toward scalable, intelligent, and resilient environmental monitoring solutions.

II. REVIEW OF SENSING TECHNOLOGIES

A wide array of sensing technologies is available for environmental monitoring, each with distinct advantages and use cases. For **water level monitoring**, conventional methods like limnigraphs face reliability issues in harsh conditions [5]. Non-contact ultrasonic sensors have been proven as a viable, low-cost option for short-range measurements [6], while LiDAR offers superior accuracy and range, though its performance can be temperature-dependent [9]. For large-scale monitoring, satellite-based remote sensing provides high consistency with in-situ data [11], [12].

In **water quality**, recent developments include WSN nodes that use embedded machine learning to classify pollutants based on pH, turbidity, and EC sensor data [16]. For **soil monitoring**, batteryless technologies using NFC [18] and advanced optical fiber methods like AH-OFDR [19] are emerging. Finally, for **air quality and chemical detection**, Surface Acoustic Wave (SAW) sensors show promise for detecting gases and vapors [20], while reviews of low-cost sensors (LCS) confirm their potential to expand spatial coverage for monitoring pollutants like CO, O_3, and $PM_{2.5}$ [21].

III. KEY CHALLENGES AND EMERGING TRENDS

Beyond specific sensors, systemic challenges and trends shape the future of environmental monitoring. For **large area monitoring**, mobile data collection using vehicles equipped with

RFID readers [23] or drones serving as LoRa gateways [24] presents a scalable alternative to fixed WSNs.

In **power consumption**, ”Beat sensors” represent an innovative, ultra-low-power paradigm where sensor data is encoded in the time interval between simple ID code transmissions. This approach has demonstrated a battery life of over seven years in some applications and has been adapted for solar-powered, battery-less water level monitoring with a 2 km LoRa range [25]–[27].

The integration of artificial intelligence, or **AIoT**, is a major trend, enabling smarter, context-aware sensors and predictive analytics [28], [29]. However, this integration elevates the importance of **security and privacy**. The constrained nature of embedded systems often leads to security being an afterthought, creating vulnerabilities to both software and hardware-level attacks that can compromise entire networks [30], [31], [33].

IV. CONCLUSIONS AND CONTRIBUTIONS

This review consolidates recent advances across a wide spectrum of environmental monitoring technologies, providing an integrated perspective that connects sensor development with communication infrastructures and systemic challenges. We identify a clear trend towards more autonomous, intelligent, and energy-efficient systems capable of operating in remote and harsh environments.

Our analysis concludes that while sensor maturity is improving, the primary challenges are now shifting towards scalable data acquisition, robust security architectures, and the effective application of AI to extract value from collected data. The convergence of innovations like batteryless sensors, mobile data collection, and AIoT enables more resilient systems to meet the demands of climate adaptation and resource management. This work contributes by offering a multidisciplinary guide for researchers and engineers, highlighting a path forward for developing the next generation of intelligent environmental monitoring solutions.

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