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Advances in Wireless Sensor Networks for IoT-Enabled Environmental Monitoring and Sustainable Resource Management

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Abstract

Wireless Sensor Networks (WSNs) have emerged as pivotal tools for Internet of Things (IoT)-driven environmental monitoring, enabling real-time data acquisition and analysis across diverse ecological settings. These networks consist of numerous distributed sensor nodes equipped with sensing, processing, and wireless communication capabilities, enabling pervasive, scalable monitoring. This paper discusses the innovative applications of WSNs in environmental monitoring, emphasizing their role in enhancing data collection and risk management. Key advancements include deploying acoustic sensor networks for urban noise assessment, remote sensing techniques for plant health monitoring, and cost-effective wind data acquisition systems for studying coastal environments. Furthermore, recent methodologies for sensor deployment are explored, highlighting algorithms that optimize coverage and connectivity while. Addressing challenges posed by network dynamics and environmental constraints. IoT integration continues to evolve, and WSNs present significant opportunities for sustainable environmental management, enabling more effective responses to ecological changes and threats. This work synthesizes recent research contributions and highlights the importance of WSNs in shaping the future of environmental monitoring through an IoT framework.

Keywords: Wireless sensor network, Internet of things, Environmental monitoring, Real-time data acquisition, Sensor development, Remote sensing, Data collection.

1 | Introduction

Wireless Sensor Networks (WSNs) play a transformative role in environmental monitoring by enabling real-time data collection, wide-area coverage, long-term observation, and scalability. These networks consist of many distributed devices, each with sensors, processing units, and wireless communication capabilities [1].

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Their application has significantly enhanced remote environmental sensing, enabling efficient monitoring of various physical systems and improving risk assessment and management processes. The editorial highlights that WSNs have become essential for continuous, pervasive monitoring of environmental conditions. These networks can gather data from vast and often inaccessible areas, providing valuable insights into environmental changes and potential risks. The scalability of WSNs enables the expansion of monitoring systems without requiring significant infrastructure changes, making them a cost-effective and flexible solution.

A key benefit of WSNs is their ability to provide real-time access to environmental data, critical for timely decision-making in the face of environmental risks or disasters. This real-time capability, coupled with the ability to monitor conditions over long periods, makes WSNs indispensable for tracking gradual changes in environmental parameters, such as climate trends, deforestation, and air or water pollution.

The editorial also notes that six of the 11 papers submitted to the Special Issue were accepted following a rigorous peer-review process. These papers propose innovative solutions in environmental monitoring, each contributing unique advancements in using WSNs for environmental data acquisition, risk assessment, and management [1].

2 | Literature Review

WSNs have emerged as a pivotal component of Internet of Things (IoT)-driven environmental monitoring, attracting extensive research due to their potential for innovative solutions in real-time data acquisition and analysis across diverse ecological settings. By seamlessly integrating numerous sensor nodes capable of collecting and transmitting data, WSNs have revolutionized how environmental data is gathered, processed, and utilized. This transformation is not merely technological; it has significant implications for how stakeholders—from scientists and policymakers to urban planners—approach environmental management and decision-making. The architecture of WSNs enables the deployment of distributed sensors across diverse locations, providing extensive coverage and enabling continuous monitoring of environmental parameters such as air quality, water levels, soil moisture, and temperature. This capability is particularly beneficial in dynamic ecosystems where conditions change rapidly, and timely data is crucial for effective response strategies. The real-time data acquired by WSNs enables stakeholders to make informed decisions based on current conditions rather than relying on historical data, which may not accurately reflect ongoing environmental changes. Moreover, WSNs facilitate the integration of advanced data analytics and machine learning algorithms, allowing for deeper insights into ecological trends and identifying patterns that may not be immediately apparent through traditional monitoring methods. This analytical power enhances the predictive capabilities of environmental monitoring systems, enabling proactive management of environmental challenges such as climate change, pollution, and habitat degradation [2].

In summary, the role of WSNs in IoT-driven environmental monitoring is transformative, bridging the gap between data collection and actionable insights. By providing a robust framework for real-time data acquisition and analysis, WSNs enhance our understanding of ecological systems and empower decision-makers with the tools they need to address pressing environmental issues effectively. As research and technology in this field continue to advance, the potential applications of WSNs are expected to expand, further solidifying their importance in the global effort to achieve sustainable environmental management. These networks consist of small, distributed sensor nodes that communicate wirelessly to collect data on parameters like temperature, humidity, air quality, water levels, and pollution, making them indispensable for tracking environmental changes over time. The literature on WSNs is broad, underlining their significant impact on modern environmental monitoring systems. Researchers have explored various applications of WSNs, ranging from monitoring air and water quality in urban settings to tracking wildlife and forest conditions in remote regions. These networks are especially valuable for environmental risk assessment and disaster management, where the ability to collect real-time data from hazardous or inaccessible locations is vital for early warning systems and mitigation strategies. WSNs also play a central role in long-term

environmental studies, allowing for continuous monitoring of ecosystems and detecting gradual changes such as climate shifts, deforestation, and soil degradation. Their scalability and flexibility make them ideal for integrating into larger IoT frameworks, enabling a holistic approach to environmental management. The combination of WSNs with advanced data analytics, machine learning, and cloud computing further enhances their ability to provide insights into complex environmental phenomena, making them an essential tool in addressing the challenges posed by global environmental changes [3].

3 | Environmental Monitoring with WSNs

A substantial body of research underscores the increasing adoption of WSNs in environmental monitoring. In a notable review by Okpara et al. [4], the authors explored the diverse capabilities of WSNs in tracking various environmental parameters, highlighting their inherent flexibility, scalability, and efficiency in collecting and transmitting data over vast geographical areas.

The study emphasized that WSNs can monitor common environmental factors, such as air and water quality, temperature, and humidity, but are also well-suited for specialized tasks, such as detecting soil moisture, monitoring wildlife habitats, and assessing pollution levels in remote regions.

One of the most significant advantages of WSNs is their ability to provide continuous, real-time data from a network of distributed sensors, making them an invaluable tool for studying localized events and wide-ranging phenomena. This capability enables researchers to monitor dynamic environmental conditions, observe patterns over time, and respond quickly to emerging issues, such as sudden changes in air quality or water contamination [1].

Furthermore, WSNs can operate autonomously in challenging environments, collecting data without constant human intervention, thereby enhancing their reliability and effectiveness for long-term environmental studies. The scalability of WSNs also enables their deployment in large-scale monitoring projects, where sensors can be easily added or adjusted to cover larger areas or to focus on specific regions of interest. This adaptability, combined with their ability to integrate into IoT-based frameworks, positions WSNs as a critical technology for modern environmental monitoring and management, addressing both localized environmental issues and global challenges such as climate change, deforestation, and natural resource depletion—quality, temperature, and humidity levels, as well as more specialized monitoring tasks [5].

4 | Urban Noise Monitoring with WASNs

Wireless Acoustic Sensor Networks (WASNs) have emerged as a valuable tool for monitoring noise pollution and detecting acoustic events in urban environments. These networks are particularly effective in densely populated areas where noise pollution is a significant concern for public health and quality of life. Luo et al. [6] introduced a system that leverages WASNs to enable high-performance urban noise monitoring, allowing for the real-time creation of noise maps and the recognition of specific sound patterns, such as traffic noise, construction, or emergency sirens. The study demonstrated how this technology can be instrumental in understanding noise distribution across urban landscapes, identifying hotspots, and tracking noise trends over time. WASNs offer a cost-effective and scalable solution for urban planners, environmental agencies, and public health authorities by continuously monitoring large areas without requiring expensive infrastructure. The real-time data gathered by these networks can inform decision-making, such as implementing noise reduction strategies, enforcing zoning laws, or designing quieter urban spaces. Moreover, WANs can reduce the harmful effects of noise pollution on human health, which has been linked to stress, sleep disorders, and cardiovascular issues, by enabling timely interventions where noise levels exceed safe thresholds. Remote sensing, often integrated with WSNs, has proven to be an effective tool for monitoring plant health and detecting pathogens. Di Nisio et al. [7] explored the use of multispectral imaging from Uncrewed Aerial Vehicles (UAVs) to monitor olive trees affected by *Xylella fastidiosa*. This study demonstrated the potential of UAV-based remote sensing for real-time plant health monitoring, allowing for early detection and intervention in agricultural and ecological settings. The combination of WSNs provides a powerful platform

for enhancing agricultural productivity and ecosystem management. The flexibility and scalability of WASNs make them well-suited for dynamic urban environments. Sensors can be strategically deployed across a city, and the system can be easily expanded or adapted as new areas are developed or noise concerns shift. This adaptability and the ability to generate real-time noise maps allow for a more proactive approach to managing urban noise, making WASNs a vital tool in creating healthier, more livable cities.

5 | Remote Sensing for Plant Health Monitoring

Remote sensing, particularly when integrated with WSNs, has become a highly effective tool for monitoring plant health and detecting pathogens in real time. Di Nisio et al. [7] conducted a significant study that utilized multispectral imaging from UAVs to monitor olive trees impacted by the plant pathogen *Xylella fastidiosa*. This bacterium has devastated olive groves in several regions. Using UAV-based remote sensing, the researchers could monitor large farmland areas and detect early signs of disease stress in the trees long before symptoms become visible to the naked eye. The capability to detect destructive pathogens early through the integration of UAV-based remote sensing and WSNs is invaluable, enabling timely interventions critical to preventing the spread of such threats to agricultural and ecological systems. The study emphasizes the synergistic advantages of combining these two technologies to establish a comprehensive, real-time monitoring system that enhances our ability to manage plant health and environmental conditions effectively. With advanced imaging technologies, UAVs can efficiently cover large geographical areas, capturing high-resolution data and providing a broad overview of crop health and environmental changes. This aerial perspective is particularly beneficial for identifying potential outbreaks of pathogens or pests across extensive landscapes, enabling farmers and agronomists to pinpoint areas of concern that may require immediate attention [5].

In contrast, WSNs excel in providing detailed, localized data that complements the broader insights gained from UAVs. By deploying sensor nodes throughout the monitored area, WSNs can continuously measure critical environmental parameters such as soil moisture, temperature, humidity, and light intensity. This localized data is essential for understanding microclimatic variations that influence plant health and growth, enabling more precise management decisions tailored to specific areas within a field or ecosystem. Together, UAVs and WSNs create a robust monitoring framework that enhances data collection efficiency and improves the quality of information available to decision-makers. Integrating real-time data from both sources enables stakeholders to respond swiftly to emerging threats, optimizing resource allocation and intervention strategies. This holistic approach is vital for sustainable agriculture and ecosystem management, as it empowers farmers and conservationists to make informed decisions that safeguard plant health and enhance productivity.

In conclusion, combining UAV-based remote sensing with WSNs represents a significant advancement in environmental monitoring. By facilitating early detection and enabling timely interventions, this integrated system enhances our capacity to manage agricultural and ecological challenges, ultimately improving outcomes in both productivity and sustainability. As technology continues to evolve, the potential for further innovation in this field promises even greater capabilities for monitoring and managing our vital natural resources. This dual approach enhances monitoring precision and enables farmers and environmental managers to take proactive measures, such as targeted pesticide application or irrigation adjustments, thereby improving crop productivity and resource efficiency. Integrating remote sensing technologies, such as UAVs, with WSNs provides a powerful platform for sustainable agriculture and ecosystem management. It enables continuous monitoring of plant health at a scale previously unattainable, facilitating better disease management, improving yield, and minimizing environmental impact. This approach is poised to play a critical role in future agricultural practices, particularly in the context of precision farming and the growing need for more efficient, resilient food production systems.

6 | Coastal and Wind Data Monitoring

WSNs have proven invaluable for monitoring critical ecological processes in coastal environments. Domínguez-Brito et al. [8] developed a low-cost WSN specifically designed for wind data acquisition, allowing researchers to study the complex interactions between foredune systems and shrub vegetation. This research highlights the significance of continuous environmental monitoring in fragile coastal ecosystems, where even subtle changes in wind patterns can influence sand movement, vegetation dynamics, and overall ecosystem stability. Coastal areas are highly susceptible to environmental shifts, and understanding these interactions is essential for preserving biodiversity and mitigating erosion or habitat loss. WSNs are particularly well-suited for monitoring coastal and other remote environments due to their cost-effectiveness, ease of deployment, and scalability. These networks can be installed in hard-to-reach locations without extensive infrastructure, enabling real-time collection of data on environmental factors such as wind speed, temperature, and humidity. Continuous data collected by WSNs can be used to track seasonal changes, assess the impact of extreme weather events, and inform conservation efforts to protect vulnerable coastal regions. Moreover, the flexibility of WSNs enables integration with other monitoring systems, such as remote sensing technologies and ecological models, thereby enhancing the precision and scope of environmental assessments. In coastal management, WSNs offer a robust solution for ongoing monitoring. They can play a crucial role in detecting early signs of ecosystem stress, enabling timely interventions that help maintain the health and resilience of these sensitive environments [7], [9], [10].

7 | WSN Deployment Strategies for Improved Coverage and Connectivity

Deploying sensors in WSNs is pivotal for determining the network's overall efficacy, particularly in terms of coverage, connectivity, and robustness. Alablani and Alenazi [11] contributed significantly to this field by introducing a novel deployment algorithm based on Delaunay triangulation to optimize sensor placement in environments with obstacles, such as urban landscapes or heavily vegetated areas. Their innovative approach demonstrated marked improvements in coverage. It enhanced the network's resilience, ensuring WSNs can continue functioning effectively even under challenging conditions where traditional placement methods may falter. By utilizing Delaunay triangulation, the algorithm strategically positions sensors to maximize area coverage while minimizing gaps in data collection. It is particularly important in environments where physical obstructions impede sensor communication and limit data transmission. The result is an overall increase in the network's reliability, as the algorithm optimally locates sensors to capture comprehensive data, enabling more accurate monitoring and analysis. This enhanced performance is crucial across applications, from environmental monitoring to smart city initiatives, where maintaining consistent, reliable data streams is essential for effective decision-making. As the demand for IoT services grows exponentially, the authors highlighted the critical need for effective spectrum sharing through automated frequency coordination systems. In congested environments, where multiple wireless networks may operate simultaneously, managing frequency allocation becomes increasingly complex. Effective frequency management is essential to prevent network interference, which can degrade performance and disrupt sensor communication. Implementing automated systems that dynamically allocate frequencies based on real-time conditions enables WSNs to operate more efficiently, maintaining robust connectivity and performance even in high-traffic areas. This capability is vital as WSNs increasingly integrate with other IoT applications, necessitating a system that can accommodate many devices and services without compromising data quality or network stability. Automated frequency coordination optimizes spectrum usage and enhances the network's adaptability, allowing it to respond dynamically to changing conditions and demands. Overall, the advancements proposed by Alablani and Alenazi [11] represent a significant step forward in the design and deployment of WSNs, paving the way for more effective and resilient networks well-suited to a wide range of applications in complex environments. Their work underscores the importance of innovative algorithms and automated systems in addressing the challenges posed by modern urban settings, ultimately facilitating better data collection and analysis to drive

informed decision-making across sectors. As the landscape of IoT continues to evolve, these advancements will be critical in ensuring that WSNs can meet the diverse needs of users and contribute meaningfully to the development of smart, interconnected environments [11], [12].

8 | Integration of 5G and IoT in WSNs

As technology becomes more pervasive, its integration with WSNs opens up new avenues for environmental monitoring. The advent of 5G technology represents a significant leap forward, offering faster data transmission, enhanced network reliability, and the capacity to support massive IoT services. This upgrade in connectivity enables seamless communication among multiple devices, enabling a more comprehensive and responsive monitoring framework. Future WSNs, bolstered by 5G connectivity, are poised to deliver even more sophisticated real-time monitoring capabilities. This advancement will expand the potential applications for WSNs across both urban and remote environments. In urban settings, the high-speed connectivity enabled by 5G can enable more precise, timely data collection, allowing city planners and environmental agencies to respond rapidly to changes in air quality, noise pollution, and other critical factors affecting urban living conditions. Enhanced data analytics will empower these entities to implement data-driven interventions more effectively, ultimately improving public health and quality of life. In remote and rural areas, 5G-enhanced WSNs can facilitate environmental monitoring in regions lacking reliable connectivity. This capability can play a crucial role in tracking ecological changes, including monitoring wildlife habitats, assessing the impacts of climate change, and managing natural resources sustainably. Gathering and transmitting data in real time can significantly improve our understanding of environmental dynamics and support proactive measures to mitigate adverse effects.

Moreover, the combination of 5G technology with WSNs is expected to enable advanced applications such as autonomous drones for aerial monitoring, intelligent farming solutions that optimize resource use, and integrated disaster management systems that provide real-time alerts and data during natural events like floods or wildfires. As WSNs evolve alongside advancements in communication technology, they will become increasingly capable of addressing the complex challenges faced by modern ecosystems and urban landscapes.

Integrating 5G technology with WSNs marks a transformative step toward more efficient and effective environmental monitoring. This synergy will enhance the capabilities of existing monitoring systems and unlock new opportunities for data collection, analysis, and action, paving the way for smarter, more sustainable management of our natural and urban environments [13–15].

Environmental monitoring is fundamental to understanding our ecosystem and preventing adverse effects on human health and the environment. Urban noise affects more than the quality of life and can cause long-term physiological damage. In this context, WSNs have become a promising solution for high-performance monitoring of urban noise and acoustic event recognition. The study proposed in [5], [6] provides a significant example of the development of a novel system that utilizes WSNs for the recording, transferring, post-processing, and recognition of urban noise to create and visualize noise maps of acoustic events and to present additional information and noise statistics. Experimental results demonstrated that the proposed system can measure urban noise and recognize acoustic events with a high performance in real-life scenarios.

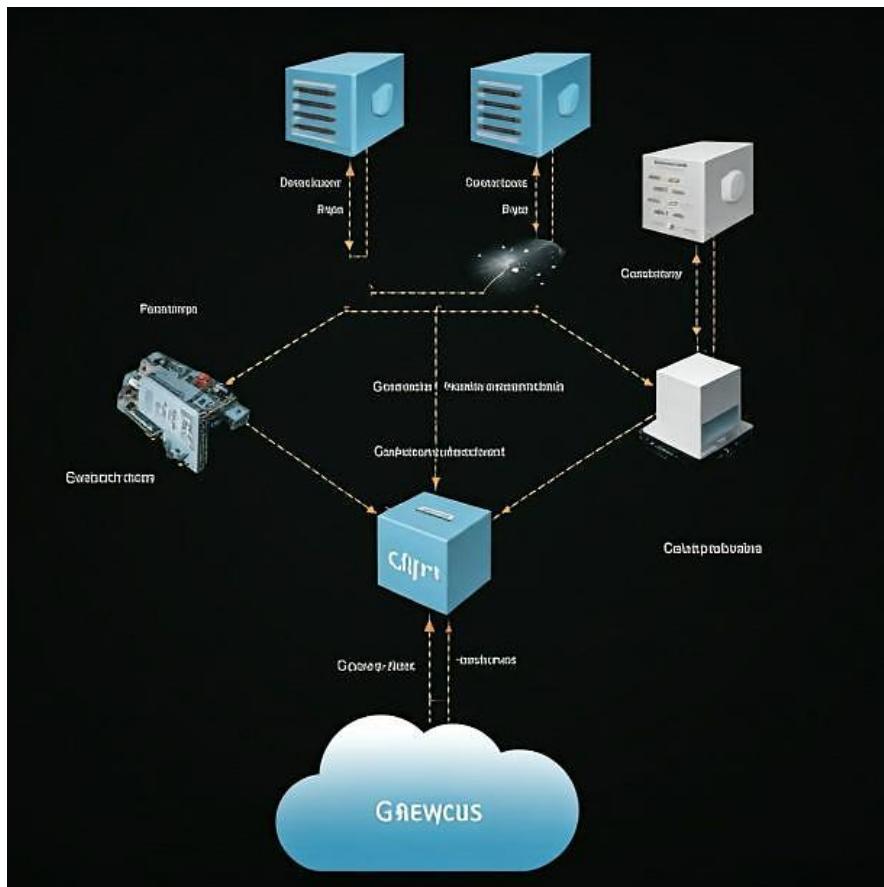


Fig. 1. Integrated 5G and IoT architecture in wireless sensor networks for environmental monitoring and urban noise assessment.

Maintaining plant health and promptly detecting pathogens are important issues in environmental monitoring. Recent advances in technology, instrumentation, and procedures have created new opportunities for real-time monitoring and rapid, accurate identification of environmental diseases. The paper [6] presents a remote sensing technique to monitor the spread of quick decline syndrome in olive trees caused by *Xylella fastidiosa* bacteria using a multispectral camera mounted on a multi-rotor UAV. The proposed method includes preprocessing to obtain calibrated reflectance images, 3D reconstruction of a sparse point cloud using stereophotogrammetry, segmentation of trees, and classification of their health status. The classifier was trained separately on each multispectral stack, but training on a set of homogeneous stacks would further increase its reliability. This technique can be self-adapted to different kinds of trees and soil. In addition to monitoring plant health status, this Special Issue includes examples of environmental studies on the identification of changes in coastal dunes induced by human activities. In [7], a low-cost, wireless wind data acquisition system that enabled multiple synchronized wind measurement points enabled data-intensive modeling of the interaction between an arid foredune system and its shrub vegetation. Given the global change scenario, monitoring environmental conditions is very important in coastal areas, as many areas are characterized by aeolian sedimentary environments in arid zones that require special protection. Deploying IoT sensors in WSNs is a crucial issue in network design. It affects the most important performance metrics, such as increasing coverage, strengthening connectivity, improving robustness, and extending the lifetime. Therefore, a sensor deployment method must be carefully designed to achieve such objective functions without exceeding the available budget. The authors of [8] introduced a novel deployment algorithm based on Delaunay triangulation to find optimal locations to improve coverage while maintaining connectivity and robustness, even in the presence of obstacles in the sensing area. The performance of the proposed method was evaluated in terms of area coverage, end-to-end delay, and resilience to attacks, and it proved promising results [7], [16].

In addition, a dynamic network deployment method based on the hybrid hierarchical network was proposed in [11] to realize a low-cost, energy-saving, and real-time dynamic sensing system for overhead high-voltage transmission lines. The proposed method enhances the network's practicability and improves the smart grid's monitoring efficiency. Another hot topic in WSNs is connectivity among different nodes and systems; with the advent of 5G technology, various types of massive wireless (IoT) services are becoming pervasive. As the demand for wireless communication grows, the spectrum becomes increasingly congested, creating a scarcity of available frequency resources. This challenge necessitates innovative solutions, including spectrum sharing facilitated by an automated frequency coordination system. In this context, recent research has focused on developing systems capable of determining the eligibility of requested frequency bands for sharing. A notable contribution in this area is the proposed frequency coordination system that employs a modified version of Kriging interpolation combined with a Support Vector Machine (SVM)-based variogram model. This sophisticated approach creates an accurate radio environment map, enabling the system to make informed spectrum-sharing decisions.

The non-parametric modeling method introduced in this study is pivotal in enhancing the reliability of spectrum-sharing decisions. Accurately characterizing the radio environment helps mitigate interference and optimize the use of available frequency resources. This argument is crucial for developing wider WSNs dedicated to environmental monitoring. As WSNs become more integrated with other IoT applications, effective spectrum management will be essential for maintaining robust communication and data transmission capabilities. The six papers featured in this Special Issue exemplify the advancements in WSNs applications for environmental monitoring. They showcase a range of innovative methodologies and applications that address various environmental challenges, highlighting the versatility and potential of WSNs in diverse contexts. Readers will likely find the contents of this special section engaging and instrumental in fostering new developments and insights in scientific research. We sincerely thank all the authors for their dedication and hard work in preparing these compelling contributions. Their efforts have enriched the discourse in this field and provided valuable perspectives on the role of WSNs in environmental monitoring. Additionally, we would like to acknowledge the highly qualified reviewers whose constructive feedback has been essential in refining these works. Their expertise has ensured the high quality of the published papers [17], [18].

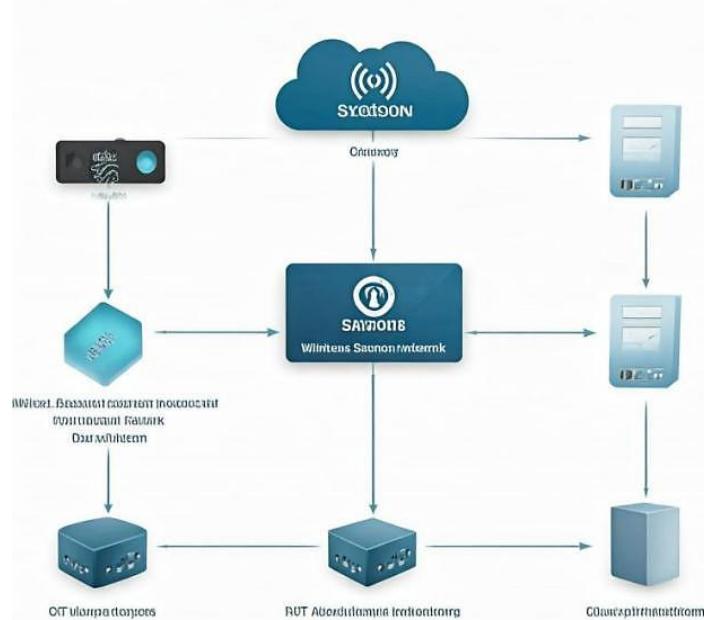


Fig. 2. WSN–IoT system architecture for plant health monitoring, environmental sensing, and spectrum-aware data transmission.

9 | Conclusion

In conclusion, WSNs are crucial in advancing IoT-based environmental monitoring. Innovative applications such as acoustic sensor networks for urban noise analysis, UAV-based plant health monitoring, and wind data collection for coastal studies demonstrate the transformative potential of WSNs for ecological monitoring. Integrating WSNs with IoT frameworks paves the way for sustainable environmental management, addressing current challenges and future risks. The research reviewed highlights the importance of WSNs in enhancing environmental data collection and analysis, contributing significantly to the evolving field of IoT-driven monitoring.

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Data Availability

The authors declare no conflicts of interest regarding the publication of this paper.

If necessary, these sections should be tailored to reflect the specific details and contributions.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding this research. Authors should disclose personal circumstances or interests that might be perceived as having an inappropriate influence on the presentation or interpretation of the research findings. Transparency in this regard helps maintain the integrity of the scientific process and ensures that readers can trust the objectivity of the reported results. Furthermore, any involvement of funding sources in the research process must be clearly outlined. Authors must disclose the role of funders in various stages of the research, including study design, data collection, analysis, interpretation, manuscript writing, or the decision to publish the results. Suppose there are no such influences or contributions from funders. In that case, authors should explicitly state, "Funders played no role in the design of the study, in the collection, analysis, or interpretation of the data, in the writing of the manuscript, or in the decision to publish the results." For further clarification and detailed guidelines regarding these disclosures, authors are encouraged to refer to the CID file. It ensures that all relevant information is communicated effectively, fostering transparency and accountability within the research.

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