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Internet of Things Applications in Environmental Sustainability: A Comprehensive Review of Smart Monitoring Systems in Agriculture and Water Management

Aplikasi Internet of Things untuk Keberlanjutan Lingkungan: Tinjauan Komprehensif Sistem Pemantauan Pintar dalam Pertanian dan Pengelolaan Air

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ABSTRAK

Internet of Things (IoT) telah menjadi teknologi utama dalam meningkatkan keberlanjutan lingkungan, terutama dalam pengelolaan air dan pertanian. Namun, masih terdapat tantangan dalam efisiensi penggunaan sumber daya, pemantauan real-time, dan pengambilan keputusan berbasis data. Tanpa sistem pemantauan cerdas yang terintegrasi, praktik pengelolaan air dan pertanian sering kali tidak optimal, menyebabkan pemborosan sumber daya dan dampak lingkungan yang lebih besar. Tinjauan literatur ini mengeksplorasi berbagai aplikasi IoT dalam sistem pemantauan cerdas, dengan fokus pada solusi yang diterapkan, teknologi sensor, parameter lingkungan yang dipantau, hasil implementasi, serta tantangan dan rekomendasi. Hasil kajian menunjukkan bahwa IoT dapat meningkatkan efisiensi penggunaan sumber daya, mendukung pengambilan keputusan berbasis data, serta mengoptimalkan praktik pertanian dan distribusi air. Namun, tantangan seperti biaya implementasi yang tinggi, privasi data, dan interoperabilitas masih menghambat adopsi secara luas. Untuk mengatasi hal ini, studi ini merekomendasikan peningkatan aksesibilitas teknologi IoT, pengembangan komunikasi nirkabel bawah tanah, serta keterlibatan publik dalam pengelolaan air pintar. Dengan solusi ini, IoT berpotensi menciptakan sistem pemantauan lingkungan yang lebih efisien dan berkelanjutan di masa depan.

Kata kunci: Internet of Things (IoT), Keberlanjutan, Pemantauan lingkungan, Pertanian cerdas, Manajemen air.

ABSTRACT

The Internet of Things (IoT) has become a key technology in enhancing environmental sustainability, particularly in water management and agriculture. However, challenges remain in resource efficiency, real-time monitoring, and data-driven decision-making. Without an integrated smart monitoring system, water and agricultural management practices are often suboptimal, leading to resource waste and greater environmental impact. This literature review explores various IoT applications in smart monitoring systems, focusing on implemented solutions, sensor technologies, monitored environmental parameters, implementation outcomes, challenges, and recommendations. The findings indicate that IoT can significantly improve resource efficiency, support data-driven decision-making, and optimize agricultural practices and water distribution. However, challenges such as high implementation costs, data privacy concerns, and interoperability issues still hinder widespread adoption. To address these challenges, this study recommends improving IoT technology accessibility, developing underground wireless communication systems, and increasing public engagement in smart water management initiatives. By implementing these solutions, IoT has the potential to create more efficient and sustainable environmental monitoring systems in the future.

Keywords: *Environmental monitoring, Internet of Things (IoT), Smart agriculture, Sustainability, Water management.*

INTRODUCTION

The rapid advancement of technology has ushered in a new era characterized by the proliferation of the Internet of Things (IoT), which has emerged as a transformative force across various sectors. Among its most promising applications is the enhancement of environmental sustainability, particularly in agriculture and water management. As the global population continues to rise, coupled with the increasing pressures of climate change, the need for innovative solutions to manage natural resources sustainably has never been more urgent. The integration of IoT technologies in these sectors presents a unique opportunity to optimize resource use, improve efficiency, and mitigate environmental impacts (Rosca *et al.*, 2021; Yasin *et al.*, 2021).

Agriculture is a critical sector that significantly influences environmental sustainability. It is responsible for a substantial portion of global freshwater consumption and is heavily impacted by climate variability. Traditional agricultural practices often lead to inefficient water usage, soil degradation, and excessive application of fertilizers and pesticides, which can harm ecosystems and human health. The application of IoT in agriculture, often referred to as Ag-IoT, enables farmers to monitor crop conditions, soil moisture levels, and weather patterns in real-time. This data-driven approach allows for precision farming, where resources are allocated more effectively, reducing waste and enhancing crop yields. Research indicates that IoT-based systems can lead to a reduction in water usage by up to 30% while simultaneously increasing agricultural productivity (Kamienski *et al.*, 2018; Sanjeevi *et al.*, 2020).

In parallel, water management is another area where IoT technologies can play a pivotal role in promoting sustainability. Water scarcity is a pressing global issue, exacerbated by population growth, urbanization, and climate change. Effective water management is essential not only for agricultural productivity but also for ensuring the availability of clean drinking water. IoT-enabled smart water management systems facilitate real-time monitoring of water quality and quantity, allowing for timely interventions to prevent pollution and over-extraction of water resources. For instance, sensors can detect contaminants in water bodies, enabling swift action to protect public health and aquatic ecosystems (Maroli *et al.*, 2021; Pérez-Padillo *et al.*, 2020). Furthermore, IoT applications in water distribution networks can identify leaks and inefficiencies, significantly reducing water loss and improving service delivery (Abebe, 2024; Kadar *et al.*, 2018).

The literature on IoT applications in environmental sustainability is growing, with numerous studies exploring various aspects of smart monitoring systems in agriculture and water management. For instance, the article "Internet of Things for Environmental Sustainability and Climate Change" provides a comprehensive overview of how IoT can be leveraged to address environmental challenges, highlighting its potential to enhance resilience against climate change impacts (Roşca *et al.*, 2021). Similarly, "Ag-IoT for Crop and Environment Monitoring: Past, Present, and Future" traces the evolution of IoT technologies in agriculture, offering insights into their current applications and future prospects (Bashar, 2020). The article "Advances in Smart Environment Monitoring Systems Using IoT and Sensors" delves into the technological advancements that have enabled more sophisticated monitoring systems, while "Internet of Things and Wireless Sensor Networks for Smart Agriculture Applications: A Survey" presents a survey of existing IoT solutions tailored for agricultural applications (Kamienski *et al.*, 2018; Yasin *et al.*, 2021). Lastly, "Internet of Things for Water Sustainability" focuses specifically on the role of IoT in promoting sustainable water management practices (Pérez-Padillo *et al.*, 2020).

This literature review aims to synthesize findings from these key articles, providing a comprehensive understanding of the current state of IoT applications in environmental sustainability. By examining the intersection of IoT technologies with agricultural practices and water management strategies, this review seeks to highlight best practices, identify gaps in the existing literature, and propose future research directions. Ultimately, the goal is to contribute to the ongoing discourse on how IoT can be harnessed to foster sustainable development and address pressing environmental challenges (Aivazidou *et al.*, 2021; Rosca *et al.*, 2021).

The integration of IoT technologies into agriculture and water management represents a significant advancement towards achieving environmental sustainability. As the body of research continues to grow, it is imperative to critically assess the effectiveness of these technologies and their potential to create resilient and sustainable systems. This literature review will serve as a foundational resource for researchers, practitioners, and policymakers seeking to understand and implement IoT solutions that promote environmental sustainability in the face of global challenges (Aivazidou *et al.*, 2021; Bashar, 2020).

RESEARCH METHODOLOGY

This research employs a literature review method to analyze and examine research articles related to IoT applications in environmental sustainability, specifically focusing on smart monitoring systems in agriculture and water management. The review analyzes five articles from Q1 Scopus journals, selected based on their relevance to IoT implementations in agriculture and water management sectors. Only five articles are reviewed for the following reasons: 1) focus on the most influential studies and 2) depth of analysis. Articles published in Q1 journals generally have a greater impact on the academic community. By limiting the review to five articles from these journals, this study can focus on research that significantly contributes to the development of IoT in water management and agriculture. By selecting five high-quality articles, this review can provide a more in-depth analysis of each study rather than conducting a broad review of many articles with only a superficial analysis. The data from the five reviewed articles are presented in Table 1.

Table 1. Reviewed Articles Data

No.	Article Data	Journal/Publisher
1	Ag-IoT for crop and environment monitoring: Past, present, and future. Chamara, N., Islam, M. D., Bai, G. F., Shi, Y., & Ge, Y. 2022	*Agricultural systems*, *203*, 103497. ELSEVIER
2	Framework for the implementation of an Internet of Things (IoT)-based water distribution and	*Clean Technologies and Environmental Policy*, *23*(1),

	management system. Maroli, A. A., Narwane, V. S., Raut, R. D., & Narkhede, B. E. 2021	271–283. https://doi.org/10.1007/s10098-020-01975-z SPRINGER
3	Smart technologies for sustainable water management: An urban analysis. Aivazidou, E., Banias, G., Lampridi, M., Vasileiadis, G., Anagnostis, A., Papageorgiou, E., & Bochtis, D. 2021	*Sustainability*, *13*(24), 13940. MDPI
4	Design and implementation of a pressure monitoring system based on iot for water supply networks. Pérez-Padillo, J., García Morillo, J., Ramirez-Faz, J., Torres Roldán, M., & Montesinos, P. 2020	*Sensors*, *20*(15), 4247. MDPI
5	Advances in smart environment monitoring systems using IoT and sensors. Ullo, S. L., & Sinha, G. R. 2020	*Sensors*, *20*(11), 3113. MDPI

The analysis process involves several key steps in examining each selected article. Initially, the main ideas and findings from each article are identified and documented. These findings are then categorized based on relevant themes to facilitate a comprehensive understanding of the subject matter. The analysis focuses on various aspects, including: 1) the types of IoT applications implemented, 2) sensor technologies utilized, 3) environmental parameters monitored, 4) implementation results and benefits, 5) challenges and limitations encountered, and 6) recommendations for future development. This approach allows for a thorough examination of how IoT technologies are being applied in agricultural and water management systems.

In analyzing the selected articles, particular attention is paid to comparing and integrating findings from different studies to identify common themes, patterns, and variations in IoT implementations. The review examines both technical aspects, such as sensor specifications and monitoring systems, as well as practical considerations including implementation challenges and success factors. This comprehensive approach ensures that the review captures both theoretical frameworks and practical applications of IoT in environmental monitoring systems.

The findings from this literature review are presented through descriptive discussions, and synthesized findings. The presentation of results aims to provide a clear and comprehensive understanding of the current state of IoT applications in environmental sustainability, particularly in agriculture and water management. Through this analysis, the review seeks to identify trends, gaps, and opportunities in the field, contributing to the broader understanding of IoT applications in environmental monitoring systems.

This methodology enables a comprehensive review of existing literature while maintaining focus on practical applications and implementations. The approach allows for the identification of best practices, common challenges, and potential areas for future research and development in the field of IoT-based environmental monitoring systems.

RESULT AND DISCUSSION

The integration of Internet of Things (IoT) technologies in environmental management has led to significant advancements across various sectors, particularly in water management and agricultural practices that examine cases on a global scale. The study by Maroli *et al.* (2021) discusses the implementation of an Internet of Things (IoT)-based water distribution and management system in rural India. Chamara *et al.*, (2022) has conducted research in Asia. Aivazidou's *et al.*, (2021) work discusses the implementation of smart water management technologies in urban settings across European countries. And other research conducted by Ullo and Perez-Padillo (2020) discusses water management and agricultural practices in a global context.

This synthesis will explore the types of IoT applications implemented, the sensor technologies utilized, the environmental parameters monitored, the implementation results and benefits, the challenges and limitations encountered, and recommendations for future development.

1. Types of IoT Applications Implemented

IoT applications are diverse, spanning water distribution systems, agricultural monitoring, and urban environmental management. In water management, IoT systems are employed for real-time monitoring of water quality and distribution efficiency, as demonstrated by Maroli, who proposed a cloud-centric architecture for smart metering in urban settings (Maroli *et al.*, 2021). In agriculture, the Ag-IoT framework enhances crop management through real-time data collection and analysis, improving decision-making processes (Chamara *et al.*, 2022). These applications not only optimize resource use but also foster sustainable practices in urban and rural environments.

Based on these findings, it is evident that IoT applications have evolved beyond simple monitoring systems to become comprehensive management solutions. The integration of cloud-centric architectures in water management, as proposed by Maroli et al., represents a significant advancement in urban resource management. This approach not only enables real-time monitoring but also facilitates predictive maintenance and efficient resource allocation, which are crucial for sustainable urban development. The implementation of such systems indicates a shift towards more proactive and data-driven management approaches in urban water infrastructure.

Similarly, the Ag-IoT framework's application in agricultural settings demonstrates the versatility of IoT technologies in addressing different environmental challenges. The real-time data collection and analysis capabilities have transformed traditional farming practices into precision agriculture, enabling farmers to make informed decisions based on accurate, timely data. This transformation is particularly significant as it addresses both productivity and sustainability concerns in agricultural sectors. The adoption of these technologies suggests a growing recognition of the need to balance agricultural productivity with environmental sustainability.

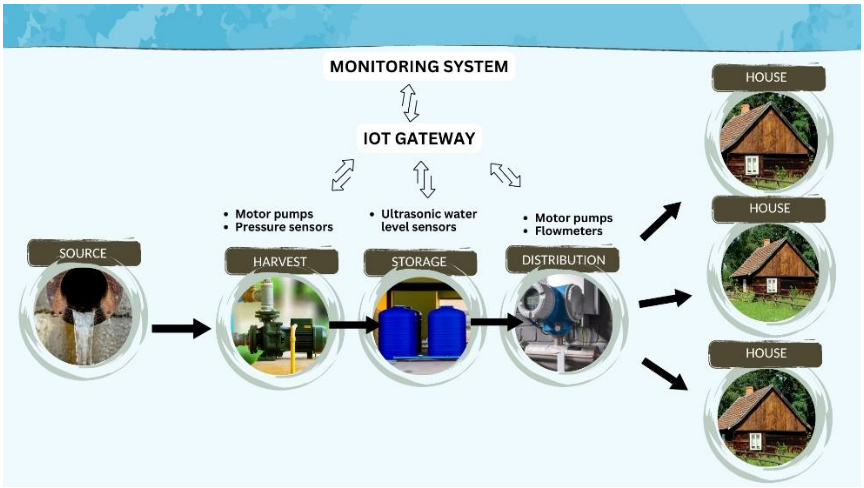

Figure 1. General outline of water management and distribution system
Source: (Maroli *et al.*, 2021)

Furthermore, the successful implementation of IoT applications across both urban and rural environments highlights the technology's adaptability and scalability. This versatility is crucial for addressing diverse environmental challenges and suggests that IoT-based solutions can be effectively customized for different contexts while maintaining their core functionality of resource optimization and sustainable management.

2. Sensor Technologies Utilized

A variety of sensor technologies are integral to IoT applications. For instance, wireless sensor networks are utilized for monitoring water quality parameters such as pH, turbidity, and nutrient levels (Aivazidou *et al.*, 2021). In agricultural contexts, sensors for soil moisture, temperature, and humidity are commonly deployed to facilitate precision farming (Chamara *et al.*, 2022). The use of advanced sensors, including gas sensors for air quality monitoring and thermal sensors for crop health assessment, underscores the versatility of IoT technologies in environmental monitoring (Ullo & Sinha, 2020).

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The deployment of diverse sensor technologies across different environmental monitoring applications reveals several important insights about the current state and future direction of IoT implementations. The widespread adoption of wireless sensor networks for water quality monitoring, as demonstrated by Aivazidou *et al.*, (2021) represents a significant advancement in environmental monitoring capabilities. This technology choice is particularly noteworthy as it enables comprehensive data collection while minimizing infrastructure disruption, suggesting a growing emphasis on both effectiveness and practical implementation considerations.

The integration of multiple sensor types in agricultural applications, as shown in Chamara *et al.* (2022) work, indicates a sophisticated understanding of the interconnected nature of agricultural parameters. The combination of soil moisture, temperature, and humidity sensors demonstrates a holistic approach to precision farming, acknowledging that successful crop management requires monitoring multiple environmental factors simultaneously. This multi-parameter monitoring approach marks a significant evolution from traditional single-factor monitoring methods.

Moreover, the implementation of advanced sensors such as gas and thermal sensors, as discussed by Ullo & Sinha (2020), suggests a trend toward more sophisticated and comprehensive monitoring solutions. The ability to monitor air quality and crop health through thermal imaging represents a technological leap that enables more precise and proactive environmental management. This advancement in sensor technology not only improves the accuracy of environmental monitoring but also expands the scope of what can be measured and managed in real-time.

These developments in sensor technology deployment also highlight the growing maturity of IoT implementations in environmental monitoring. The transition from basic environmental parameters to more complex measurements indicates both technological advancement and a deeper understanding of environmental monitoring requirements. This evolution suggests that future IoT implementations will likely continue to incorporate increasingly sophisticated sensor technologies, potentially leading to even more comprehensive and effective environmental monitoring systems.

3. Environmental Parameters Monitored

The environmental parameters monitored through IoT systems are extensive. In water management, parameters such as water flow rate, quality indicators (e.g., chlorophyll-A concentration), and leak detection are critical (Aivazidou *et al.*, 2021). In agricultural settings, parameters include soil moisture, crop canopy temperature, and atmospheric conditions, which are essential for optimizing irrigation and enhancing crop yield (Chamara *et al.*, 2022). Additionally, urban air quality is monitored through sensors that track concentrations of pollutants like O^3, NO^2, and SO^2, providing vital data for public health and environmental policy (Ullo & Sinha, 2020).

Based on the literature summary, it can be interpreted that the implementation of IoT systems in environmental monitoring has developed holistically, covering various vital aspects of life. These systems are not only focused on one sector but are integrated into water management, agriculture, and urban air quality, demonstrating the complexity and interconnection in modern environmental management.

The application of IoT technology in monitoring environmental parameters reflects a paradigm shift in environmental management, from a reactive approach to a more proactive and data-driven one. The ability to monitor various parameters in real-time and simultaneously enables more accurate and rapid decision-making, which ultimately can improve resource use efficiency and support long-term environmental sustainability.

4. Implementation Results and Benefits

The implementation of IoT technologies has yielded significant benefits, including improved resource efficiency and enhanced decision-making capabilities. For example, the use of IoT in water management has led to timely detection of leaks and better allocation of water resources, ultimately reducing waste and operational costs (Aivazidou *et al.*, 2021). In agriculture, real-time monitoring has enabled farmers to optimize irrigation schedules and apply fertilizers more effectively, resulting in increased crop yields and reduced environmental impact (Chamara *et al.*, 2022). Furthermore, the integration of big data analytics with IoT systems enhances the predictive capabilities of these applications, allowing for proactive management strategies (Aivazidou *et al.*, 2021; Maroli *et al.*, 2021).

Based on the synthesis of these studies, it is evident that IoT implementation has revolutionized environmental resource management by introducing sophisticated monitoring and control systems. The documented improvements in both water management and agricultural practices demonstrate that IoT technologies are not just technological additions but fundamental tools that transform operational efficiency and resource utilization across different environmental sectors.

The integration of IoT with big data analytics, as highlighted in the literature, marks a significant advancement in environmental management practices. This technological convergence enables a shift from traditional reactive approaches to more sophisticated predictive management strategies, suggesting that the future of environmental resource management will increasingly rely on data-driven decision-making processes. The consistent positive outcomes reported across different applications indicate that IoT-based solutions are becoming essential tools for achieving sustainable environmental management practices.

5. Challenges and Limitations Encountered

Despite the advantages, several challenges hinder the widespread adoption of IoT in environmental management. High implementation costs, particularly for sensor deployment and maintenance, pose significant barriers (Aivazidou *et al.*, 2021; Ullo & Sinha, 2020). Additionally, issues related to data privacy and cybersecurity are critical, as the reliance on cloud-based systems increases vulnerability to cyber threats (Aivazidou *et al.*, 2021). Furthermore, the integration of diverse sensor technologies and the need for standardized protocols can complicate system interoperability ("Framework for the implementation of an Internet of Things (Aivazidou *et al.*, 2021; Maroli *et al.*, 2021).

Based on the literature review findings, it appears that the widespread adoption of IoT in environmental management faces a complex web of interconnected challenges. The economic barriers, particularly in terms of implementation and maintenance costs, suggest that IoT adoption may be particularly challenging for smaller organizations or developing regions, potentially creating a technological divide in environmental management capabilities.

The identified security and integration challenges point to a critical need for systematic solutions in IoT implementation. The recurring mention of cybersecurity concerns and standardization issues across multiple studies indicates that these are not merely technical hurdles but fundamental challenges that require coordinated efforts from technology developers, policymakers, and end-users. This suggests that the future success of IoT in environmental management will likely depend not only on technological advancements but also on the development of comprehensive frameworks that address both security and interoperability concerns while maintaining cost-effectiveness.

6. Recommendations for Future Development

To overcome these challenges, future development should focus on enhancing the affordability and accessibility of IoT technologies. Research into underground wireless communication and the Internet of Underground Things could alleviate logistical issues related to sensor installation in agricultural settings (Chamara *et al.*, 2022). Additionally, fostering public engagement in smart water management initiatives can enhance community involvement and support for sustainable practices (Aivazidou *et al.*, 2021).

Finally, addressing cybersecurity concerns through robust frameworks and regulations will be essential to ensure the reliability and safety of IoT systems in environmental management (Aivazidou *et al.*, 2021). In conclusion, the application of IoT technologies in environmental management presents a promising avenue for enhancing sustainability and efficiency. By addressing the existing challenges and leveraging the benefits of IoT, stakeholders can significantly improve resource management practices in both urban and rural contexts.

CONCLUSION

In conclusion, the integration of Internet of Things (IoT) technologies in environmental management has demonstrated significant potential across various sectors, particularly in water management and agriculture. The diverse applications of IoT, ranging from real-time water quality monitoring to precision farming, underscore its versatility and effectiveness in optimizing resource use and promoting sustainable practices. The utilization of advanced sensor technologies, such as wireless sensor networks and environmental sensors, has enabled comprehensive monitoring of critical parameters, including water quality, soil moisture, and air pollution levels.

However, the widespread adoption of IoT in environmental management is not without its challenges. High implementation costs, data privacy concerns, and issues related to system interoperability pose significant barriers to the effective deployment of these technologies. Addressing these challenges will require focused efforts on enhancing the affordability and accessibility of IoT solutions, as well as fostering public engagement in sustainable practices.

Looking ahead, future development should prioritize research into innovative communication technologies, such as underground wireless communication, to facilitate sensor deployment in challenging environments. Additionally, establishing standardized protocols for data sharing and enhancing cybersecurity measures will be crucial for building trust and ensuring the integrity of IoT systems in environmental management. By overcoming these obstacles, IoT has the potential to play a transformative role in promoting sustainable environmental practices and improving overall resource management.

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